Lab 2: Cats vs Dogs

In this lab, you will train a convolutional neural network to classify an image into one of two classes: "cat" or "dog". The code for the neural networks you train will be written for you, and you are not (yet!) expected to understand all provided code. However, by the end of the lab, you should be able to:

1. Understand at a high level the training loop for a machine learning model.
2. Understand the distinction between training, validation, and test data.
3. The concepts of overfitting and underfitting.
4. Investigate how different hyperparameters, such as learning rate and batch size, affect the success of training.
5. Compare an ANN (aka Multi-Layer Perceptron) with a CNN.

What to submit

Submit a PDF file containing all your code, outputs, and write-up from parts 1-5. You can produce a PDF of your Google Colab file by going to **File > Print** and then save as PDF. The Colab instructions has more information.

Do not submit any other files produced by your code.

Include a link to your colab file in your submission.

Please use Google Colab to complete this assignment. If you want to use Jupyter Notebook, please complete the assignment and upload your Jupyter Notebook file to Google Colab for submission.

With Colab, you can export a PDF file using the menu option `File -> Print` and save as PDF file. **Adjust the scaling to ensure that the text is not cutoff at the margins.**

Colab Link

Include a link to your colab file here

Colab Link: https://colab.research.google.com/drive/19yU_e179LvCwu_me09V5rCA-WMwa4r-D?usp=sharing

In [ ]:
```
import numpy as np
import time
import torch
import torch.nn as nn
import torch.nn.functional as F
import torch.optim as optim
import torchvision
from torch.utils.data.sampler import SubsetRandomSampler
import torchvision.transforms as transforms
```

Part 0. Helper Functions

We will be making use of the following helper functions. You will be asked to look at and possibly modify some of these, but you are not expected to understand all of them.

You should look at the function names and read the docstrings. If you are curious, come back and explore the code *after* making some progress on the lab.

In [ ]:

```
################################################################################
# Data Loading

def get_relevant_indices(dataset, classes, target_classes):
    """ Return the indices for datapoints in the dataset that belongs to the
    desired target classes, a subset of all possible classes.

    Args:
        dataset: Dataset object
        classes: A list of strings denoting the name of each class
        target_classes: A list of strings denoting the name of desired classes
                        Should be a subset of the 'classes'
    Returns:
        indices: list of indices that have labels corresponding to one of the
                 target classes
    """
    indices = []
    for i in range(len(dataset)):
        # Check if the label is in the target classes
        label_index = dataset[i][1] # ex: 3
        label_class = classes[label_index] # ex: 'cat'
        if label_class in target_classes:
            indices.append(i)
    return indices

def get_data_loader(target_classes, batch_size):
    """ Loads images of cats and dogs, splits the data into training, validation
    and testing datasets. Returns data loaders for the three preprocessed datasets.

    Args:
        target_classes: A list of strings denoting the name of the desired
                        classes. Should be a subset of the argument 'classes'
        batch_size: A int representing the number of samples per batch

    Returns:
        train_loader: iterable training dataset organized according to batch size
        val_loader: iterable validation dataset organized according to batch size
        test_loader: iterable testing dataset organized according to batch size
        classes: A list of strings denoting the name of each class
    """

    classes = ('plane', 'car', 'bird', 'cat',
               'deer', 'dog', 'frog', 'horse', 'ship', 'truck')
    ########################################################################
    # The output of torchvision datasets are PILImage images of range [0, 1].
    # We transform them to Tensors of normalized range [-1, 1].
    transform = transforms.Compose(
        [transforms.ToTensor(),
         transforms.Normalize((0.5, 0.5, 0.5), (0.5, 0.5, 0.5))])
    # Load CIFAR10 training data
    trainset = torchvision.datasets.CIFAR10(root='./data', train=True,
                                            download=True, transform=transform)
    # Get the list of indices to sample from
    relevant_indices = get_relevant_indices(trainset, classes, target_classes)

    # Split into train and validation
    np.random.seed(1000) # Fixed numpy random seed for reproducible shuffling
    np.random.shuffle(relevant_indices)
    split = int(len(relevant_indices) * 0.8) #split at 80%

    # split into training and validation indices
    relevant_train_indices, relevant_val_indices = relevant_indices[:split], relevant
    train_sampler = SubsetRandomSampler(relevant_train_indices)
    train_loader = torch.utils.data.DataLoader(trainset, batch_size=batch_size,
                                               num_workers=1, sampler=train_sampler)
    val_sampler = SubsetRandomSampler(relevant_val_indices)
    val_loader = torch.utils.data.DataLoader(trainset, batch_size=batch_size,
                                             num_workers=1, sampler=val_sampler)
    # Load CIFAR10 testing data
```

```
    # Load CIFAR10 testing data
    testset = torchvision.datasets.CIFAR10(root='./data', train=False,
                                           download=True, transform=transform)
    # Get the list of indices to sample from
    relevant_test_indices = get_relevant_indices(testset, classes, target_classes)
    test_sampler = SubsetRandomSampler(relevant_test_indices)
    test_loader = torch.utils.data.DataLoader(testset, batch_size=batch_size,
                                              num_workers=1, sampler=test_sampler)
    return train_loader, val_loader, test_loader, classes

################################################################################
# Training
def get_model_name(name, batch_size, learning_rate, epoch):
    """ Generate a name for the model consisting of all the hyperparameter values

    Args:
        config: Configuration object containing the hyperparameters
    Returns:
        path: A string with the hyperparameter name and value concatenated
    """
    path = "model_{0}_bs{1}_lr{2}_epoch{3}".format(name,
                                                   batch_size,
                                                   learning_rate,
                                                   epoch)
    return path

def normalize_label(labels):
    """
    Given a tensor containing 2 possible values, normalize this to 0/1

    Args:
        labels: a 1D tensor containing two possible scalar values
    Returns:
        A tensor normalize to 0/1 value
    """
    max_val = torch.max(labels)
    min_val = torch.min(labels)
    norm_labels = (labels - min_val)/(max_val - min_val)
    return norm_labels

def evaluate(net, loader, criterion):
    """ Evaluate the network on the validation set.

     Args:
         net: PyTorch neural network object
         loader: PyTorch data loader for the validation set
         criterion: The loss function
     Returns:
         err: A scalar for the avg classification error over the validation set
         loss: A scalar for the average loss function over the validation set
     """
    total_loss = 0.0
    total_err = 0.0
    total_epoch = 0
    for i, data in enumerate(loader, 0):
        inputs, labels = data
        labels = normalize_label(labels)  # Convert labels to 0/1
        outputs = net(inputs)
        loss = criterion(outputs, labels.float())
        corr = (outputs > 0.0).squeeze().long() != labels
        total_err += int(corr.sum())
        total_loss += loss.item()
        total_epoch += len(labels)
    err = float(total_err) / total_epoch
    loss = float(total_loss) / (i + 1)
    return err, loss

################################################################################
# Training Curve
def plot_training_curve(path):
```

```
def plot_training_curve(path):
    """ Plots the training curve for a model run, given the csv files
    containing the train/validation error/loss.

    Args:
        path: The base path of the csv files produced during training
    """
    import matplotlib.pyplot as plt
    train_err = np.loadtxt("{}_train_err.csv".format(path))
    val_err = np.loadtxt("{}_val_err.csv".format(path))
    train_loss = np.loadtxt("{}_train_loss.csv".format(path))
    val_loss = np.loadtxt("{}_val_loss.csv".format(path))
    plt.title("Train vs Validation Error")
    n = len(train_err) # number of epochs
    plt.plot(range(1,n+1), train_err, label="Train")
    plt.plot(range(1,n+1), val_err, label="Validation")
    plt.xlabel("Epoch")
    plt.ylabel("Error")
    plt.legend(loc='best')
    plt.show()
    plt.title("Train vs Validation Loss")
    plt.plot(range(1,n+1), train_loss, label="Train")
    plt.plot(range(1,n+1), val_loss, label="Validation")
    plt.xlabel("Epoch")
    plt.ylabel("Loss")
    plt.legend(loc='best')
    plt.show()
```

Part 1. Visualizing the Data [7 pt]

We will make use of some of the CIFAR-10 data set, which consists of colour images of size 32x32 pixels belonging to 10 categories. You can find out more about the dataset at https://www.cs.toronto.edu/~kriz/cifar.html

For this assignment, we will only be using the cat and dog categories. We have included code that automatically downloads the dataset the first time that the main script is run.

In [ ]:
```
# This will download the CIFAR-10 dataset to a folder called "data"
# the first time you run this code.
train_loader, val_loader, test_loader, classes = get_data_loader(
    target_classes=["cat", "dog"],
    batch_size=1) # One image per batch
```

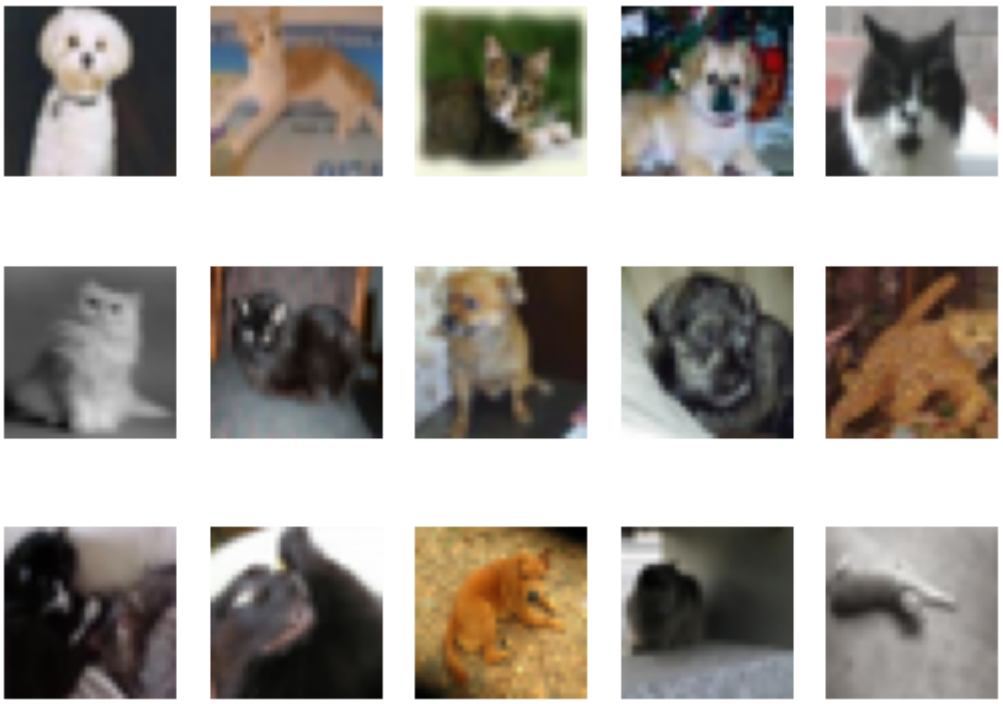
```
Downloading https://www.cs.toronto.edu/~kriz/cifar-10-python.tar.gz to ./data/cifar-10-python.tar.gz
100%|██████████| 170498071/170498071 [00:02<00:00, 61676333.37it/s]
Extracting ./data/cifar-10-python.tar.gz to ./data
Files already downloaded and verified
```

Part (a) -- 1 pt

Visualize some of the data by running the code below. Include the visualization in your writeup.

(You don't need to submit anything else.)

In [ ]:
```
import matplotlib.pyplot as plt

k = 0
for images, labels in train_loader:
    # since batch_size = 1, there is only 1 image in `images`
    image = images[0]
    # place the colour channel at the end, instead of at the beginning
    img = np.transpose(image, [1,2,0])
    # normalize pixel intensity values to [0, 1]
    img = img / 2 + 0.5
    plt.subplot(3, 5, k+1)
    plt.axis('off')
    plt.imshow(img)

    k += 1
    if k > 14:
        break
```



Part (b) -- 3 pt

How many training examples do we have for the combined `cat` and `dog` classes? What about validation examples? What about test examples?

In [ ]:
```
print("number of training:", len(train_loader))
print("number of validation:", len(val_loader))
print("number of test:", len(test_loader))
```

```
number of training: 8000
number of validation: 2000
number of test: 2000
```

Part (c) -- 3pt

Why do we need a validation set when training our model? What happens if we judge the performance of our models using the training set loss/error instead of the validation set loss/error?

We need the validation set because we want a set of examples to tune the program's hyperparameters. We use the validation set to find the appropriate pause point for the backpropagation process. If we judge the performance of our models using the training set loss/error instead of the validation set ones, we could create an overfitted model with biases and a too-optimistic error rate estimation.

Part 2. Training [15 pt]

We define two neural networks, a `LargeNet` and `SmallNet`. We'll be training the networks in this section.

You won't understand fully what these networks are doing until the next few classes, and that's okay. For this assignment, please focus on learning how to train networks, and how hyperparameters affect training.

In [ ]:
```
class LargeNet(nn.Module):
    def __init__(self):
        super(LargeNet, self).__init__()
        self.name = "large"
        self.conv1 = nn.Conv2d(3, 5, 5)
        self.pool = nn.MaxPool2d(2, 2)
        self.conv2 = nn.Conv2d(5, 10, 5)
        self.fc1 = nn.Linear(10 * 5 * 5, 32)
        self.fc2 = nn.Linear(32, 1)

    def forward(self, x):
        x = self.pool(F.relu(self.conv1(x)))
        x = self.pool(F.relu(self.conv2(x)))
        x = x.view(-1, 10 * 5 * 5)
        x = F.relu(self.fc1(x))
        x = self.fc2(x)
        x = x.squeeze(1) # Flatten to [batch_size]
        return x
```

In [ ]:
```
class SmallNet(nn.Module):
    def __init__(self):
        super(SmallNet, self).__init__()
        self.name = "small"
        self.conv = nn.Conv2d(3, 5, 3)
        self.pool = nn.MaxPool2d(2, 2)
        self.fc = nn.Linear(5 * 7 * 7, 1)

    def forward(self, x):
        x = self.pool(F.relu(self.conv(x)))
        x = self.pool(x)
        x = x.view(-1, 5 * 7 * 7)
        x = self.fc(x)
        x = x.squeeze(1) # Flatten to [batch_size]
        return x
```

In [ ]:
```
small_net = SmallNet()
large_net = LargeNet()
```

Part (a) -- 2pt

The methods `small_net.parameters()` and `large_net.parameters()` produces an iterator of all the trainable parameters of the network. These parameters are torch tensors containing many scalar values.

We haven't learned how how the parameters in these high-dimensional tensors will be used, but we should be able to count the number of parameters. Measuring the number of parameters in a network is one way of measuring the "size" of a network.

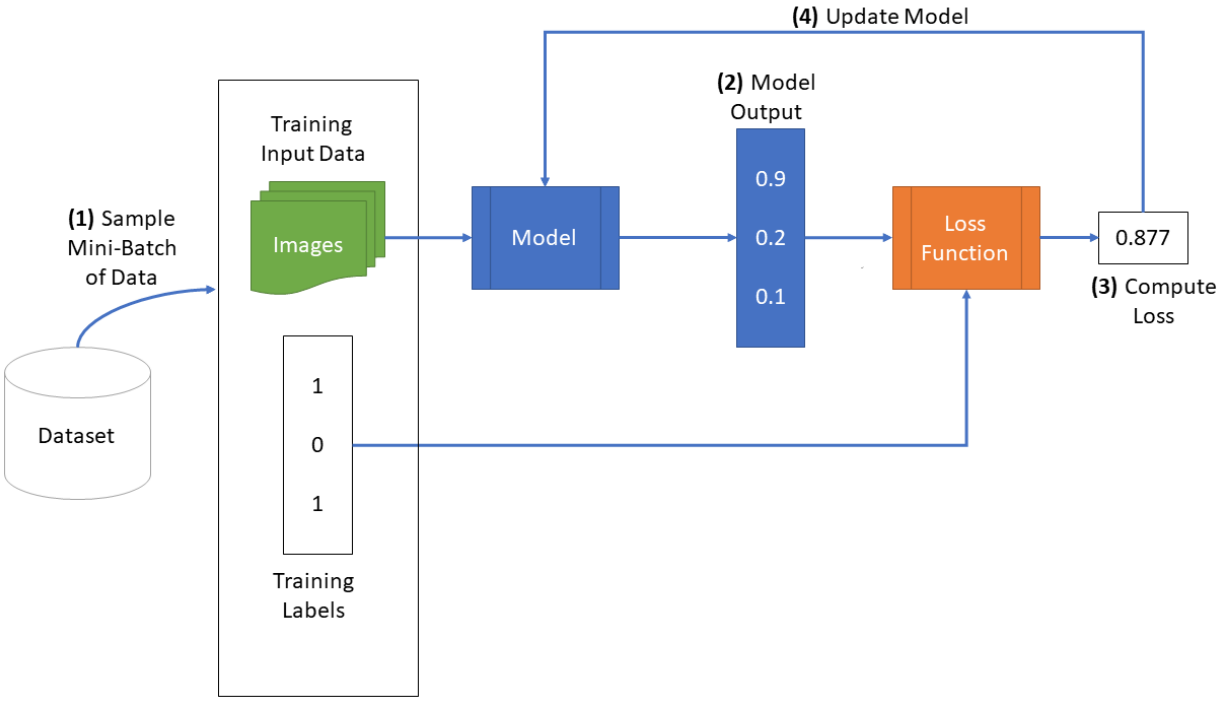
What is the total number of parameters in `small_net` and in `large_net` ? (Hint: how many numbers are in each tensor?)

In [ ]:
```
small = 0
large= 0

for param in small_net.parameters():
    small += param.numel()

for param in large_net.parameters():
    large += param.numel()

print("The number of small parameters is", small)
print("The number of large parameters is", large)
```

```
The number of small parameters is 386
The number of large parameters is 9705
```

The function train_net

The function `train_net` below takes an untrained neural network (like `small_net` and `large_net`) and several other parameters. You should be able to understand how this function works. The figure below shows the high level training loop for a machine learning model:



In [ ]:

```
def train_net(net, batch_size=64, learning_rate=0.01, num_epochs=30):
    ###########################################################################
    # Train a classifier on cats vs dogs
    target_classes = ["cat", "dog"]
    ###########################################################################
    # Fixed PyTorch random seed for reproducible result
    torch.manual_seed(1000)
    ###########################################################################
    # Obtain the PyTorch data loader objects to load batches of the datasets
    train_loader, val_loader, test_loader, classes = get_data_loader(
            target_classes, batch_size)
    ###########################################################################
    # Define the Loss function and optimizer
    # The loss function will be Binary Cross Entropy (BCE). In this case we
    # will use the BCEWithLogitsLoss which takes unnormalized output from
    # the neural network and scalar label.
    # Optimizer will be SGD with Momentum.
    criterion = nn.BCEWithLogitsLoss()
    optimizer = optim.SGD(net.parameters(), lr=learning_rate, momentum=0.9)
    ###########################################################################
    # Set up some numpy arrays to store the training/test loss/erruracy
    train_err = np.zeros(num_epochs)
    train_loss = np.zeros(num_epochs)
    val_err = np.zeros(num_epochs)
    val_loss = np.zeros(num_epochs)
    ###########################################################################
    # Train the network
    # Loop over the data iterator and sample a new batch of training data
    # Get the output from the network, and optimize our loss function.
    start_time = time.time()
    for epoch in range(num_epochs):  # loop over the dataset multiple times
        total_train_loss = 0.0
        total_train_err = 0.0
        total_epoch = 0
        for i, data in enumerate(train_loader, 0):
            # Get the inputs
            inputs, labels = data
            labels = normalize_label(labels) # Convert labels to 0/1
            # Zero the parameter gradients
            optimizer.zero_grad()
            # Forward pass, backward pass, and optimize
            outputs = net(inputs)
            loss = criterion(outputs, labels.float())
            loss.backward()
            optimizer.step()
            # Calculate the statistics
            corr = (outputs > 0.0).squeeze().long() != labels
            total_train_err += int(corr.sum())
            total_train_loss += loss.item()
            total_epoch += len(labels)
        train_err[epoch] = float(total_train_err) / total_epoch
        train_loss[epoch] = float(total_train_loss) / (i+1)
        val_err[epoch], val_loss[epoch] = evaluate(net, val_loader, criterion)
        print(("Epoch {}: Train err: {}, Train loss: {} |"+
               "Validation err: {}, Validation loss: {}").format(
                   epoch + 1,
                   train_err[epoch],
                   train_loss[epoch],
                   val_err[epoch],
                   val_loss[epoch]))
        # Save the current model (checkpoint) to a file
        model_path = get_model_name(net.name, batch_size, learning_rate, epoch)
        torch.save(net.state_dict(), model_path)
    print('Finished Training')
    end_time = time.time()
    elapsed_time = end_time - start_time
    print("Total time elapsed: {:.2f} seconds".format(elapsed_time))
    # Write the train/test loss/err into CSV file for plotting later
```

```
    epochs = np.arange(1, num_epochs + 1)
    np.savetxt("{}_train_err.csv".format(model_path), train_err)
    np.savetxt("{}_train_loss.csv".format(model_path), train_loss)
    np.savetxt("{}_val_err.csv".format(model_path), val_err)
    np.savetxt("{}_val_loss.csv".format(model_path), val_loss)
```

Part (b) -- 1pt

The parameters to the function `train_net` are hyperparameters of our neural network. We made these hyperparameters easy to modify so that we can tune them later on.

What are the default values of the parameters `batch_size`, `learning_rate`, and `num_epochs`?

The default values are batch_size=64, learning_rate=0.01, and num_epochs=30.

Part (c) -- 3 pt

What files are written to disk when we call `train_net` with `small_net`, and train for 5 epochs? Provide a list of all the files written to disk, and what information the files contain.

five disk file that saves the version of the neural network that was developed per epoch:

- model_small_bs64_lr0.01_epoch0
- model_small_bs64_lr0.01_epoch1
- model_small_bs64_lr0.01_epoch2
- model_small_bs64_lr0.01_epoch3
- model_small_bs64_lr0.01_epoch4

These files contain the values on the train error/values and validation error/loss values at epoch 4 as .csv file:

- model_small_bs64_lr0.01_epoch4_train_err.csv
- model_small_bs64_lr0.01_epoch4_train_loss.csv
- model_small_bs64_lr0.01_epoch4_val_err.csv
- model_small_bs64_lr0.01_epoch4_val_loss.csv

Part (d) -- 2pt

Train both `small_net` and `large_net` using the function `train_net` and its default parameters. The function will write many files to disk, including a model checkpoint (saved values of model weights) at the end of each epoch.

If you are using Google Colab, you will need to mount Google Drive so that the files generated by `train_net` gets saved. We will be using these files in part (d). (See the Google Colab tutorial for more information about this.)

Report the total time elapsed when training each network. Which network took longer to train? Why?

In [ ]:
```
# Since the function writes files to disk, you will need to mount
# your Google Drive. If you are working on the lab locally, you
# can comment out this code.

from google.colab import drive
drive.mount('/content/gdrive')
```

```
Mounted at /content/gdrive
```

In [ ]:

```
# small_net train
train_net(small_net,64,0.01,30)

# large_net train
train_net(large_net,64,0.01,30)
```

```
Files already downloaded and verified
Files already downloaded and verified
Epoch 1: Train err: 0.42275, Train loss: 0.673784264087677 |Validation err: 0.378, Va
lidation loss: 0.6565281003713608
Epoch 2: Train err: 0.37, Train loss: 0.6458141713142395 |Validation err: 0.371, Vali
dation loss: 0.652947960421443
Epoch 3: Train err: 0.3495, Train loss: 0.6265174641609191 |Validation err: 0.3465, V
alidation loss: 0.6212373971939087
Epoch 4: Train err: 0.3325, Train loss: 0.6074911532402039 |Validation err: 0.36, Val
idation loss: 0.6289773602038622
Epoch 5: Train err: 0.323125, Train loss: 0.5964790120124817 |Validation err: 0.333,
Validation loss: 0.6159699466079473
Epoch 6: Train err: 0.31325, Train loss: 0.5861919419765472 |Validation err: 0.3325,
Validation loss: 0.613245127722621
Epoch 7: Train err: 0.308625, Train loss: 0.5836091318130493 |Validation err: 0.327,
Validation loss: 0.6075554452836514
Epoch 8: Train err: 0.303, Train loss: 0.5773005082607269 |Validation err: 0.324, Val
idation loss: 0.6029766276478767
Epoch 9: Train err: 0.303875, Train loss: 0.5767975461483001 |Validation err: 0.3185,
Validation loss: 0.6037592180073261
Epoch 10: Train err: 0.293375, Train loss: 0.5699512040615082 |Validation err: 0.317
5, Validation loss: 0.5982077224180102
Epoch 11: Train err: 0.2935, Train loss: 0.5700712842941285 |Validation err: 0.322, V
alidation loss: 0.5998525805771351
Epoch 12: Train err: 0.289375, Train loss: 0.5639399707317352 |Validation err: 0.325,
Validation loss: 0.6080638393759727
Epoch 13: Train err: 0.29375, Train loss: 0.5663222675323486 |Validation err: 0.318,
Validation loss: 0.6010407824069262
Epoch 14: Train err: 0.2845, Train loss: 0.560958818435669 |Validation err: 0.3245, V
alidation loss: 0.6148435082286596
Epoch 15: Train err: 0.290125, Train loss: 0.5602795343399047 |Validation err: 0.318
5, Validation loss: 0.59780084900558
Epoch 16: Train err: 0.29325, Train loss: 0.5637793521881104 |Validation err: 0.3255,
Validation loss: 0.6122169774025679
Epoch 17: Train err: 0.29075, Train loss: 0.560834774017334 |Validation err: 0.3215,
Validation loss: 0.6003245310857892
Epoch 18: Train err: 0.2905, Train loss: 0.5571012151241302 |Validation err: 0.32, Va
lidation loss: 0.6020927708595991
Epoch 19: Train err: 0.282625, Train loss: 0.5534428579807281 |Validation err: 0.328
5, Validation loss: 0.6135602109134197
Epoch 20: Train err: 0.2785, Train loss: 0.5525541863441468 |Validation err: 0.3195,
Validation loss: 0.6038764305412769
Epoch 21: Train err: 0.282625, Train loss: 0.5538638341426849 |Validation err: 0.319
5, Validation loss: 0.5984117649495602
Epoch 22: Train err: 0.27825, Train loss: 0.552840069770813 |Validation err: 0.322, V
alidation loss: 0.6106614442542195
Epoch 23: Train err: 0.28175, Train loss: 0.5518606379032135 |Validation err: 0.314,
Validation loss: 0.6038471991196275
Epoch 24: Train err: 0.279875, Train loss: 0.54989315366745 |Validation err: 0.3185,
Validation loss: 0.5973033271729946
Epoch 25: Train err: 0.275875, Train loss: 0.5451359975337983 |Validation err: 0.32,
Validation loss: 0.5983396405354142
Epoch 26: Train err: 0.27125, Train loss: 0.5449220223426818 |Validation err: 0.3145,
Validation loss: 0.596646387130022
Epoch 27: Train err: 0.272625, Train loss: 0.5443974087238311 |Validation err: 0.318,
Validation loss: 0.6095356112346053
Epoch 28: Train err: 0.27875, Train loss: 0.5466459100246429 |Validation err: 0.3205,
Validation loss: 0.603284515440464
Epoch 29: Train err: 0.273375, Train loss: 0.5453076586723328 |Validation err: 0.317
5, Validation loss: 0.6121445139870048
Epoch 30: Train err: 0.27325, Train loss: 0.543932067155838 |Validation err: 0.3255,
Validation loss: 0.6097493972629309
Finished Training
Total time elapsed: 138.48 seconds
Files already downloaded and verified
Files already downloaded and verified
Epoch 1: Train err: 0.45775, Train loss: 0.69027272939682 |Validation err: 0.415, Val
idation loss: 0.6807656120508909
Epoch 2: Train err: 0.40925, Train loss: 0.6729092464447022 |Validation err: 0.4315,
```

```
Validation loss: 0.6825121473520994
Epoch 3: Train err: 0.375875, Train loss: 0.6522225971221924 |Validation err: 0.338,
Validation loss: 0.6330283954739571
Epoch 4: Train err: 0.351375, Train loss: 0.6300180983543396 |Validation err: 0.353,
Validation loss: 0.6273993402719498
Epoch 5: Train err: 0.337625, Train loss: 0.6148874776363373 |Validation err: 0.323,
Validation loss: 0.6140869669616222
Epoch 6: Train err: 0.32225, Train loss: 0.6013187415599823 |Validation err: 0.325, V
alidation loss: 0.6088777799159288
Epoch 7: Train err: 0.3145, Train loss: 0.5918594233989716 |Validation err: 0.311, Va
lidation loss: 0.592976869083941
Epoch 8: Train err: 0.308, Train loss: 0.5772480311393737 |Validation err: 0.304, Val
idation loss: 0.5887311827391386
Epoch 9: Train err: 0.293125, Train loss: 0.5665752182006836 |Validation err: 0.307,
Validation loss: 0.586168852634728
Epoch 10: Train err: 0.287125, Train loss: 0.555210394859314 |Validation err: 0.3005,
Validation loss: 0.585071581415832
Epoch 11: Train err: 0.277, Train loss: 0.543303409576416 |Validation err: 0.307, Val
idation loss: 0.5888719754293561
Epoch 12: Train err: 0.270875, Train loss: 0.5306087613105774 |Validation err: 0.294,
Validation loss: 0.581076767295599
Epoch 13: Train err: 0.263125, Train loss: 0.5219863255023957 |Validation err: 0.300
5, Validation loss: 0.5811596605926752
Epoch 14: Train err: 0.253, Train loss: 0.510135217666626 |Validation err: 0.294, Val
idation loss: 0.5754655599594116
Epoch 15: Train err: 0.2445, Train loss: 0.501783432006836 |Validation err: 0.29, Val
idation loss: 0.5752244368195534
Epoch 16: Train err: 0.244625, Train loss: 0.4957042653560638 |Validation err: 0.289,
Validation loss: 0.5713661070913076
Epoch 17: Train err: 0.230875, Train loss: 0.4785855526924133 |Validation err: 0.289
5, Validation loss: 0.5648566987365484
Epoch 18: Train err: 0.224, Train loss: 0.46488813710212706 |Validation err: 0.286, V
alidation loss: 0.5823792535811663
Epoch 19: Train err: 0.225375, Train loss: 0.46417798709869384 |Validation err: 0.29
9, Validation loss: 0.5749336136505008
Epoch 20: Train err: 0.216125, Train loss: 0.45193399739265444 |Validation err: 0.33
2, Validation loss: 0.6579947713762522
Epoch 21: Train err: 0.2135, Train loss: 0.4469692120552063 |Validation err: 0.2945,
Validation loss: 0.5697514023631811
Epoch 22: Train err: 0.1955, Train loss: 0.4249165999889374 |Validation err: 0.294, V
alidation loss: 0.6051656221970916
Epoch 23: Train err: 0.199125, Train loss: 0.4251439971923828 |Validation err: 0.292,
Validation loss: 0.5836178418248892
Epoch 24: Train err: 0.191875, Train loss: 0.4117721457481384 |Validation err: 0.287
5, Validation loss: 0.6119848368689418
Epoch 25: Train err: 0.178125, Train loss: 0.39021603655815124 |Validation err: 0.29,
Validation loss: 0.6349665550515056
Epoch 26: Train err: 0.17125, Train loss: 0.3766976846456528 |Validation err: 0.294,
Validation loss: 0.6567586557939649
Epoch 27: Train err: 0.167875, Train loss: 0.37085654997825623 |Validation err: 0.30
2, Validation loss: 0.6838512010872364
Epoch 28: Train err: 0.158375, Train loss: 0.3524437836408615 |Validation err: 0.301,
Validation loss: 0.6814888548105955
Epoch 29: Train err: 0.15625, Train loss: 0.34255521118640897 |Validation err: 0.3, V
alidation loss: 0.7227485198527575
Epoch 30: Train err: 0.146875, Train loss: 0.33216684496402743 |Validation err: 0.301
5, Validation loss: 0.7114248964935541
Finished Training
Total time elapsed: 154.10 seconds
```

- Large: 145.72 seconds
- small: 132.75 seconds

The large_net takes longer to train because it has more parameters (9705) than the small_net parameters (386) proven in part 2 (a). Thus, there are more computes and updates, resulting in the time increase.

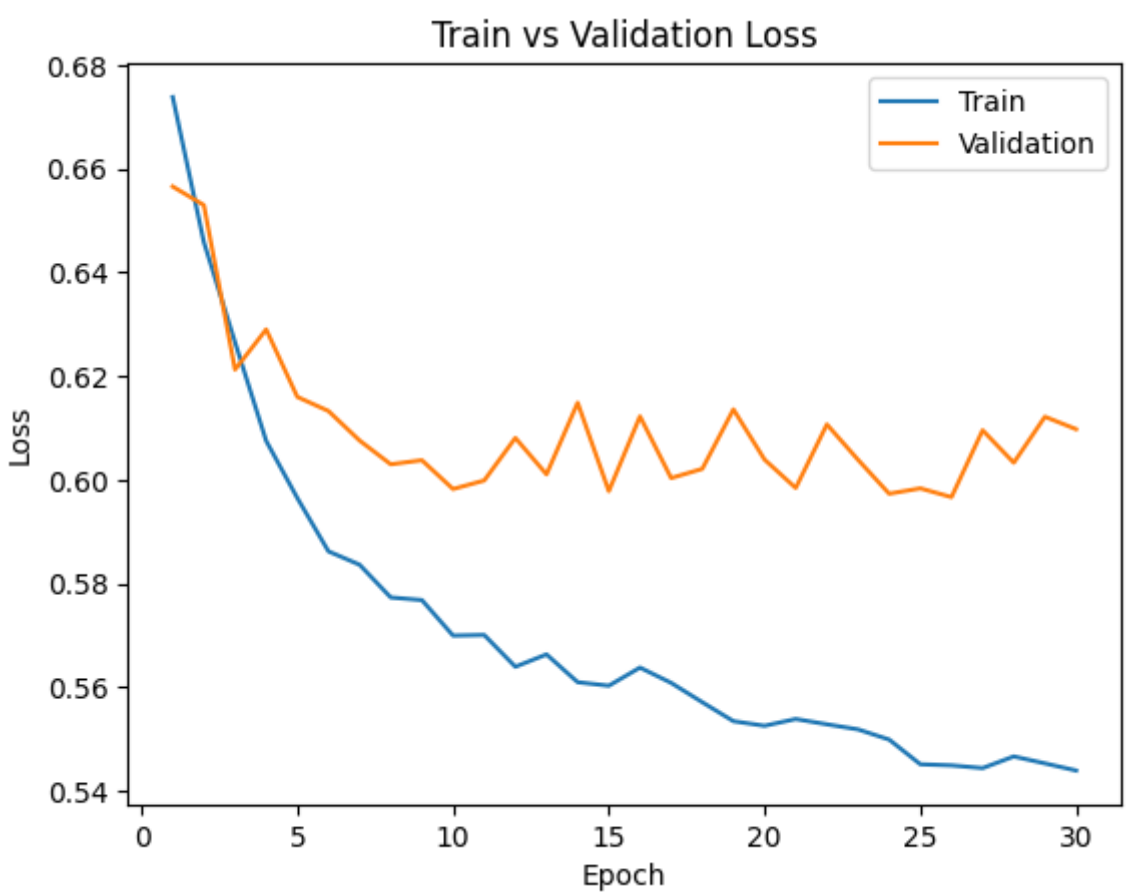
Part (e) - 2pt

Use the function `plot_training_curve` to display the trajectory of the training/validation error and the training/validation loss. You will need to use the function `get_model_name` to generate the argument to the `plot_training_curve` function.

Do this for both the small network and the large network. Include both plots in your writeup.

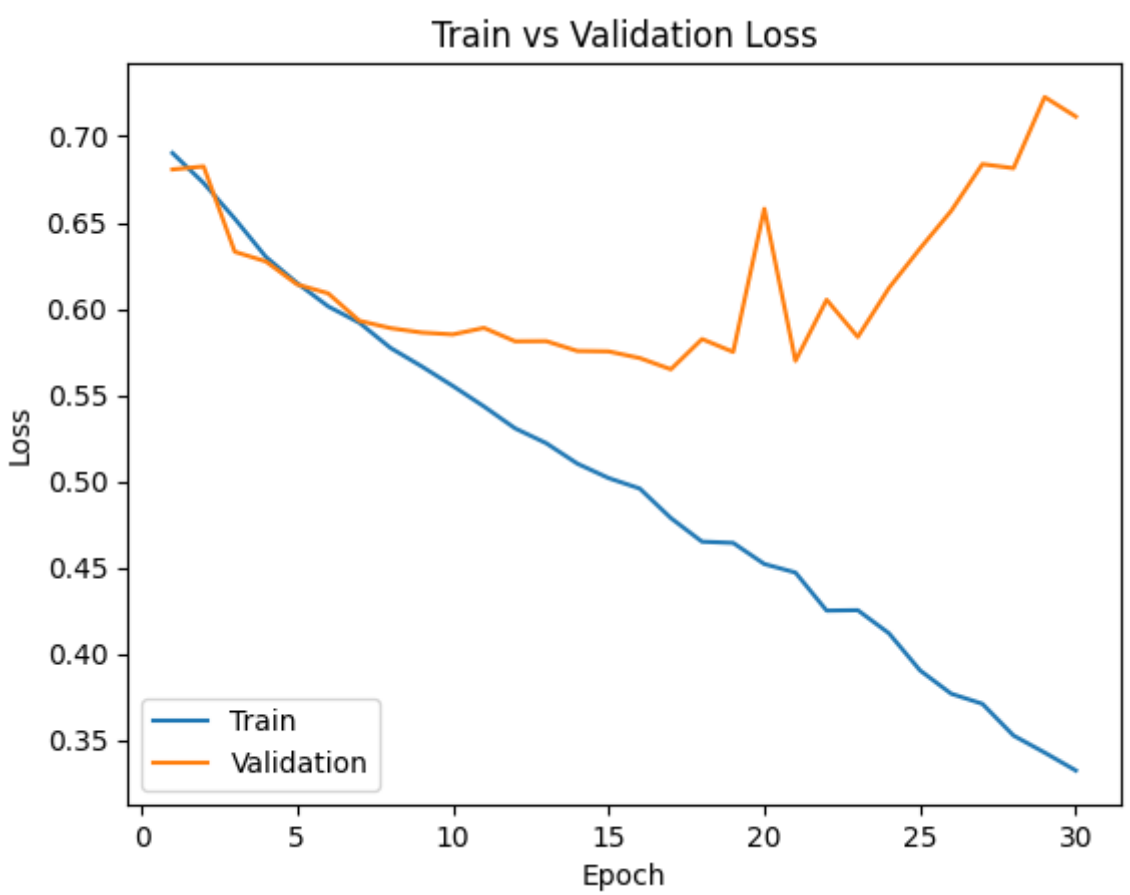
In [ ]:
```
small_path = get_model_name("small", batch_size=64, learning_rate=0.01, epoch=29)
large_path = get_model_name("large", batch_size=64, learning_rate=0.01, epoch=29)

print("small_net training curve")
plot_training_curve(small_path)
```

```
small_net training curve
```



In [ ]:
```
print("large_net training curve")
plot_training_curve(large_path)
```

```
large_net training curve
```



Part (f) - 5pt

Describe what you notice about the training curve. How do the curves differ for `small_net` and `large_net` ? Identify any occurences of underfitting and overfitting.

small_net curve: For the small_net learning curve, the training loss is slightly decreasing while the validation loss is fluctuating without a clear decreasing trend. This shows that the model is not learning the data pattern and underfitting the validation dataset.

large_net curve: For the large_net learning curve, the graph presents a clear downward trend for both training data and validation data at epoch 0-10. This shows that this model is underfitting at the beginning. However, after that, although training loss/error is still decreasing at approximately a similar roughly linear rate, the validation loss/error stops decreasing along. The error remains somewhat constant, and the loss instead increases starting around epoch 15, indicating overfitting of the model.

Part 3. Optimization Parameters [12 pt]

For this section, we will work with `large_net` only.

Part (a) - 3pt

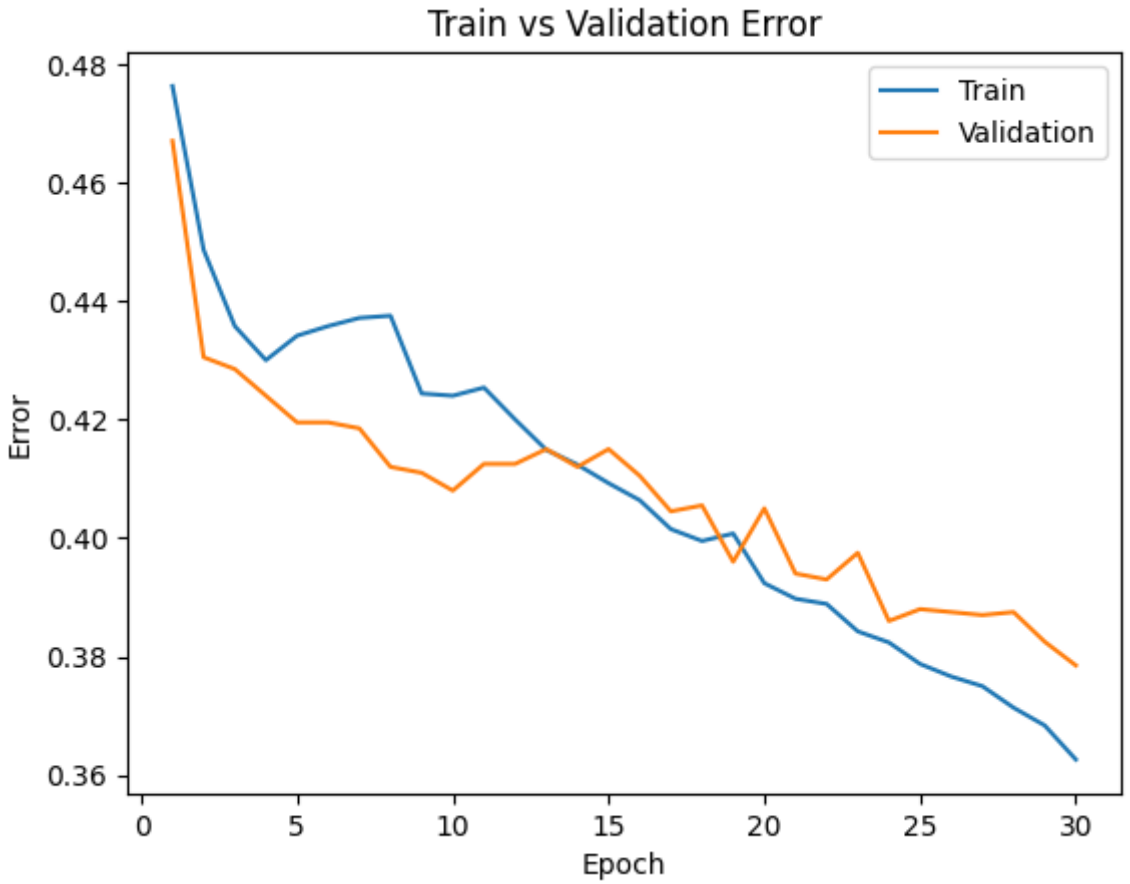
Train `large_net` with all default parameters, except set `learning_rate=0.001` . Does the model take longer/shorter to train? Plot the training curve. Describe the effect of *lowering* the learning rate.

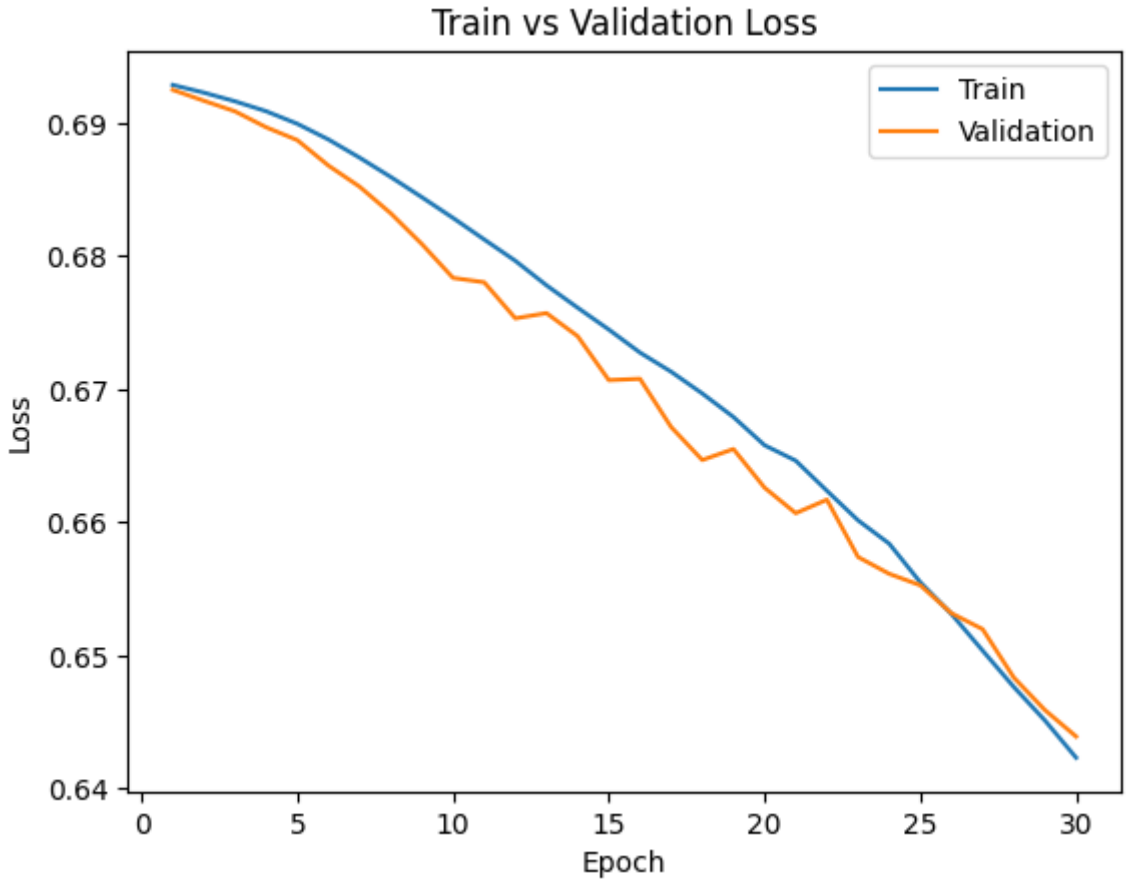
In [ ]:
```
# Note: When we re-construct the model, we start the training
# with *random weights*. If we omit this code, the values of
# the weights will still be the previously trained values.
large_net = LargeNet()
train_net(large_net, learning_rate=0.001)
```

```
Files already downloaded and verified
Files already downloaded and verified
Epoch 1: Train err: 0.47625, Train loss: 0.6928360004425049 |Validation err: 0.467, V
alidation loss: 0.6924686580896378
Epoch 2: Train err: 0.448625, Train loss: 0.6922589740753173 |Validation err: 0.4305,
Validation loss: 0.6916493494063616
Epoch 3: Train err: 0.43575, Train loss: 0.6916067256927491 |Validation err: 0.4285,
Validation loss: 0.6908544301986694
Epoch 4: Train err: 0.43, Train loss: 0.6908613419532776 |Validation err: 0.424, Vali
dation loss: 0.6896595824509859
Epoch 5: Train err: 0.434125, Train loss: 0.6899194955825806 |Validation err: 0.4195,
Validation loss: 0.6886935662478209
Epoch 6: Train err: 0.43575, Train loss: 0.688741192817688 |Validation err: 0.4195, V
alidation loss: 0.6867824867367744
Epoch 7: Train err: 0.437125, Train loss: 0.6873774199485779 |Validation err: 0.4185,
Validation loss: 0.6851983051747084
Epoch 8: Train err: 0.4375, Train loss: 0.6859278454780579 |Validation err: 0.412, Va
lidation loss: 0.6831997763365507
Epoch 9: Train err: 0.424375, Train loss: 0.6844058051109314 |Validation err: 0.411,
Validation loss: 0.6808880735188723
Epoch 10: Train err: 0.424, Train loss: 0.6828502945899964 |Validation err: 0.408, Va
lidation loss: 0.6783502567559481
Epoch 11: Train err: 0.425375, Train loss: 0.6812348775863647 |Validation err: 0.412
5, Validation loss: 0.6780214440077543
Epoch 12: Train err: 0.42, Train loss: 0.6796319665908813 |Validation err: 0.4125, Va
lidation loss: 0.6753159128129482
Epoch 13: Train err: 0.414875, Train loss: 0.6777918725013733 |Validation err: 0.415,
Validation loss: 0.6757059413939714
Epoch 14: Train err: 0.412375, Train loss: 0.6761112008094787 |Validation err: 0.412,
Validation loss: 0.673973485827446
Epoch 15: Train err: 0.40925, Train loss: 0.6744726777076722 |Validation err: 0.415,
Validation loss: 0.6706762481480837
Epoch 16: Train err: 0.406375, Train loss: 0.6727448830604553 |Validation err: 0.410
5, Validation loss: 0.6707733031362295
Epoch 17: Train err: 0.4015, Train loss: 0.6713076605796814 |Validation err: 0.4045,
Validation loss: 0.6671545337885618
Epoch 18: Train err: 0.3995, Train loss: 0.6696742882728577 |Validation err: 0.4055,
Validation loss: 0.6646782532334328
Epoch 19: Train err: 0.40075, Train loss: 0.6679086318016052 |Validation err: 0.396,
Validation loss: 0.6655019484460354
Epoch 20: Train err: 0.392375, Train loss: 0.6657879824638366 |Validation err: 0.405,
Validation loss: 0.6626011151820421
Epoch 21: Train err: 0.38975, Train loss: 0.6646300611495972 |Validation err: 0.394,
Validation loss: 0.6606878526508808
Epoch 22: Train err: 0.388875, Train loss: 0.6623730535507202 |Validation err: 0.393,
Validation loss: 0.6616998631507158
Epoch 23: Train err: 0.38425, Train loss: 0.6601516304016113 |Validation err: 0.3975,
Validation loss: 0.6573981866240501
Epoch 24: Train err: 0.382375, Train loss: 0.6584009370803833 |Validation err: 0.386,
Validation loss: 0.6561364699155092
Epoch 25: Train err: 0.37875, Train loss: 0.6554971733093262 |Validation err: 0.388,
Validation loss: 0.6552744191139936
Epoch 26: Train err: 0.376625, Train loss: 0.6531173238754272 |Validation err: 0.387
5, Validation loss: 0.6531743723899126
Epoch 27: Train err: 0.375, Train loss: 0.6503696317672729 |Validation err: 0.387, Va
lidation loss: 0.6519789230078459
Epoch 28: Train err: 0.371375, Train loss: 0.6476435804367066 |Validation err: 0.387
5, Validation loss: 0.6483502611517906
Epoch 29: Train err: 0.368375, Train loss: 0.645125765323639 |Validation err: 0.3825,
Validation loss: 0.6459067296236753
Epoch 30: Train err: 0.362625, Train loss: 0.6423329501152039 |Validation err: 0.378
5, Validation loss: 0.6439236979931593
Finished Training
Total time elapsed: 149.88 seconds
```

In [ ]:

```
model_path = get_model_name("large", batch_size=64, learning_rate=0.001, epoch=29)
plot_training_curve(model_path)
```





The eplased time is 149.88, thus takes around the same time (slightly more) to train.

Lowering the learning rate slows down the training progress, making small updates to the weights in the networks to gain a more precise parameter updates while taking a longer time. The model get higher error and higher loss in training data. For validation, the error is higher, but the loss shows overfitting is avoided. 0.001 is too slow.

Part (b) - 3pt

Train `large_net` with all default parameters, except set `learning_rate=0.1` . Does the model take longer/shorter to train? Plot the training curve. Describe the effect of *increasing* the learning rate.

In [ ]:
```
large_net = LargeNet()
train_net(large_net, learning_rate=0.1)
```

```
Files already downloaded and verified
Files already downloaded and verified
Epoch 1: Train err: 0.4295, Train loss: 0.6743778004646301 |Validation err: 0.3595, V
alidation loss: 0.6350856963545084
Epoch 2: Train err: 0.36075, Train loss: 0.6411805462837219 |Validation err: 0.3535,
Validation loss: 0.6361209936439991
Epoch 3: Train err: 0.365125, Train loss: 0.6321813464164734 |Validation err: 0.3385,
Validation loss: 0.6056603863835335
Epoch 4: Train err: 0.352625, Train loss: 0.623345623254776 |Validation err: 0.3575,
Validation loss: 0.6362800160422921
Epoch 5: Train err: 0.34075, Train loss: 0.610801386833191 |Validation err: 0.3305, V
alidation loss: 0.6064918749034405
Epoch 6: Train err: 0.323375, Train loss: 0.5921835992336273 |Validation err: 0.317,
Validation loss: 0.5967769687995315
Epoch 7: Train err: 0.3145, Train loss: 0.5817317562103271 |Validation err: 0.3365, V
alidation loss: 0.6204487904906273
Epoch 8: Train err: 0.29825, Train loss: 0.5660300071239471 |Validation err: 0.3285,
Validation loss: 0.5983372181653976
Epoch 9: Train err: 0.290875, Train loss: 0.5528094999790192 |Validation err: 0.3315,
Validation loss: 0.6084455195814371
Epoch 10: Train err: 0.278625, Train loss: 0.5390326056480408 |Validation err: 0.306,
Validation loss: 0.5918631944805384
Epoch 11: Train err: 0.272375, Train loss: 0.5236025860309601 |Validation err: 0.33,
Validation loss: 0.6430060267448425
Epoch 12: Train err: 0.267375, Train loss: 0.5220149426460267 |Validation err: 0.292
5, Validation loss: 0.6413561562076211
Epoch 13: Train err: 0.266, Train loss: 0.5160510141849518 |Validation err: 0.3125, V
alidation loss: 0.6349832899868488
Epoch 14: Train err: 0.24875, Train loss: 0.49515900206565855 |Validation err: 0.314
5, Validation loss: 0.7193072661757469
Epoch 15: Train err: 0.264625, Train loss: 0.5192319476604461 |Validation err: 0.314,
Validation loss: 0.6381420735269785
Epoch 16: Train err: 0.252625, Train loss: 0.5020012385845184 |Validation err: 0.322
5, Validation loss: 0.6551959468051791
Epoch 17: Train err: 0.23875, Train loss: 0.48171478748321533 |Validation err: 0.357,
Validation loss: 0.6440742611885071
Epoch 18: Train err: 0.23375, Train loss: 0.4764550621509552 |Validation err: 0.3375,
Validation loss: 0.6777342865243554
Epoch 19: Train err: 0.218125, Train loss: 0.45134368777275086 |Validation err: 0.344
5, Validation loss: 0.7232250459492207
Epoch 20: Train err: 0.217875, Train loss: 0.45516351199150085 |Validation err: 0.324
5, Validation loss: 0.6354951094835997
Epoch 21: Train err: 0.23275, Train loss: 0.47897080254554747 |Validation err: 0.325
5, Validation loss: 0.8348111072555184
Epoch 22: Train err: 0.234875, Train loss: 0.4808810555934906 |Validation err: 0.334,
Validation loss: 0.7191346473991871
Epoch 23: Train err: 0.21575, Train loss: 0.45636477398872377 |Validation err: 0.316,
Validation loss: 0.7083508120849729
Epoch 24: Train err: 0.2355, Train loss: 0.477182511806488 |Validation err: 0.327, Va
lidation loss: 0.7333047613501549
Epoch 25: Train err: 0.22025, Train loss: 0.45834142971038816 |Validation err: 0.331
5, Validation loss: 0.7806987632066011
Epoch 26: Train err: 0.209625, Train loss: 0.4519626944065094 |Validation err: 0.343
5, Validation loss: 0.7715998683124781
Epoch 27: Train err: 0.22175, Train loss: 0.4636160418987274 |Validation err: 0.3215,
Validation loss: 0.7656293641775846
Epoch 28: Train err: 0.219375, Train loss: 0.4631477723121643 |Validation err: 0.348,
Validation loss: 0.8202023096382618
Epoch 29: Train err: 0.235875, Train loss: 0.49053542375564574 |Validation err: 0.32
6, Validation loss: 0.8150459919124842
Epoch 30: Train err: 0.22, Train loss: 0.4623157210350037 |Validation err: 0.3165, Va
lidation loss: 0.7585078477859497
Finished Training
Total time elapsed: 162.05 seconds
```

In [ ]:

```
model_path = get_model_name("large", batch_size=64, learning_rate=0.1, epoch=29)
plot_training_curve(model_path)
```

The eplased time is 162.05, thus takes slightly longer to train.

The learning rate being too high creates noise and is detrimental to the training. It is "jumping" to suboptimal set of biases and weights as the optimal values are missed due to the large learning rate. Increasing the learning rate makes the model get higher error and higher loss in training and validation data. Also, the error and loss shows overfitting. 0.1 is too fast.

Part (c) - 3pt

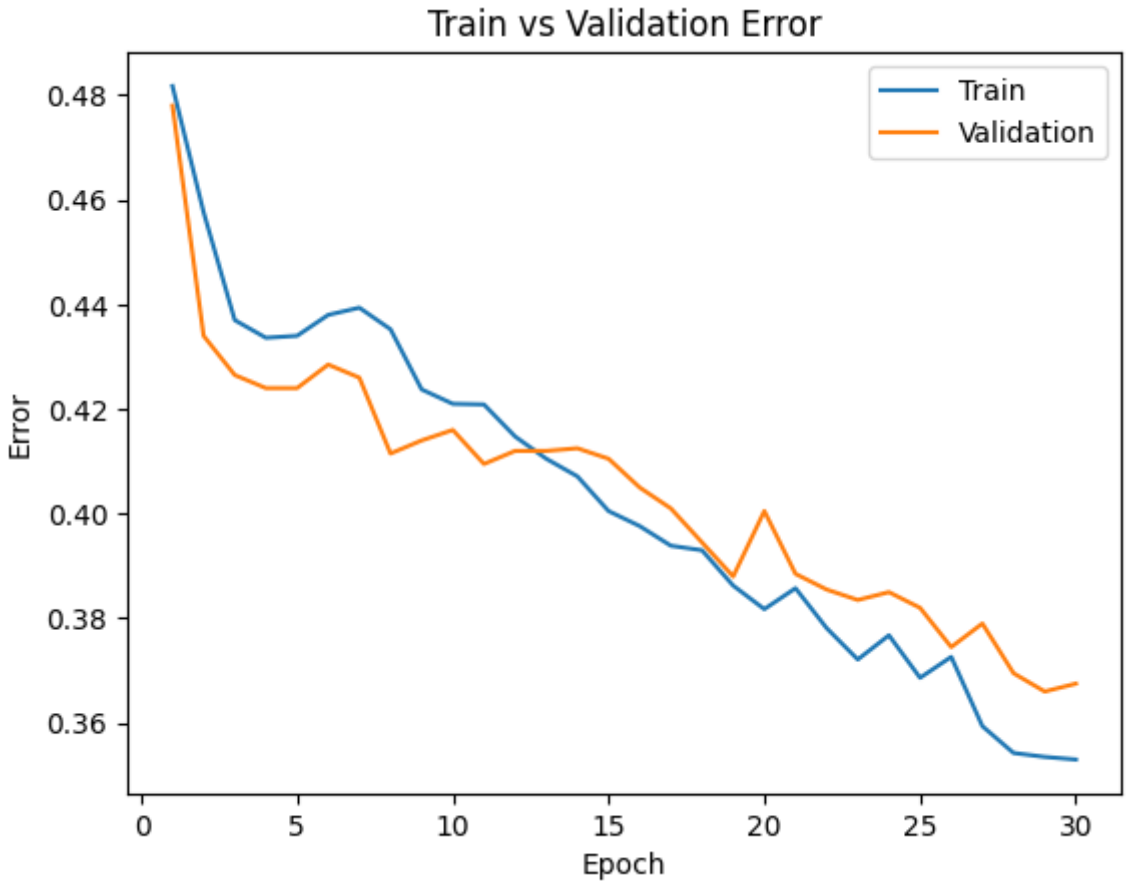
Train `large_net` with all default parameters, including with `learning_rate=0.01`. Now, set `batch_size=512`. Does the model take longer/shorter to train? Plot the training curve. Describe the effect of *increasing* the batch size.

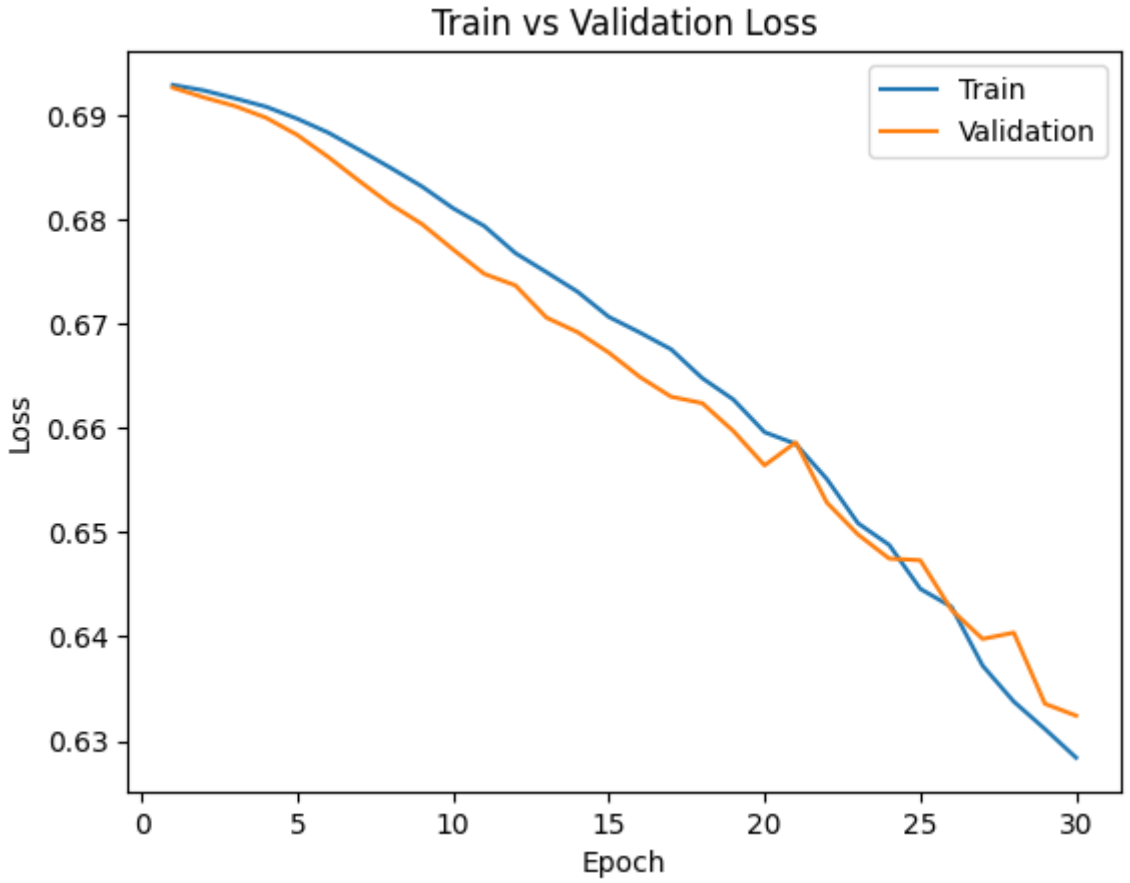
In [ ]:
```
large_net = LargeNet()
train_net(large_net,batch_size=512)
```

```
Files already downloaded and verified
Files already downloaded and verified
Epoch 1: Train err: 0.48175, Train loss: 0.6929379552602768 |Validation err: 0.478, V
alidation loss: 0.6926824003458023
Epoch 2: Train err: 0.457625, Train loss: 0.6924104057252407 |Validation err: 0.434,
Validation loss: 0.6917425245046616
Epoch 3: Train err: 0.437, Train loss: 0.6916500627994537 |Validation err: 0.4265, Va
lidation loss: 0.6909129917621613
Epoch 4: Train err: 0.433625, Train loss: 0.6908449903130531 |Validation err: 0.424,
Validation loss: 0.6897870302200317
Epoch 5: Train err: 0.434, Train loss: 0.6896935515105724 |Validation err: 0.424, Val
idation loss: 0.6881355047225952
Epoch 6: Train err: 0.438, Train loss: 0.6883532106876373 |Validation err: 0.4285, Va
lidation loss: 0.686011865735054
Epoch 7: Train err: 0.439375, Train loss: 0.6866871751844883 |Validation err: 0.426,
Validation loss: 0.6836968660354614
Epoch 8: Train err: 0.43525, Train loss: 0.6849770732223988 |Validation err: 0.4115,
Validation loss: 0.68146713078022
Epoch 9: Train err: 0.42375, Train loss: 0.6832009293138981 |Validation err: 0.414, V
alidation loss: 0.679591491818428
Epoch 10: Train err: 0.421, Train loss: 0.6811089366674423 |Validation err: 0.416, Va
lidation loss: 0.6771548539400101
Epoch 11: Train err: 0.420875, Train loss: 0.6794026605784893 |Validation err: 0.409
5, Validation loss: 0.6748111099004745
Epoch 12: Train err: 0.41475, Train loss: 0.6768048144876957 |Validation err: 0.412,
Validation loss: 0.6737060546875
Epoch 13: Train err: 0.4105, Train loss: 0.6749702766537666 |Validation err: 0.412, V
alidation loss: 0.6706101596355438
Epoch 14: Train err: 0.407125, Train loss: 0.6730880849063396 |Validation err: 0.412
5, Validation loss: 0.6692148000001907
Epoch 15: Train err: 0.4005, Train loss: 0.6706806868314743 |Validation err: 0.4105,
Validation loss: 0.6672526895999908
Epoch 16: Train err: 0.397625, Train loss: 0.6691771373152733 |Validation err: 0.405,
Validation loss: 0.6649097055196762
Epoch 17: Train err: 0.393875, Train loss: 0.6675694584846497 |Validation err: 0.401,
Validation loss: 0.6630225032567978
Epoch 18: Train err: 0.393, Train loss: 0.6648042872548103 |Validation err: 0.3945, V
alidation loss: 0.6624014377593994
Epoch 19: Train err: 0.38625, Train loss: 0.6627466157078743 |Validation err: 0.388,
Validation loss: 0.6597220301628113
Epoch 20: Train err: 0.38175, Train loss: 0.6596181951463223 |Validation err: 0.4005,
Validation loss: 0.6564337313175201
Epoch 21: Train err: 0.38575, Train loss: 0.6584899760782719 |Validation err: 0.3885,
Validation loss: 0.6586423963308334
Epoch 22: Train err: 0.378125, Train loss: 0.6551233902573586 |Validation err: 0.385
5, Validation loss: 0.6528600305318832
Epoch 23: Train err: 0.372125, Train loss: 0.6508794091641903 |Validation err: 0.383
5, Validation loss: 0.6497963666915894
Epoch 24: Train err: 0.37675, Train loss: 0.6488028429448605 |Validation err: 0.385,
Validation loss: 0.6474899798631668
Epoch 25: Train err: 0.368625, Train loss: 0.6445869281888008 |Validation err: 0.382,
Validation loss: 0.6473268419504166
Epoch 26: Train err: 0.372625, Train loss: 0.6428566128015518 |Validation err: 0.374
5, Validation loss: 0.6425703316926956
Epoch 27: Train err: 0.359375, Train loss: 0.6372117511928082 |Validation err: 0.379,
Validation loss: 0.6397799849510193
Epoch 28: Train err: 0.35425, Train loss: 0.6337667480111122 |Validation err: 0.3695,
Validation loss: 0.6403782963752747
Epoch 29: Train err: 0.3535, Train loss: 0.6311352998018265 |Validation err: 0.366, V
alidation loss: 0.6335585117340088
Epoch 30: Train err: 0.353, Train loss: 0.6283832415938377 |Validation err: 0.3675, V
alidation loss: 0.6324127167463303
Finished Training
Total time elapsed: 132.86 seconds
```

In [ ]:

```
model_path = get_model_name("large", batch_size=512, learning_rate=0.01, epoch=29)
plot_training_curve(model_path)
```





The eplased time is 132.86, thus takes shorter to train.

The model needs to do less passes to cover the entire training set as it considers more data each time. Therefore, it calculates the gradients and updates weights less times. Increasing the batch size makes the model get higher error and higher loss in training data. In validation, the error and loss are around the same, but the new loss shows no sign of overfitting

Part (d) - 3pt

Train `large_net` with all default parameters, including with `learning_rate=0.01`. Now, set `batch_size=16`. Does the model take longer/shorter to train? Plot the training curve. Describe the effect of *decreasing* the batch size.

In [ ]:
```
large_net = LargeNet()
train_net(large_net,batch_size=16)
```

```
Files already downloaded and verified
Files already downloaded and verified
Epoch 1: Train err: 0.43175, Train loss: 0.6774994033575058 |Validation err: 0.382, V
alidation loss: 0.6513170146942139
Epoch 2: Train err: 0.369, Train loss: 0.6396398993134499 |Validation err: 0.3465, Va
lidation loss: 0.6161113579273224
Epoch 3: Train err: 0.34375, Train loss: 0.6098222960829734 |Validation err: 0.3325,
Validation loss: 0.6260210766792297
Epoch 4: Train err: 0.314375, Train loss: 0.584969149172306 |Validation err: 0.34, Va
lidation loss: 0.6044013905525207
Epoch 5: Train err: 0.301125, Train loss: 0.5689119317531586 |Validation err: 0.3125,
Validation loss: 0.5769183149337769
Epoch 6: Train err: 0.281, Train loss: 0.5452213580608368 |Validation err: 0.308, Val
idation loss: 0.570844743013382
Epoch 7: Train err: 0.270875, Train loss: 0.5272981309890747 |Validation err: 0.307,
Validation loss: 0.5854293291568756
Epoch 8: Train err: 0.259375, Train loss: 0.507090549826622 |Validation err: 0.313, V
alidation loss: 0.5877130846977234
Epoch 9: Train err: 0.242375, Train loss: 0.49683444169163704 |Validation err: 0.313,
Validation loss: 0.5922425067424775
Epoch 10: Train err: 0.236375, Train loss: 0.47561015680432317 |Validation err: 0.29
7, Validation loss: 0.5718690168857574
Epoch 11: Train err: 0.222125, Train loss: 0.45997694665193556 |Validation err: 0.297
5, Validation loss: 0.6376970813274384
Epoch 12: Train err: 0.211, Train loss: 0.4454492364227772 |Validation err: 0.2995, V
alidation loss: 0.609202568769455
Epoch 13: Train err: 0.19875, Train loss: 0.42454217198491095 |Validation err: 0.307
5, Validation loss: 0.6494987757205963
Epoch 14: Train err: 0.18675, Train loss: 0.4007472902536392 |Validation err: 0.3085,
Validation loss: 0.6610016564130783
Epoch 15: Train err: 0.1645, Train loss: 0.3759974044710398 |Validation err: 0.3105,
Validation loss: 0.7106090523004532
Epoch 16: Train err: 0.16125, Train loss: 0.35914554065465926 |Validation err: 0.300
5, Validation loss: 0.7310364973545075
Epoch 17: Train err: 0.15775, Train loss: 0.3463234778419137 |Validation err: 0.307,
Validation loss: 0.7263009355068207
Epoch 18: Train err: 0.141625, Train loss: 0.32175366409868 |Validation err: 0.3195,
Validation loss: 0.7913952922821045
Epoch 19: Train err: 0.13375, Train loss: 0.3061810576841235 |Validation err: 0.335,
Validation loss: 0.8032052783966065
Epoch 20: Train err: 0.126625, Train loss: 0.30290717820078134 |Validation err: 0.32,
Validation loss: 0.8106685200929642
Epoch 21: Train err: 0.12025, Train loss: 0.28682796521484855 |Validation err: 0.320
5, Validation loss: 0.8259474363327026
Epoch 22: Train err: 0.1165, Train loss: 0.2748908795714378 |Validation err: 0.352, V
alidation loss: 0.8937610728740693
Epoch 23: Train err: 0.104375, Train loss: 0.2467898515611887 |Validation err: 0.331
5, Validation loss: 1.0021928179264068
Epoch 24: Train err: 0.101, Train loss: 0.23970085600204766 |Validation err: 0.331, V
alidation loss: 1.1290796512365342
Epoch 25: Train err: 0.09575, Train loss: 0.23643119525164366 |Validation err: 0.331
5, Validation loss: 1.1338514356613159
Epoch 26: Train err: 0.094125, Train loss: 0.23259535063058137 |Validation err: 0.336
5, Validation loss: 1.141426316022873
Epoch 27: Train err: 0.08425, Train loss: 0.21040759443677962 |Validation err: 0.333
5, Validation loss: 1.182367821574211
Epoch 28: Train err: 0.0825, Train loss: 0.20643112601805477 |Validation err: 0.323,
Validation loss: 1.2668361866474152
Epoch 29: Train err: 0.0845, Train loss: 0.21273409315384925 |Validation err: 0.3245,
Validation loss: 1.406717713713646
Epoch 30: Train err: 0.071375, Train loss: 0.18387044004537165 |Validation err: 0.34
5, Validation loss: 1.4871552119255065
Finished Training
Total time elapsed: 228.17 seconds
```

In [ ]:

```
model_path = get_model_name("large", batch_size=16, learning_rate=0.01, epoch=29)
plot_training_curve(model_path)
```

The eplased time is 228.17, thus takes much longer to train. Because the batch_size decreases, so inside each epoch, the times of iteration is larger, which will take more time.

Having a small batch size introduced too much 'noises' in the training process, causing the training loss significantly diverges with the validation loss. Decreasing the batch size makes the model get lower error and lower loss in training data. But in validation, it is an extremely overfitted model that is unable to perform well on new data.

Part 4. Hyperparameter Search [6 pt]

Part (a) - 2pt

Based on the plots from above, choose another set of values for the hyperparameters (network, batch_size, learning_rate) that you think would help you improve the validation accuracy. Justify your choice.

I choose network = large_net, batch_size = 128, learning_rate = 0.01, and epoch = 30. Proven above, large net works better than small net. From part3, 0.01 is a good learning rate, it does not cause a too small or too large "jump". When batch_size is small, the model would get overfitting, when batch_size increases not by a lot, the peformance is better and does not overfit.

Part (b) - 1pt

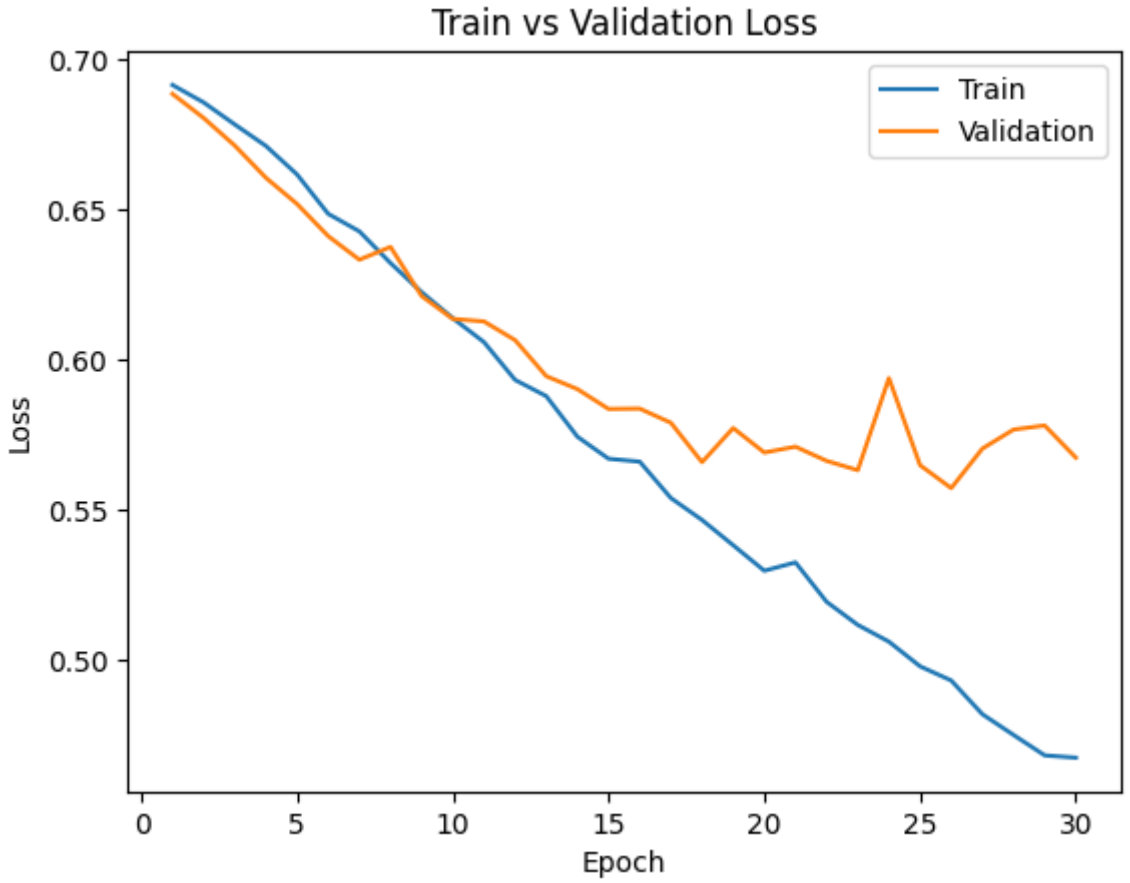
Train the model with the hyperparameters you chose in part(a), and include the training curve.

In [ ]:
```
large_net = LargeNet()
train_net(large_net,learning_rate=0.01,batch_size=128, num_epochs = 30)
```

```
Files already downloaded and verified
Files already downloaded and verified
Epoch 1: Train err: 0.47025, Train loss: 0.6915813807457213 |Validation err: 0.4435,
Validation loss: 0.6885984316468239
Epoch 2: Train err: 0.441625, Train loss: 0.685759805497669 |Validation err: 0.4165,
Validation loss: 0.6805880069732666
Epoch 3: Train err: 0.4295, Train loss: 0.6784176694022285 |Validation err: 0.413, Va
lidation loss: 0.6713756285607815
Epoch 4: Train err: 0.41875, Train loss: 0.6712553614661807 |Validation err: 0.3955,
Validation loss: 0.6606401465833187
Epoch 5: Train err: 0.393125, Train loss: 0.6617401554470971 |Validation err: 0.371,
Validation loss: 0.6519135050475597
Epoch 6: Train err: 0.380625, Train loss: 0.6486233908032614 |Validation err: 0.352,
Validation loss: 0.6411975361406803
Epoch 7: Train err: 0.369, Train loss: 0.6427794562445747 |Validation err: 0.3575, Va
lidation loss: 0.6333399601280689
Epoch 8: Train err: 0.35525, Train loss: 0.632211811012692 |Validation err: 0.369, Va
lidation loss: 0.6375936791300774
Epoch 9: Train err: 0.343, Train loss: 0.6225005038200863 |Validation err: 0.347, Val
idation loss: 0.6212191879749298
Epoch 10: Train err: 0.3365, Train loss: 0.6138413065955752 |Validation err: 0.337, V
alidation loss: 0.6135980561375618
Epoch 11: Train err: 0.33225, Train loss: 0.6058698911515493 |Validation err: 0.339,
Validation loss: 0.6127671115100384
Epoch 12: Train err: 0.32175, Train loss: 0.5932677236814348 |Validation err: 0.338,
Validation loss: 0.6065276302397251
Epoch 13: Train err: 0.312625, Train loss: 0.5878614868436541 |Validation err: 0.316
5, Validation loss: 0.5945213697850704
Epoch 14: Train err: 0.302875, Train loss: 0.5743346242677598 |Validation err: 0.311,
Validation loss: 0.5902013182640076
Epoch 15: Train err: 0.29775, Train loss: 0.5669934044754694 |Validation err: 0.308,
Validation loss: 0.5835822373628616
Epoch 16: Train err: 0.302875, Train loss: 0.5660247462136405 |Validation err: 0.309,
Validation loss: 0.5836991630494595
Epoch 17: Train err: 0.2865, Train loss: 0.5538960335746644 |Validation err: 0.2975,
Validation loss: 0.5789858400821686
Epoch 18: Train err: 0.280125, Train loss: 0.5465867557222881 |Validation err: 0.293,
Validation loss: 0.5658432170748711
Epoch 19: Train err: 0.273875, Train loss: 0.538162092367808 |Validation err: 0.3065,
Validation loss: 0.5772284083068371
Epoch 20: Train err: 0.273, Train loss: 0.5296616204201229 |Validation err: 0.2985, V
alidation loss: 0.5690633058547974
Epoch 21: Train err: 0.26475, Train loss: 0.5324348835718065 |Validation err: 0.2935,
Validation loss: 0.571011969819665
Epoch 22: Train err: 0.260375, Train loss: 0.5192929345463949 |Validation err: 0.292,
Validation loss: 0.5662802159786224
Epoch 23: Train err: 0.2585, Train loss: 0.5116074421103038 |Validation err: 0.2935,
Validation loss: 0.5631771124899387
Epoch 24: Train err: 0.25175, Train loss: 0.5060165084543682 |Validation err: 0.306,
Validation loss: 0.5938595496118069
Epoch 25: Train err: 0.25125, Train loss: 0.4978017277187771 |Validation err: 0.2845,
Validation loss: 0.5648467801511288
Epoch 26: Train err: 0.241875, Train loss: 0.49307247807109167 |Validation err: 0.29
1, Validation loss: 0.5571986772119999
Epoch 27: Train err: 0.235, Train loss: 0.4818402017865862 |Validation err: 0.2875, V
alidation loss: 0.5703737139701843
Epoch 28: Train err: 0.22975, Train loss: 0.4749348835339622 |Validation err: 0.292,
Validation loss: 0.5767155047506094
Epoch 29: Train err: 0.2305, Train loss: 0.4681154030656058 |Validation err: 0.2895,
Validation loss: 0.5780713204294443
Epoch 30: Train err: 0.228125, Train loss: 0.46735200143995737 |Validation err: 0.282
5, Validation loss: 0.5673696026206017
Finished Training
Total time elapsed: 173.44 seconds
```

In [ ]:

```
model_path = get_model_name("large", batch_size=128, learning_rate=0.01, epoch=29)
plot_training_curve(model_path)
```



Part (c) - 2pt

Based on your result from Part(a), suggest another set of hyperparameter values to try. Justify your choice.

I choose network = large_net, batch_size = 128, learning_rate = 0.007, and epoch = 25. Proven above, large net works better than small net. in part(b)'s training, in epoch 20 to 25, the error and loss are "converging", and since I decreased the learning_rate a little bit, the model would fits best in epoch slightly larger in the range. So I choose epoch = 25 to get a better model.

Part (d) - 1pt

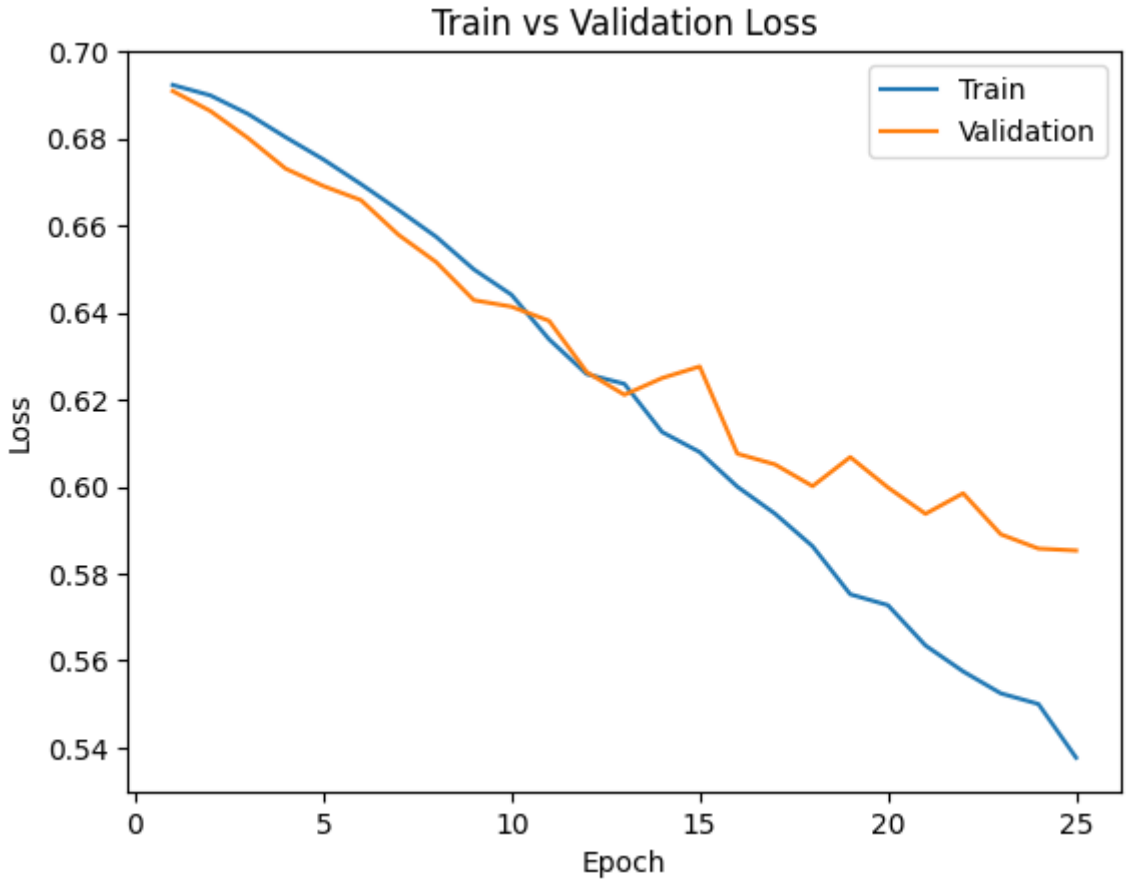
Train the model with the hyperparameters you chose in part(c), and include the training curve.

In [ ]:
```
large_net = LargeNet()
train_net(large_net,learning_rate=0.007,batch_size=128, num_epochs = 25)
```

```
Files already downloaded and verified
Files already downloaded and verified
Epoch 1: Train err: 0.456625, Train loss: 0.6923577302978152 |Validation err: 0.4225,
Validation loss: 0.6909653209149837
Epoch 2: Train err: 0.44975, Train loss: 0.6899599792465331 |Validation err: 0.422, V
alidation loss: 0.6863732673227787
Epoch 3: Train err: 0.430125, Train loss: 0.685693173181443 |Validation err: 0.412, V
alidation loss: 0.6801545657217503
Epoch 4: Train err: 0.424125, Train loss: 0.6803461994443621 |Validation err: 0.411,
Validation loss: 0.6731148324906826
Epoch 5: Train err: 0.41425, Train loss: 0.6752496891551547 |Validation err: 0.411, V
alidation loss: 0.6691230684518814
Epoch 6: Train err: 0.40275, Train loss: 0.6695615696528602 |Validation err: 0.396, V
alidation loss: 0.6658721268177032
Epoch 7: Train err: 0.391375, Train loss: 0.6636068877719697 |Validation err: 0.3935,
Validation loss: 0.657893992960453
Epoch 8: Train err: 0.385875, Train loss: 0.6574361522992452 |Validation err: 0.3885,
Validation loss: 0.6516227424144745
Epoch 9: Train err: 0.375, Train loss: 0.6499474436517746 |Validation err: 0.3855, Va
lidation loss: 0.6428735516965389
Epoch 10: Train err: 0.373, Train loss: 0.6441156495185125 |Validation err: 0.3755, V
alidation loss: 0.6413741186261177
Epoch 11: Train err: 0.3565, Train loss: 0.6338584754202101 |Validation err: 0.371, V
alidation loss: 0.6381208971142769
Epoch 12: Train err: 0.34575, Train loss: 0.6258701275265406 |Validation err: 0.3555,
Validation loss: 0.6263245604932308
Epoch 13: Train err: 0.351625, Train loss: 0.623620469418783 |Validation err: 0.346,
Validation loss: 0.621104184538126
Epoch 14: Train err: 0.338375, Train loss: 0.6125575095888168 |Validation err: 0.35,
Validation loss: 0.6249513253569603
Epoch 15: Train err: 0.33575, Train loss: 0.6079375885781788 |Validation err: 0.3615,
Validation loss: 0.627614863216877
Epoch 16: Train err: 0.3315, Train loss: 0.5999817318386502 |Validation err: 0.324, V
alidation loss: 0.6075649745762348
Epoch 17: Train err: 0.323, Train loss: 0.5937685138649411 |Validation err: 0.32, Val
idation loss: 0.6051003262400627
Epoch 18: Train err: 0.314875, Train loss: 0.586276365177972 |Validation err: 0.321,
Validation loss: 0.600101251155138
Epoch 19: Train err: 0.30425, Train loss: 0.5752310885323418 |Validation err: 0.335,
Validation loss: 0.6067818105220795
Epoch 20: Train err: 0.298875, Train loss: 0.5727307228814988 |Validation err: 0.319,
Validation loss: 0.5998083166778088
Epoch 21: Train err: 0.29325, Train loss: 0.5634498213018689 |Validation err: 0.3185,
Validation loss: 0.5937334783375263
Epoch 22: Train err: 0.292, Train loss: 0.5574950684630682 |Validation err: 0.313, Va
lidation loss: 0.5984522700309753
Epoch 23: Train err: 0.28575, Train loss: 0.5524494160735418 |Validation err: 0.3045,
Validation loss: 0.5890195220708847
Epoch 24: Train err: 0.288, Train loss: 0.5499989030853151 |Validation err: 0.308, Va
lidation loss: 0.5857409052550793
Epoch 25: Train err: 0.2765, Train loss: 0.5376601569236271 |Validation err: 0.3, Val
idation loss: 0.5852931085973978
Finished Training
Total time elapsed: 137.53 seconds
```

In [ ]:

```
model_path = get_model_name("large", batch_size=128, learning_rate=0.007, epoch=24)
plot_training_curve(model_path)
```



Part 4. Evaluating the Best Model [15 pt]

Part (a) - 1pt

Choose the **best** model that you have so far. This means choosing the best model checkpoint, including the choice of `small_net` vs `large_net`, the `batch_size`, `learning_rate`, **and the epoch number**.

Modify the code below to load your chosen set of weights to the model object `net`.

In [ ]:
```
net = LargeNet()
train_net(net, 128, 0.01, 30)
model_path = get_model_name("large", batch_size=128, learning_rate=0.01, epoch=29)
state = torch.load(model_path)
net.load_state_dict(state)
```

```
Files already downloaded and verified
Files already downloaded and verified
Epoch 1: Train err: 0.49475, Train loss: 0.6930217638848319 |Validation err: 0.4785,
Validation loss: 0.691717941313982
Epoch 2: Train err: 0.442625, Train loss: 0.6902927992835878 |Validation err: 0.4205,
Validation loss: 0.6878543831408024
Epoch 3: Train err: 0.4385, Train loss: 0.6854409717378163 |Validation err: 0.414, Va
lidation loss: 0.6805256269872189
Epoch 4: Train err: 0.42775, Train loss: 0.6785378777791583 |Validation err: 0.4175,
Validation loss: 0.6720023937523365
Epoch 5: Train err: 0.415, Train loss: 0.670867815850273 |Validation err: 0.3975, Val
idation loss: 0.663852758705616
Epoch 6: Train err: 0.395875, Train loss: 0.6599501087552025 |Validation err: 0.391,
Validation loss: 0.6539640463888645
Epoch 7: Train err: 0.383375, Train loss: 0.6531939459225488 |Validation err: 0.3805,
Validation loss: 0.6486352495849133
Epoch 8: Train err: 0.36525, Train loss: 0.6382708587343731 |Validation err: 0.3695,
Validation loss: 0.6437120959162712
Epoch 9: Train err: 0.35025, Train loss: 0.6279203901215206 |Validation err: 0.354, V
alidation loss: 0.6275049597024918
Epoch 10: Train err: 0.34525, Train loss: 0.6201465934041946 |Validation err: 0.3545,
Validation loss: 0.6196352653205395
Epoch 11: Train err: 0.337625, Train loss: 0.6101868105313134 |Validation err: 0.346,
Validation loss: 0.6186107397079468
Epoch 12: Train err: 0.32075, Train loss: 0.5977083482439556 |Validation err: 0.332,
Validation loss: 0.6056330353021622
Epoch 13: Train err: 0.321125, Train loss: 0.5960196360709176 |Validation err: 0.333,
Validation loss: 0.6073460765182972
Epoch 14: Train err: 0.312125, Train loss: 0.5822237209668235 |Validation err: 0.323,
Validation loss: 0.6035614460706711
Epoch 15: Train err: 0.30175, Train loss: 0.5742837228472271 |Validation err: 0.335,
Validation loss: 0.6098586432635784
Epoch 16: Train err: 0.2915, Train loss: 0.5678206478792523 |Validation err: 0.318, V
alidation loss: 0.5981570966541767
Epoch 17: Train err: 0.288, Train loss: 0.558592131686589 |Validation err: 0.3085, Va
lidation loss: 0.5832621231675148
Epoch 18: Train err: 0.28125, Train loss: 0.5488593587799678 |Validation err: 0.302,
Validation loss: 0.5757994297891855
Epoch 19: Train err: 0.2735, Train loss: 0.5378752719788324 |Validation err: 0.3265,
Validation loss: 0.6020590476691723
Epoch 20: Train err: 0.269375, Train loss: 0.5338658293088278 |Validation err: 0.299,
Validation loss: 0.5761913172900677
Epoch 21: Train err: 0.26725, Train loss: 0.5325955705983298 |Validation err: 0.303,
Validation loss: 0.5835884883999825
Epoch 22: Train err: 0.256375, Train loss: 0.5161200269820199 |Validation err: 0.297
5, Validation loss: 0.5748628079891205
Epoch 23: Train err: 0.253375, Train loss: 0.5129097884609586 |Validation err: 0.292
5, Validation loss: 0.5712837222963572
Epoch 24: Train err: 0.252375, Train loss: 0.512715451774143 |Validation err: 0.289,
Validation loss: 0.579069547355175
Epoch 25: Train err: 0.250125, Train loss: 0.501469795192991 |Validation err: 0.304,
Validation loss: 0.5801041312515736
Epoch 26: Train err: 0.24525, Train loss: 0.4910687856257908 |Validation err: 0.29, V
alidation loss: 0.5728969257324934
Epoch 27: Train err: 0.236125, Train loss: 0.48453891466534327 |Validation err: 0.29
9, Validation loss: 0.5860218070447445
Epoch 28: Train err: 0.2305, Train loss: 0.4756973868324643 |Validation err: 0.2895,
Validation loss: 0.5787050761282444
Epoch 29: Train err: 0.22375, Train loss: 0.4691095924566662 |Validation err: 0.296,
Validation loss: 0.6035145856440067
Epoch 30: Train err: 0.22125, Train loss: 0.4632494042790125 |Validation err: 0.291,
Validation loss: 0.5829307530075312
Finished Training
Total time elapsed: 182.87 seconds
```

```
<ipython-input-23-9d883085bf6b>:4: FutureWarning: You are using `torch.load` with `we
ights_only=False` (the current default value), which uses the default pickle module i
mplicitly. It is possible to construct malicious pickle data which will execute arbit
rary code during unpickling (See https://github.com/pytorch/pytorch/blob/main/SECURIT
Y.md#untrusted-models for more details). In a future release, the default value for `
weights_only` will be flipped to `True`. This limits the functions that could be exec
uted during unpickling. Arbitrary objects will no longer be allowed to be loaded via
this mode unless they are explicitly allowlisted by the user via `torch.serializatio
n.add_safe_globals`. We recommend you start setting `weights_only=True` for any use c
ase where you don't have full control of the loaded file. Please open an issue on Git
Hub for any issues related to this experimental feature.
  state = torch.load(model_path)
```

Out[ ]:
```
<All keys matched successfully>
```

Part (b) - 2pt

Justify your choice of model from part (a).

- default Validation err: 0.303, Validation loss: 0.67
- Hyperparameter Search (c) Validation err: 0.3, Validation loss: 0.59
- Hyperparameter Search (a); also my choice Validation err: 0.291, Validation loss: 0.583

The choice seems to be smaller than the result from the another choices

Part (c) - 2pt

Using the code in Part 0, any code from lecture notes, or any code that you write, compute and report the **test classification error** for your chosen model.

In [ ]:
```
# If you use the `evaluate` function provided in part 0, you will need to
# set batch_size > 1
train_loader, val_loader, test_loader, classes = get_data_loader(
    target_classes=["cat", "dog"],
    batch_size=64)

criterion = nn.BCEWithLogitsLoss()
test_err, test_loss = evaluate(net, test_loader, criterion)
print("test classification error:", test_err)
print("test classification loss:", test_loss)
```

```
Files already downloaded and verified
Files already downloaded and verified
test classification error: 0.2995
test classification loss: 0.5620032520964742
```

Part (d) - 3pt

How does the test classification error compare with the **validation error**? Explain why you would expect the test error to be *higher* than the validation error.

The test classification error is higher than the validation error. This is because, we are training the data in training set, and alidation on the validation set, making the model a good fir for these two sets. So, the validation error makes sense to be smaller than the test error since the testing dataset is unseen by the model before.

Part (e) - 2pt

Why did we only use the test data set at the very end? Why is it important that we use the test data as little as possible?

Because the test data are not within the training and validation data. They are unseen by the model, so they are "unbiased" and simulate how the model actually perform. However, if we use the test data too much, they will affect the model and no longer truely indicate the accuracy of the model.

Part (f) - 5pt

How does the your best CNN model compare with an 2-layer ANN model (no convolutional layers) on classifying cat and dog images. You can use a 2-layer ANN architecture similar to what you used in Lab 1. You should explore different hyperparameter settings to determine how well you can do on the validation dataset. Once satisified with the performance, you may test it out on the test data.

Hint: The ANN in lab 1 was applied on greyscale images. The cat and dog images are colour (RGB) and so you will need to flatted and concatinate all three colour layers before feeding them into an ANN.

The 2 layer ANN architecture did not perform as well as the CNN architecture. No matter what hyperparameters I tried, I was not able to get the validation error lower than CNN without heavily overfitting the training set. The error rate is 0.363, while the CNN architecture has a far lower error rate (e.g. 0.291).

In [ ]:
```
class ANN(nn.Module):
    def __init__(self):
        super(ANN, self).__init__()
        self.name = "ANN"
        self.layer1 = nn.Linear(3 * 32 * 32, 32)
        self.layer2 = nn.Linear(32, 1)
    def forward(self, x):
        x = x.view(-1, 3 * 32 * 32)
        x = self.layer1(x)
        x = F.relu(x)
        x = self.layer2(x)
        x = x.squeeze(1)
        return x
ANN_net = ANN()
train_net(ANN_net, batch_size=512, learning_rate=0.005, num_epochs=40)
ANN_model_path = get_model_name("ANN", batch_size=512, learning_rate=0.005, epoch=39)
plot_training_curve(ANN_model_path)
```

In [ ]:
```
train_loader, val_loader, test_loader, classes = get_data_loader(
    target_classes=["cat", "dog"],
    batch_size=512)

criterion = nn.BCEWithLogitsLoss()
test_err, test_loss = evaluate(ANN_net, test_loader, criterion)

print("test classification error:", test_err)
print("test classification loss:", test_loss)
```

```
Files already downloaded and verified
Files already downloaded and verified
test classification error: 0.363
test classification loss: 0.6392948627471924
```

In [ ]:
```
%%shell
jupyter nbconvert --to html /content/Lab2_Cats_vs_Dogs.ipynb
```

```
[NbConvertApp] Converting notebook /content/Lab2_Cats_vs_Dogs.ipynb to html
[NbConvertApp] Writing 1679558 bytes to /content/Lab2_Cats_vs_Dogs.html
```

Out[ ]: