CpE 520: HW#8

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Through this homework assignment we will download CIFAR-10 dataset and try to train an AlexNet-like neural network to classify the images in the dataset.

```
% to load last saved variables to worksapce of Matlab
load('HW8_code_workspace.mat')
```

0. CIFAR-10 Dataset

CIFAR-10 dataset is a collection of 60,000 labeled images (50,000 for training and 10.000 for testing) of 10 classes which were collected by Alex Krizhevsky, Vinod Nair, and Geoffrey Hinton. In this section we are going to download, unzip and load it into *Matlab*.

0.1 Downloading CIFAR-10 Dataset

The code below will check if there exist the dataset and if not, it will download both the train and test set of CIFAR-10.

```
clc; clear; close all;

if ~exist('cifar-10-batches-mat','dir')
    cifar10Dataset = 'cifar-10-matlab';
    disp('Downloading 174MB CIFAR-10 dataset...');
    websave([cifar10Dataset,'.tar.gz'],...
        ['https://www.cs.toronto.edu/~kriz/',cifar10Dataset,'.tar.gz']);
    gunzip([cifar10Dataset,'.tar.gz'])
    delete([cifar10Dataset,'.tar.gz'])
    untar([cifar10Dataset,'.tar'])
    delete([cifar10Dataset,'.tar'])
else
    disp('CIFAR-10 dataset already downloaded.')
end
```

```
CIFAR-10 dataset already downloaded.
```

0.2 Splitting CIFAR-10 into Folders by Their Labels

After downloading the dataset, we need to put every single image in a folder which has the name equal to the image's label. Doing that will make it easier for us to use built-in Matlab function to load the dataset into Matlab workspace.

```
if ~exist('cifar10Train','dir')
    disp('Saving the Images in folders. This might take some time...');
    saveCIFAR10AsFolderOfImages('cifar-10-batches-mat', pwd, true);
else
    disp('CIFAR-10 dataset already foldered!')
end
```

```
CIFAR-10 dataset already foldered!
```

0.3 Loading Training Images into *Matlab*

Using built-in ***imageDatastore*** of *Matlab* will help us to import data in batches, so they could be fit into memory easily.

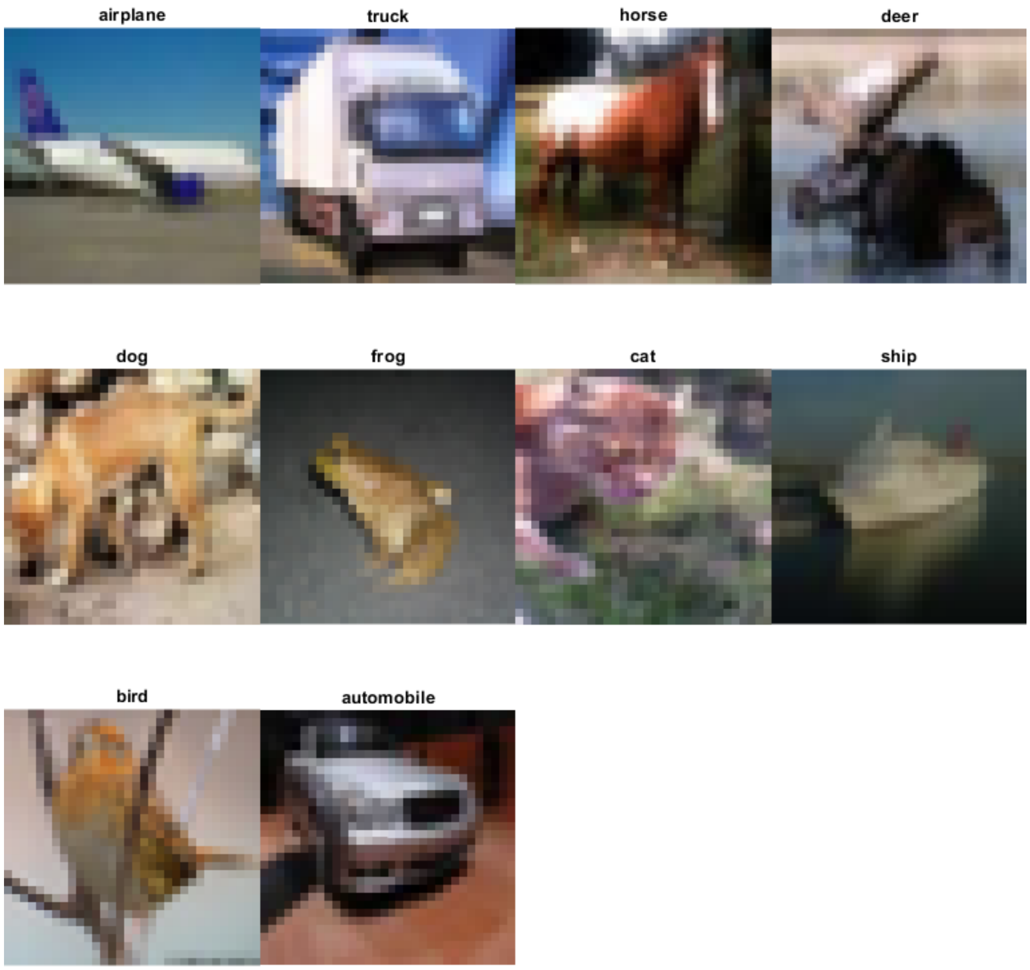
```
categories = {'airplane', 'truck', 'horse',...
              'deer','dog','frog', ...
              'cat', 'ship', 'bird', 'automobile'};

rootFolder = 'cifar10Train';
imds = imageDatastore(fullfile(rootFolder, categories), ...
    'LabelSource', 'foldernames');
clear rootFolder

disp(countEachLabel(imds));
```

```
    Label         Count
  __________     _____

  airplane       5000
  automobile     5000
  bird           5000
  cat            5000
  deer           5000
  dog            5000
  frog           5000
  horse          5000
  ship           5000
  truck          5000
```

0.4 Plot One Random Sample of Each Class

We plot one sample of every class in the training dataset.

```
rand_nums = randi(size(imds.Files, 1)/10) + [0:5000:45000];

figure('Position', [100, 100, 1000, 1000]);
for i = 1:10
    subplottight(3,4,i);
    imshow(imread(imds.Files{rand_nums(i)}), 'border', 'tight');
    title(char(imds.Labels(rand_nums(i))));
    hold on;
end
hold off
```

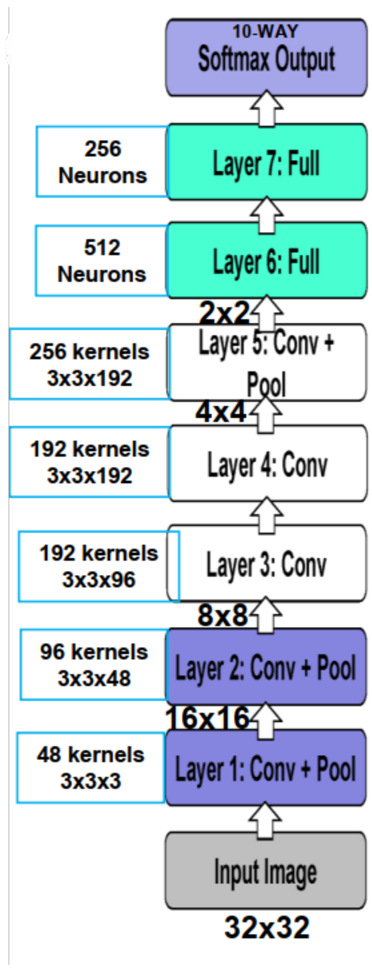

airplane
truck
horse
deer
dog
frog
cat
ship
bird
automobile

1. AlexNet-Like Neural Network to Classify CIFAR-10 Image Dataset

In this section we are going to build the neural network that was proposed in the first question. We also train it on CIFAR-10 dataset and finally evaluate it with the test subset of the dataset.

1.1 Defining Network Architecture

We define layers of the neural network according to the picture below with the code snippet that came after the picture.



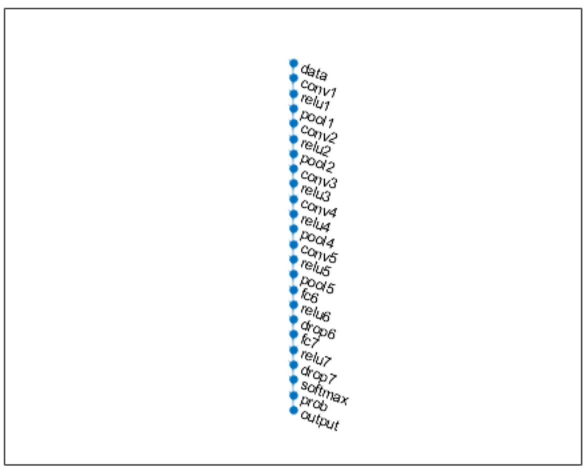

```
image_dim = [32 32 3];
kernel_dim = [3 3];
maxpool_dim = [2 2];
stride_conv_dim = [1 1];
stride_maxpool_dim = [2 2];

layers_1 = [
```

```
    imageInputLayer(image_dim, 'Name', 'data')

    convolution2dLayer(kernel_dim, 48, 'Name', 'conv1', 'BiasLearnRateFactor',
        2, 'Stride', stride_conv_dim, 'Padding', 'same')
    reluLayer('Name','relu1')
    maxPooling2dLayer(maxpool_dim, 'Name', 'pool1', 'Stride', stride_maxpool_dim
        )

    convolution2dLayer(kernel_dim, 96, 'Name', 'conv2', 'BiasLearnRateFactor',
        2, 'Stride', stride_conv_dim, 'Padding', 'same')
    reluLayer('Name','relu2')
    maxPooling2dLayer(maxpool_dim, 'Name', 'pool2', 'Stride', stride_maxpool_dim
        )

    convolution2dLayer(kernel_dim, 192, 'Name', 'conv3', 'BiasLearnRateFactor',
        2, 'Stride', stride_conv_dim, 'Padding', 'same')
    reluLayer('Name','relu3')

    convolution2dLayer(kernel_dim, 192, 'Name', 'conv4', 'BiasLearnRateFactor',
        2, 'Stride', stride_conv_dim, 'Padding', 'same')
    reluLayer('Name','relu4')
    maxPooling2dLayer(maxpool_dim, 'Name', 'pool4', 'Stride', stride_maxpool_dim
        )

    convolution2dLayer(kernel_dim, 256, 'Name', 'conv5', 'BiasLearnRateFactor',
        2, 'Stride', stride_conv_dim, 'Padding', 'same')
    reluLayer('Name','relu5')
    maxPooling2dLayer(maxpool_dim, 'Name', 'pool5', 'Stride', stride_maxpool_dim
        )

    fullyConnectedLayer(512, 'Name', 'fc6', 'BiasLearnRateFactor', 2)
    reluLayer('Name', 'relu6')
    dropoutLayer(0.5,'Name','drop6')

    fullyConnectedLayer(256, 'Name', 'fc7', 'BiasLearnRateFactor', 2)
    reluLayer('Name','relu7')
    dropoutLayer(0.5,'Name','drop7')

    fullyConnectedLayer(10, 'Name', 'softmax', 'BiasLearnRateFactor', 2)
    softmaxLayer('Name','prob')

    classificationLayer('Name','output')
    ];

clear image_dim kernel_dim maxpool_dim stride_conv_dim stride_maxpool_dim

disp(layers_1);
```

```
24x1 Layer array with layers:

   1   'data'      Image Input             32x32x3 images with 'zerocenter' normalization
   2   'conv1'     Convolution             48 3x3 convolutions with stride [1  1] and padding 'same'
   3   'relu1'     ReLU                    ReLU
   4   'pool1'     Max Pooling             2x2 max pooling with stride [2  2] and padding [0  0  0  0]
   5   'conv2'     Convolution             96 3x3 convolutions with stride [1  1] and padding 'same'
   6   'relu2'     ReLU                    ReLU
   7   'pool2'     Max Pooling             2x2 max pooling with stride [2  2] and padding [0  0  0  0]
   8   'conv3'     Convolution             192 3x3 convolutions with stride [1  1] and padding 'same'
   9   'relu3'     ReLU                    ReLU
  10   'conv4'     Convolution             192 3x3 convolutions with stride [1  1] and padding 'same'
  11   'relu4'     ReLU                    ReLU
  12   'pool4'     Max Pooling             2x2 max pooling with stride [2  2] and padding [0  0  0  0]
  13   'conv5'     Convolution             256 3x3 convolutions with stride [1  1] and padding 'same'
  14   'relu5'     ReLU                    ReLU
  15   'pool5'     Max Pooling             2x2 max pooling with stride [2  2] and padding [0  0  0  0]
  16   'fc6'       Fully Connected         512 fully connected layer
  17   'relu6'     ReLU                    ReLU
  18   'drop6'     Dropout                 50% dropout
  19   'fc7'       Fully Connected         256 fully connected layer
  20   'relu7'     ReLU                    ReLU
  21   'drop7'     Dropout                 50% dropout
  22   'softmax'   Fully Connected         10 fully connected layer
  23   'prob'      Softmax                 softmax
  24   'output'    Classification Output   crossentropyex
```

In the figure below, we can see the whole network at a glance:

```
%analyzeNetwork(layers_1);
plot(layerGraph(layers_1));
```



1.3 Training the Network

1.3.1 Split Training Data into *train* and *validation* Subsets

15 percent of the 50,000 training images are assigned to the validation set and the rest are kept for the neural network training.

```
[imdsTrain, imdsValidation] = splitEachLabel(imds,0.85,'randomized');
disp(countEachLabel(imdsTrain));
```

```
      Label        Count
    __________     _____

    airplane       4250
    automobile     4250
    bird           4250
    cat            4250
    deer           4250
    dog            4250
    frog           4250
    horse          4250
    ship           4250
    truck          4250
```

```
disp(countEachLabel(imdsValidation));
```

```
      Label        Count
    __________     _____

    airplane        750
    automobile      750
    bird            750
    cat             750
    deer            750
    dog             750
    frog            750
    horse           750
    ship            750
    truck           750
```

1.3.2 Preprocessing the Training Data

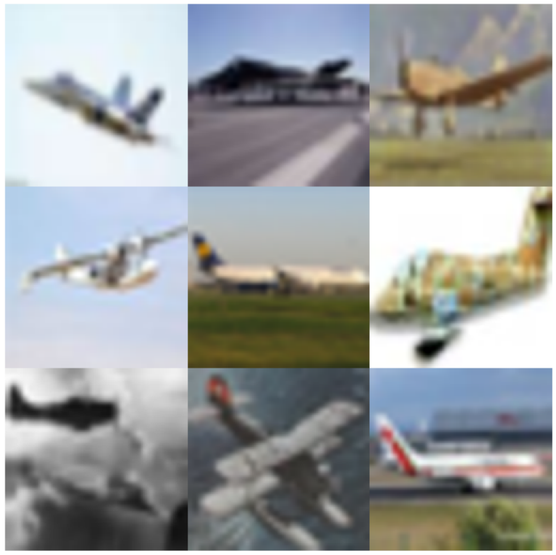
To strengthen the training process and make the network invariant to distortions in images, we did some prerpocessnig on the training subset of the images, as listed below:

- Random reflection of images in the left-right direction with probability of 0.5
- Random horizontal translation picked from a continuous distribution of range [-3 3]
- Random vertical translation picked from a continuous distribution of range [-3 3]

```
pixelRange = [-3 3];
imageAugmenter = imageDataAugmenter( ...
                        'RandXReflection',true, ...
                        'RandXTranslation',pixelRange, ...
                        'RandYTranslation',pixelRange);
augimdsTrain = augmentedImageDatastore([32 32], imdsTrain, ...
    'DataAugmentation',imageAugmenter);
```

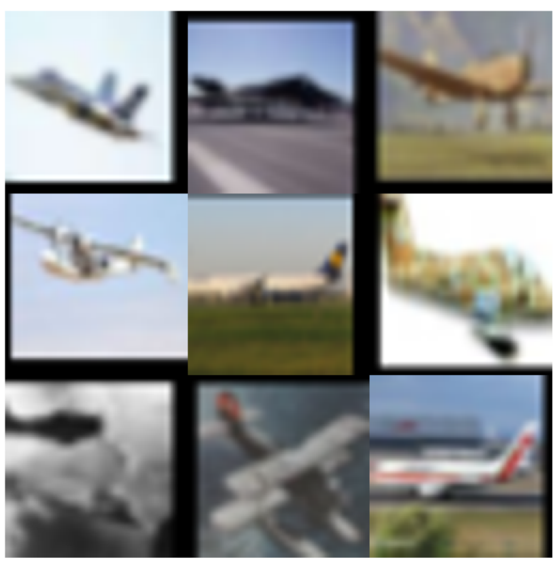
The first nine images before preprocessing:

```
montage(subset(imdsTrain, 1:9));
```



The first nine images after preprocessing:

```
montage(readByIndex(augimdsTrain, 1:9).input);
```



1.3.3 Defining Options for Training

We have used 40 epoches with mini-batch size of 512 and used the *Adam* Optimizer.

```
opts = trainingOptions('adam', ...
    'ExecutionEnvironment','auto', ...
    'MaxEpochs', 40, ...
    'MiniBatchSize', 512, ...
    'Shuffle', 'every-epoch', ...
    'Plots', 'training-progress', ...
    'Verbose', true, ...
    'ValidationData', imdsValidation);
```

1.3.4 Learning Curves and Training Process

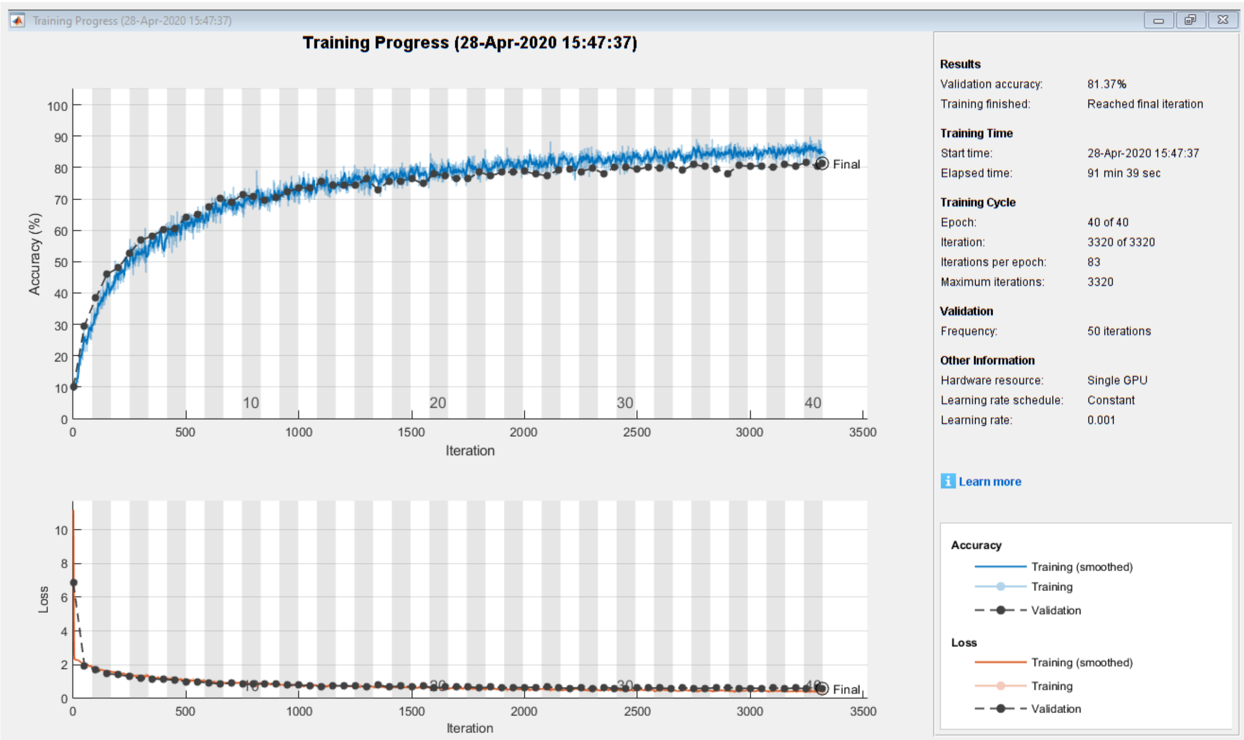
We trained the network on single GPU system nad print the results in a table every 50 iterations. Besides, the learning curves are plotted after the table. Finally the network reached 84.38% on training and 81.37% on validation subset. The training process took about 90 minutes long.

```
trained_net_1 = trainNetwork(augimdsTrain, layers_1, opts);
```

```
Warning: Support for GPU devices with Compute Capability 3.0 will be removed in a future MATLAB release. For more
    information on GPU support, see GPU Support by Release.
Training on single GPU.
Initializing input data normalization.
|=======================================================================================================================|
|  Epoch  |  Iteration  |  Time Elapsed  |  Mini-batch  |  Validation  |  Mini-batch  |  Validation  |  Base
    Learning  |
|         |             |   (hh:mm:ss)   |   Accuracy   |   Accuracy   |     Loss     |     Loss     |       Rate
          |
|=======================================================================================================================|
|       1 |           1 |       00:02:46 |       10.55% |       10.00% |      11.1746 |       6.8502 |
    0.0010 |
|       1 |          50 |       00:04:05 |       23.05% |       29.56% |       2.0305 |       1.9423 |
    0.0010 |
|       2 |         100 |       00:05:24 |       31.84% |       38.39% |       1.8032 |       1.6916 |
    0.0010 |
|       2 |         150 |       00:06:45 |       39.84% |       46.04% |       1.6340 |       1.4730 |
    0.0010 |
|       3 |         200 |       00:08:05 |       48.44% |       48.04% |       1.4497 |       1.4095 |
    0.0010 |
|       4 |         250 |       00:09:25 |       47.46% |       52.71% |       1.4264 |       1.3147 |
    0.0010 |
|       4 |         300 |       00:10:45 |       51.95% |       56.84% |       1.3355 |       1.1858 |
    0.0010 |
|       5 |         350 |       00:12:05 |       56.64% |       58.21% |       1.1940 |       1.1769 |
    0.0010 |
|       5 |         400 |       00:13:26 |       56.05% |       60.15% |       1.2226 |       1.1227 |
    0.0010 |
|       6 |         450 |       00:14:45 |       57.81% |       60.47% |       1.2050 |       1.1112 |
    0.0010 |
|       7 |         500 |       00:16:06 |       64.84% |       64.23% |       1.0189 |       1.0050 |
    0.0010 |
|       7 |         550 |       00:17:28 |       62.89% |       64.88% |       1.0022 |       0.9921 |
    0.0010 |
|       8 |         600 |       00:18:49 |       65.43% |       67.41% |       1.0184 |       0.9291 |
    0.0010 |
|       8 |         650 |       00:20:10 |       68.16% |       70.23% |       0.9114 |       0.8688 |
    0.0010 |
|       9 |         700 |       00:21:31 |       71.48% |       68.93% |       0.8441 |       0.9062 |
    0.0010 |
|      10 |         750 |       00:22:52 |       68.36% |       71.39% |       0.9565 |       0.8422 |
    0.0010 |
```

10	800	00:24:13	67.19%	70.61%	0.9368	0.8515	0.0010
11	850	00:25:35	67.19%	69.53%	0.9207	0.8781	0.0010
11	900	00:26:55	71.48%	70.40%	0.8185	0.8636	0.0010
12	950	00:28:16	71.48%	72.16%	0.8344	0.8269	0.0010
13	1000	00:29:37	74.41%	73.60%	0.7181	0.7854	0.0010
13	1050	00:30:57	73.05%	73.35%	0.8046	0.7736	0.0010
14	1100	00:32:17	72.85%	75.48%	0.8163	0.7243	0.0010
14	1150	00:33:36	75.78%	74.41%	0.7186	0.7637	0.0010
15	1200	00:34:56	78.91%	74.48%	0.6884	0.7551	0.0010
16	1250	00:36:16	76.17%	74.37%	0.7158	0.7408	0.0010
16	1300	00:37:36	73.83%	76.40%	0.7440	0.7034	0.0010
17	1350	00:38:56	75.59%	72.89%	0.6730	0.7962	0.0010
17	1400	00:40:15	77.34%	75.68%	0.6674	0.7034	0.0010
18	1450	00:41:37	79.69%	75.72%	0.6195	0.7294	0.0010
19	1500	00:42:57	78.13%	76.39%	0.6104	0.6912	0.0010
19	1550	00:44:17	77.34%	74.83%	0.7288	0.7506	0.0010
20	1600	00:45:37	77.15%	78.03%	0.6956	0.6359	0.0010
20	1650	00:46:56	79.49%	77.44%	0.6096	0.6763	0.0010
21	1700	00:48:17	78.91%	76.44%	0.6358	0.6896	0.0010
22	1750	00:49:37	83.59%	76.37%	0.4726	0.7047	0.0010
22	1800	00:50:58	79.49%	78.59%	0.6246	0.6303	0.0010
23	1850	00:52:17	79.69%	77.28%	0.6480	0.6792	0.0010
23	1900	00:53:45	80.86%	78.53%	0.5494	0.6419	0.0010
24	1950	00:55:05	81.45%	78.51%	0.5932	0.6484	0.0010
25	2000	00:56:24	82.62%	78.75%	0.5143	0.6555	0.0010
25	2050	00:57:45	81.45%	77.91%	0.5461	0.6688	0.0010
26	2100	00:59:04	81.05%	77.41%	0.5522	0.6912	0.0010
26	2150	01:00:24	83.40%	79.15%	0.5004	0.6260	0.0010
27	2200	01:01:45	81.05%	79.36%	0.5271	0.6145	0.0010
28	2250	01:03:05	80.27%	78.72%	0.5737	0.6449	0.0010
28	2300	01:04:25	79.69%	79.76%	0.5618	0.6105	0.0010
29	2350	01:05:44	82.62%	78.12%	0.5440	0.6619	0.0010
29	2400	01:07:04	82.42%	80.03%	0.4902	0.6073	0.0010
30	2450	01:08:24	83.59%	80.17%	0.5028	0.5901	0.0010
31	2500	01:09:44	83.40%	79.40%	0.4549	0.6185	0.0010
31	2550	01:11:04	81.05%	80.09%	0.5590	0.6206	0.0010
32	2600	01:12:23	83.01%	79.92%	0.4975	0.6255	0.0010
32	2650	01:13:43	79.10%	80.68%	0.6294	0.5893	0.0010
33	2700	01:15:03	81.84%	79.11%	0.5202	0.6425	0.0010
34	2750	01:16:23	86.33%	80.97%	0.4711	0.5894	0.0010
34	2800	01:17:42	84.57%	80.29%	0.4627	0.6106	0.0010
35	2850	01:19:02	86.52%	79.55%	0.3983	0.6292	0.0010
35	2900	01:20:21	84.18%	78.05%	0.4886	0.6640	0.0010
36	2950	01:21:40	85.55%	80.63%	0.4258	0.6036	0.0010

```
|     37  |      3000  |     01:23:00  |       86.52%  |       80.41%  |       0.3825  |       0.6077  |
    0.0010  |
|     37  |      3050  |     01:24:21  |       84.18%  |       80.53%  |       0.4640  |       0.6091  |
    0.0010  |
|     38  |      3100  |     01:25:40  |       87.11%  |       79.97%  |       0.4125  |       0.6326  |
    0.0010  |
|     38  |      3150  |     01:26:59  |       83.20%  |       80.95%  |       0.5435  |       0.5906  |
    0.0010  |
|     39  |      3200  |     01:28:18  |       87.11%  |       80.52%  |       0.4022  |       0.6182  |
    0.0010  |
|     40  |      3250  |     01:29:38  |       84.18%  |       81.56%  |       0.4500  |       0.5816  |
    0.0010  |
|     40  |      3300  |     01:30:57  |       84.77%  |       80.25%  |       0.4485  |       0.6182  |
    0.0010  |
|     40  |      3320  |     01:31:32  |       84.38%  |       81.37%  |       0.4713  |       0.5919  |
    0.0010  |
|=====================================================================================================|
```



1.4 Evaluating the Network

Here we use the test partition of the dataset to evaluate the trained network.

1.4.1 Loading the Test Set of CIFAR-10

```
rootFolder = 'cifar10Test';
imds_test = imageDatastore(fullfile(rootFolder, categories), ...
    'LabelSource', 'foldernames');
clear rootFolder

disp(countEachLabel(imds_test));
```

```
    Label         Count
 ___________     _____

 airplane         1000
 automobile       1000
 bird             1000
 cat              1000
 deer             1000
 dog              1000
 frog             1000
 horse            1000
 ship             1000
 truck            1000
```

1.4.2 Classifying the Test Dataset

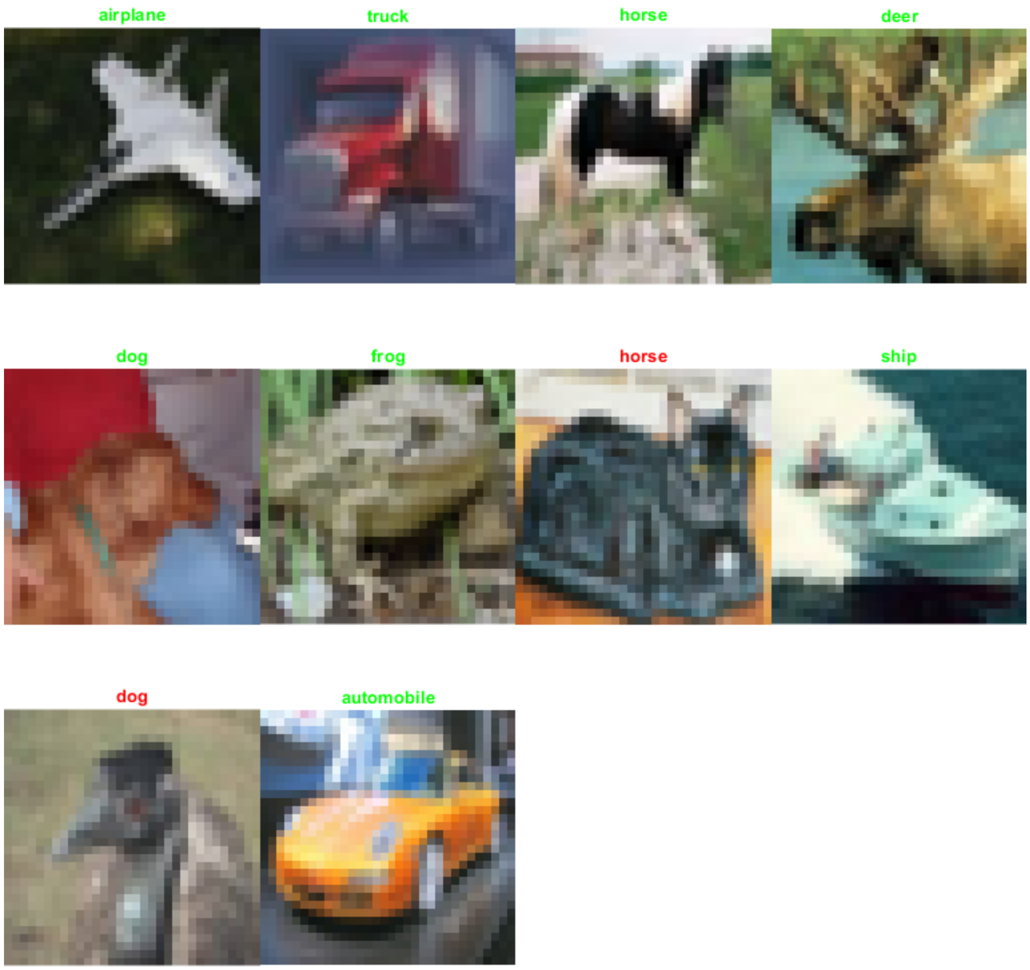
The line below will classify all images in the test dataset.

```
predicted_labels_1 = classify(trained_net_1, imds_test);
```

1.4.3 Plot Some Samples of the Test Dataset with the Predicted Label

Here we plot one sample of every class of the test dataset and display its predicted label on top of it. If it was predicted correctly the title will be in green color otherwise in red.

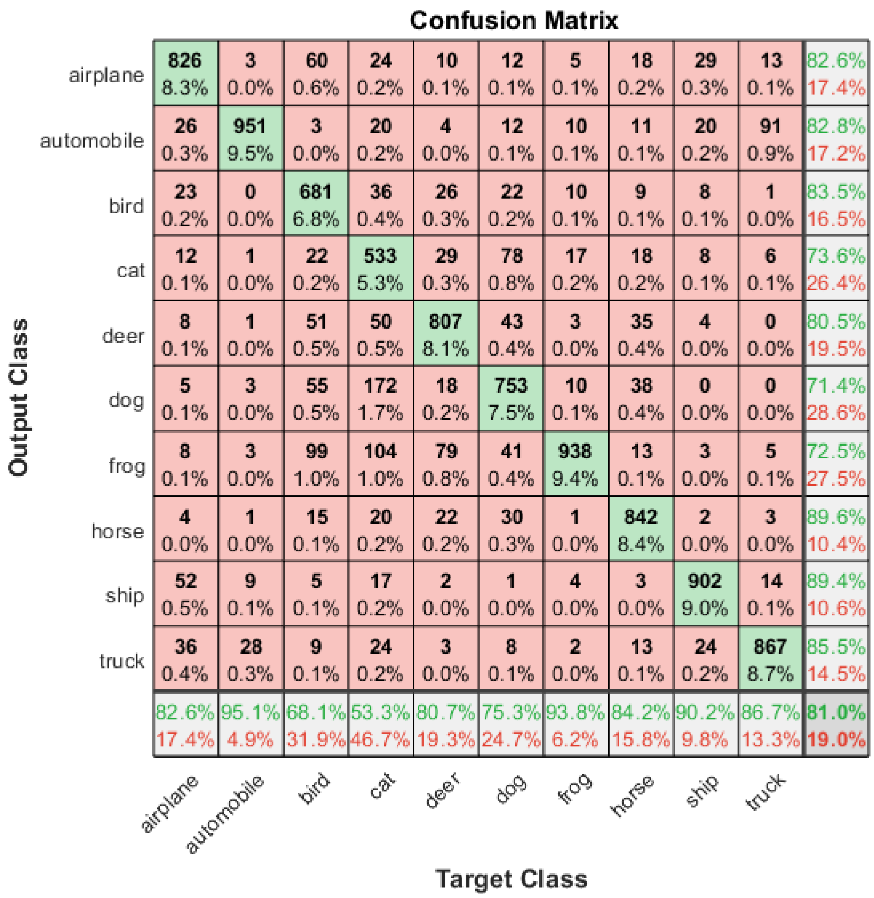
```
rand_nums = randi(size(imds_test.Files, 1)/10) + [0:1000:9000];

figure('Position', [100, 100, 1000, 1000]);
for i = 1:10
    if predicted_labels_1(rand_nums(i)) == imds_test.Labels(rand_nums(i))
        colorText = 'g';
    else
        colorText = 'r';
    end
    subplottight(3,4,i);
    imshow(imread(imds_test.Files{rand_nums(i)}));
    title(char(predicted_labels_1(rand_nums(i))), 'Color', colorText);
    hold on;
end
hold off
```



1.4.4 Classification Performance

As the final step of this section, we plot the confusion matrix. Final performance of the network is 81.0% over the whole test dataset.

```
plotconfusion(imds_test.Labels, predicted_labels_1);
```


Confusion Matrix
Output Class
Target Class
airplane 826 8.3% 3 0.0% 60 0.6% 24 0.2% 10 0.1% 12 0.1% 5 0.1% 18 0.2% 29 0.3% 13 0.1% 82.6% 17.4%
automobile 26 0.3% 951 9.5% 3 0.0% 20 0.2% 4 0.0% 12 0.1% 10 0.1% 11 0.1% 20 0.2% 91 0.9% 82.8% 17.2%
bird 23 0.2% 0 0.0% 681 6.8% 36 0.4% 26 0.3% 22 0.2% 10 0.1% 9 0.1% 8 0.1% 1 0.0% 83.5% 16.5%
cat 12 0.1% 1 0.0% 22 0.2% 533 5.3% 29 0.3% 78 0.8% 17 0.2% 18 0.2% 8 0.1% 6 0.1% 73.6% 26.4%
deer 8 0.1% 1 0.0% 51 0.5% 50 0.5% 807 8.1% 43 0.4% 3 0.0% 35 0.4% 4 0.0% 0 0.0% 80.5% 19.5%
dog 5 0.1% 3 0.0% 55 0.5% 172 1.7% 18 0.2% 753 7.5% 10 0.1% 38 0.4% 0 0.0% 0 0.0% 71.4% 28.6%
frog 8 0.1% 3 0.0% 99 1.0% 104 1.0% 79 0.8% 41 0.4% 938 9.4% 13 0.1% 3 0.0% 5 0.1% 72.5% 27.5%
horse 4 0.0% 1 0.0% 15 0.1% 20 0.2% 22 0.2% 30 0.3% 1 0.0% 842 8.4% 2 0.0% 3 0.0% 89.6% 10.4%
ship 52 0.5% 9 0.1% 5 0.1% 17 0.2% 2 0.0% 1 0.0% 4 0.0% 3 0.0% 902 9.0% 14 0.1% 89.4% 10.6%
truck 36 0.4% 28 0.3% 9 0.1% 24 0.2% 3 0.0% 8 0.1% 2 0.0% 13 0.1% 24 0.2% 867 8.7% 85.5% 14.5%
82.6% 17.4% 95.1% 4.9% 68.1% 31.9% 53.3% 46.7% 80.7% 19.3% 75.3% 24.7% 93.8% 6.2% 84.2% 15.8% 90.2% 9.8% 86.7% 13.3% 81.0% 19.0%
airplane automobile bird cat deer dog frog horse ship truck

2. Deleting Convolutional Layer 5 with Its Max-Pooling

2.1 Defining Network Architecture

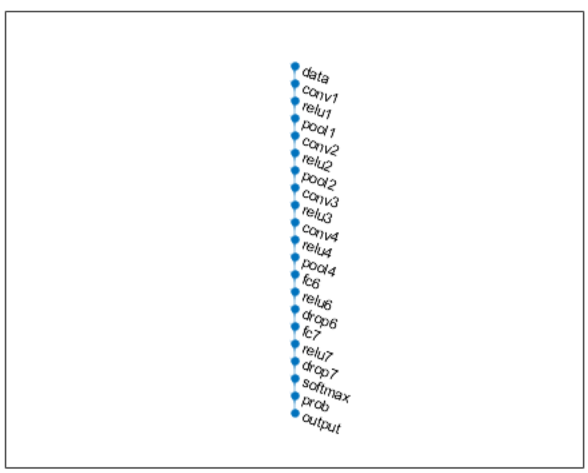
We define the layers of the network again as below. Convolutional layer 5 is deleted in comparison with question 1.

```
image_dim = [32 32 3];
kernel_dim = [3 3];
maxpool_dim = [2 2];
stride_conv_dim = [1 1];
stride_maxpool_dim = [2 2];

layers_2 = [
    imageInputLayer(image_dim, 'Name', 'data')

    convolution2dLayer(kernel_dim, 48, 'Name', 'conv1', 'BiasLearnRateFactor',
        2, 'Stride', stride_conv_dim, 'Padding', 'same')
    reluLayer('Name','relu1')
    maxPooling2dLayer(maxpool_dim, 'Name', 'pool1', 'Stride', stride_maxpool_dim
        )

    convolution2dLayer(kernel_dim, 96, 'Name', 'conv2', 'BiasLearnRateFactor',
        2, 'Stride', stride_conv_dim, 'Padding', 'same')
    reluLayer('Name','relu2')
    maxPooling2dLayer(maxpool_dim, 'Name', 'pool2', 'Stride', stride_maxpool_dim
        )

    convolution2dLayer(kernel_dim, 192, 'Name', 'conv3', 'BiasLearnRateFactor',
        2, 'Stride', stride_conv_dim, 'Padding', 'same')
    reluLayer('Name','relu3')

    convolution2dLayer(kernel_dim, 192, 'Name', 'conv4', 'BiasLearnRateFactor',
        2, 'Stride', stride_conv_dim, 'Padding', 'same')
    reluLayer('Name','relu4')
    maxPooling2dLayer(maxpool_dim, 'Name', 'pool4', 'Stride', stride_maxpool_dim
        )

    fullyConnectedLayer(512, 'Name', 'fc6', 'BiasLearnRateFactor', 2)
    reluLayer('Name', 'relu6')
    dropoutLayer(0.5,'Name','drop6')

    fullyConnectedLayer(256, 'Name', 'fc7', 'BiasLearnRateFactor', 2)
    reluLayer('Name','relu7')
    dropoutLayer(0.5,'Name','drop7')

    fullyConnectedLayer(10, 'Name', 'softmax', 'BiasLearnRateFactor', 2)
    softmaxLayer('Name','prob')
```

```

    classificationLayer('Name','output')
    ];

clear image_dim kernel_dim maxpool_dim stride_conv_dim stride_maxpool_dim

disp(layers_2);
```

```
21x1 Layer array with layers:

     1   'data'      Image Input             32x32x3 images with 'zerocenter' normalization
     2   'conv1'     Convolution             48 3x3 convolutions with stride [1  1] and padding 'same'
     3   'relu1'     ReLU                    ReLU
     4   'pool1'     Max Pooling             2x2 max pooling with stride [2  2] and padding [0  0  0  0]
     5   'conv2'     Convolution             96 3x3 convolutions with stride [1  1] and padding 'same'
     6   'relu2'     ReLU                    ReLU
     7   'pool2'     Max Pooling             2x2 max pooling with stride [2  2] and padding [0  0  0  0]
     8   'conv3'     Convolution             192 3x3 convolutions with stride [1  1] and padding 'same'
     9   'relu3'     ReLU                    ReLU
    10   'conv4'     Convolution             192 3x3 convolutions with stride [1  1] and padding 'same'
    11   'relu4'     ReLU                    ReLU
    12   'pool4'     Max Pooling             2x2 max pooling with stride [2  2] and padding [0  0  0  0]
    13   'fc6'       Fully Connected         512 fully connected layer
    14   'relu6'     ReLU                    ReLU
    15   'drop6'     Dropout                 50% dropout
    16   'fc7'       Fully Connected         256 fully connected layer
    17   'relu7'     ReLU                    ReLU
    18   'drop7'     Dropout                 50% dropout
    19   'softmax'   Fully Connected         10 fully connected layer
    20   'prob'      Softmax                 softmax
    21   'output'    Classification Output   crossentropyex
```

```
%analyzeNetwork(layers_2);
plot(layerGraph(layers_2));
```



2.2 Learning Curves and Training Process

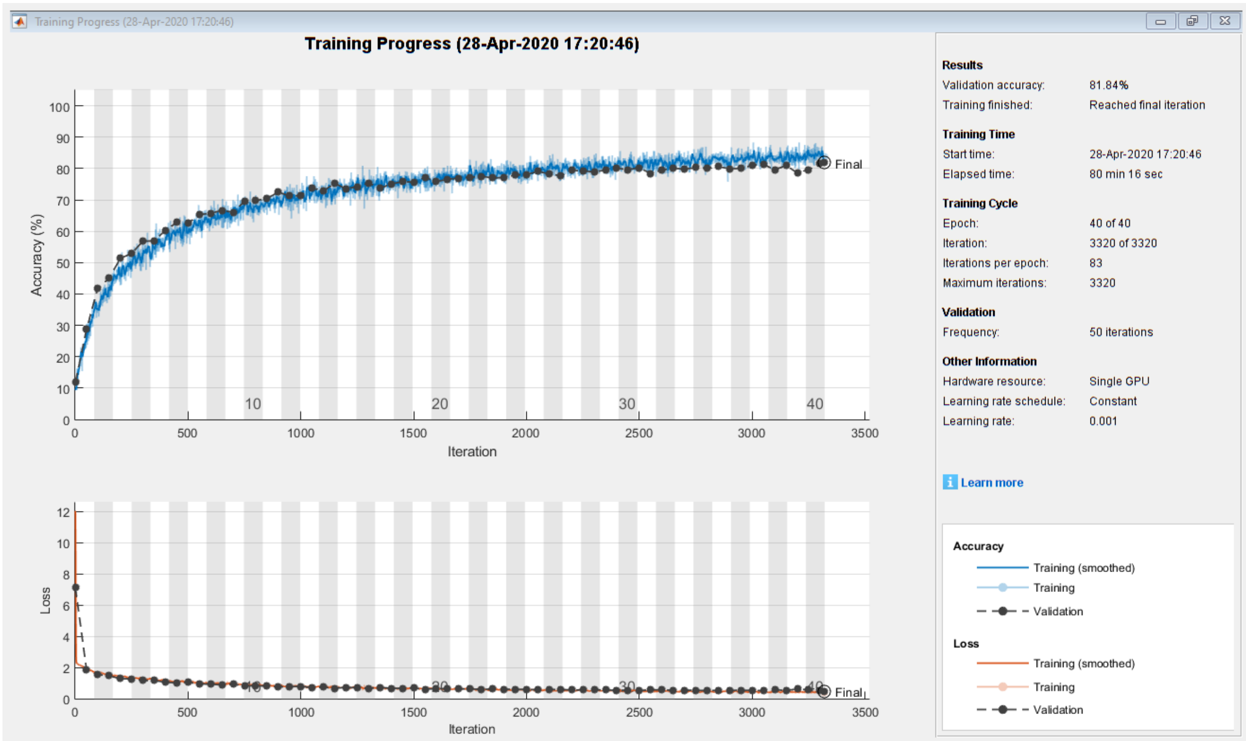
We trained the network on single GPU system nad print the results in a table every 50 iterations. Besides, the learning curves are plotted after the table. Finally the network reached 83.59% on training and 81.84%

on validation subset. The training process took about 90 minutes long.

```
trained_net_2 = trainNetwork(augimdsTrain, layers_2, opts);
```

```
Training on single GPU.
Initializing input data normalization.
|==========================================================================================================|
|  Epoch  |  Iteration  |  Time Elapsed  |  Mini-batch  |  Validation  |  Mini-batch  |  Validation  |  Base
    Learning  |
|         |             |  (hh:mm:ss)    |  Accuracy    |  Accuracy    |  Loss        |  Loss        |  Rate
          |
|==========================================================================================================|
|       1 |           1 |       00:00:09 |        9.38% |       11.89% |      12.0610 |       7.1610 |
    0.0010 |
|       1 |          50 |       00:01:17 |       24.61% |       28.69% |       2.0013 |       1.9260 |
    0.0010 |
|       2 |         100 |       00:02:27 |       35.74% |       41.84% |       1.7440 |       1.6063 |
    0.0010 |
|       2 |         150 |       00:03:36 |       38.28% |       44.99% |       1.6553 |       1.5126 |
    0.0010 |
|       3 |         200 |       00:04:46 |       42.77% |       51.33% |       1.5858 |       1.3373 |
    0.0010 |
|       4 |         250 |       00:05:56 |       50.98% |       52.97% |       1.3348 |       1.3207 |
    0.0010 |
|       4 |         300 |       00:07:05 |       48.63% |       56.79% |       1.3816 |       1.2178 |
    0.0010 |
|       5 |         350 |       00:08:15 |       56.45% |       56.97% |       1.2503 |       1.2198 |
    0.0010 |
|       5 |         400 |       00:09:25 |       57.03% |       60.29% |       1.1812 |       1.1059 |
    0.0010 |
|       6 |         450 |       00:10:34 |       58.98% |       62.77% |       1.1712 |       1.0679 |
    0.0010 |
|       7 |         500 |       00:11:44 |       59.96% |       62.55% |       1.1371 |       1.1027 |
    0.0010 |
|       7 |         550 |       00:12:54 |       61.52% |       65.28% |       1.1597 |       1.0064 |
    0.0010 |
|       8 |         600 |       00:14:04 |       61.91% |       65.73% |       1.0565 |       0.9785 |
    0.0010 |
|       8 |         650 |       00:15:18 |       63.48% |       66.64% |       1.0920 |       0.9404 |
    0.0010 |
|       9 |         700 |       00:16:28 |       69.92% |       66.04% |       0.9164 |       0.9692 |
    0.0010 |
|      10 |         750 |       00:17:38 |       66.60% |       69.52% |       0.9411 |       0.8815 |
    0.0010 |
|      10 |         800 |       00:18:48 |       71.48% |       69.76% |       0.7699 |       0.8761 |
    0.0010 |
|      11 |         850 |       00:20:00 |       65.23% |       70.47% |       0.9358 |       0.8700 |
    0.0010 |
|      11 |         900 |       00:21:10 |       70.70% |       72.47% |       0.9084 |       0.8083 |
    0.0010 |
|      12 |         950 |       00:22:19 |       68.36% |       71.25% |       0.8975 |       0.8242 |
    0.0010 |
|      13 |        1000 |       00:23:28 |       68.55% |       71.35% |       0.8692 |       0.8445 |
    0.0010 |
|      13 |        1050 |       00:24:38 |       73.44% |       73.73% |       0.8148 |       0.7670 |
    0.0010 |
|      14 |        1100 |       00:25:49 |       73.63% |       72.89% |       0.7771 |       0.7887 |
    0.0010 |
|      14 |        1150 |       00:29:23 |       76.17% |       75.27% |       0.7079 |       0.7233 |
    0.0010 |
|      15 |        1200 |       00:31:07 |       71.48% |       73.53% |       0.8016 |       0.7810 |
    0.0010 |
|      16 |        1250 |       00:32:16 |       73.24% |       74.20% |       0.7701 |       0.7504 |
    0.0010 |
|      16 |        1300 |       00:33:26 |       75.78% |       75.41% |       0.6784 |       0.7155 |
    0.0010 |
|      17 |        1350 |       00:34:35 |       76.76% |       73.65% |       0.6671 |       0.7765 |
    0.0010 |
|      17 |        1400 |       00:35:44 |       77.54% |       75.12% |       0.6493 |       0.7253 |
    0.0010 |
|      18 |        1450 |       00:36:54 |       74.61% |       75.76% |       0.7402 |       0.7145 |
    0.0010 |
|      19 |        1500 |       00:38:03 |       76.56% |       75.68% |       0.6916 |       0.7319 |
    0.0010 |
|      19 |        1550 |       00:39:13 |       73.83% |       77.16% |       0.7549 |       0.6655 |
    0.0010 |
|      20 |        1600 |       00:40:22 |       76.37% |       75.81% |       0.6699 |       0.6971 |
    0.0010 |
|      20 |        1650 |       00:41:32 |       80.86% |       76.53% |       0.5834 |       0.7003 |
    0.0010 |
|      21 |        1700 |       00:42:42 |       77.15% |       76.93% |       0.6758 |       0.6791 |
```

```
     0.0010 |
|      22 |        1750 |     00:43:51 |     81.05% |     77.19% |     0.5636 |     0.6791 |
     0.0010 |
|      22 |        1800 |     00:45:01 |     75.00% |     77.51% |     0.7534 |     0.6539 |
     0.0010 |
|      23 |        1850 |     00:46:10 |     78.13% |     76.97% |     0.6281 |     0.6714 |
     0.0010 |
|      23 |        1900 |     00:47:20 |     75.39% |     77.09% |     0.7354 |     0.6630 |
     0.0010 |
|      24 |        1950 |     00:48:29 |     80.86% |     77.93% |     0.5824 |     0.6567 |
     0.0010 |
|      25 |        2000 |     00:49:38 |     79.88% |     78.03% |     0.6081 |     0.6421 |
     0.0010 |
|      25 |        2050 |     00:50:47 |     76.37% |     79.05% |     0.6632 |     0.6310 |
     0.0010 |
|      26 |        2100 |     00:51:57 |     81.05% |     78.31% |     0.5620 |     0.6360 |
     0.0010 |
|      26 |        2150 |     00:53:06 |     75.98% |     77.65% |     0.7153 |     0.6562 |
     0.0010 |
|      27 |        2200 |     00:54:15 |     79.69% |     79.37% |     0.5905 |     0.6066 |
     0.0010 |
|      28 |        2250 |     00:55:24 |     80.47% |     79.25% |     0.5553 |     0.6123 |
     0.0010 |
|      28 |        2300 |     00:56:33 |     84.38% |     78.88% |     0.4753 |     0.6269 |
     0.0010 |
|      29 |        2350 |     00:57:43 |     79.30% |     79.51% |     0.5687 |     0.6096 |
     0.0010 |
|      29 |        2400 |     00:58:52 |     79.69% |     80.08% |     0.5822 |     0.5920 |
     0.0010 |
|      30 |        2450 |     01:00:01 |     81.64% |     79.64% |     0.5390 |     0.6008 |
     0.0010 |
|      31 |        2500 |     01:01:10 |     83.40% |     80.20% |     0.4910 |     0.5718 |
     0.0010 |
|      31 |        2550 |     01:02:19 |     82.42% |     78.44% |     0.5220 |     0.6315 |
     0.0010 |
|      32 |        2600 |     01:03:28 |     80.47% |     79.51% |     0.5769 |     0.6148 |
     0.0010 |
|      32 |        2650 |     01:04:38 |     80.08% |     80.07% |     0.5332 |     0.5917 |
     0.0010 |
|      33 |        2700 |     01:05:47 |     81.05% |     79.80% |     0.5771 |     0.6039 |
     0.0010 |
|      34 |        2750 |     01:06:56 |     81.64% |     80.25% |     0.5067 |     0.5886 |
     0.0010 |
|      34 |        2800 |     01:08:05 |     79.10% |     80.00% |     0.5623 |     0.5812 |
     0.0010 |
|      35 |        2850 |     01:09:15 |     84.77% |     80.63% |     0.4710 |     0.5896 |
     0.0010 |
|      35 |        2900 |     01:10:24 |     81.64% |     79.89% |     0.5543 |     0.5858 |
     0.0010 |
|      36 |        2950 |     01:11:33 |     82.81% |     80.01% |     0.5047 |     0.6002 |
     0.0010 |
|      37 |        3000 |     01:12:42 |     83.40% |     81.03% |     0.4941 |     0.5815 |
     0.0010 |
|      37 |        3050 |     01:13:52 |     82.03% |     81.28% |     0.4730 |     0.5653 |
     0.0010 |
|      38 |        3100 |     01:15:01 |     83.20% |     79.64% |     0.5356 |     0.6305 |
     0.0010 |
|      38 |        3150 |     01:16:10 |     85.74% |     80.91% |     0.4294 |     0.5786 |
     0.0010 |
|      39 |        3200 |     01:17:19 |     84.38% |     78.64% |     0.4582 |     0.6789 |
     0.0010 |
|      40 |        3250 |     01:18:28 |     83.40% |     79.57% |     0.4886 |     0.6115 |
     0.0010 |
|      40 |        3300 |     01:19:38 |     83.20% |     81.63% |     0.4353 |     0.5549 |
     0.0010 |
|      40 |        3320 |     01:20:10 |     83.59% |     81.84% |     0.4765 |     0.5440 |
     0.0010 |
|========================================================================================|
```



2.3 Evaluating the Network

Here we use the test partition of the dataset to evaluate the trained network.

2.3.1 Classifying the Test Dataset

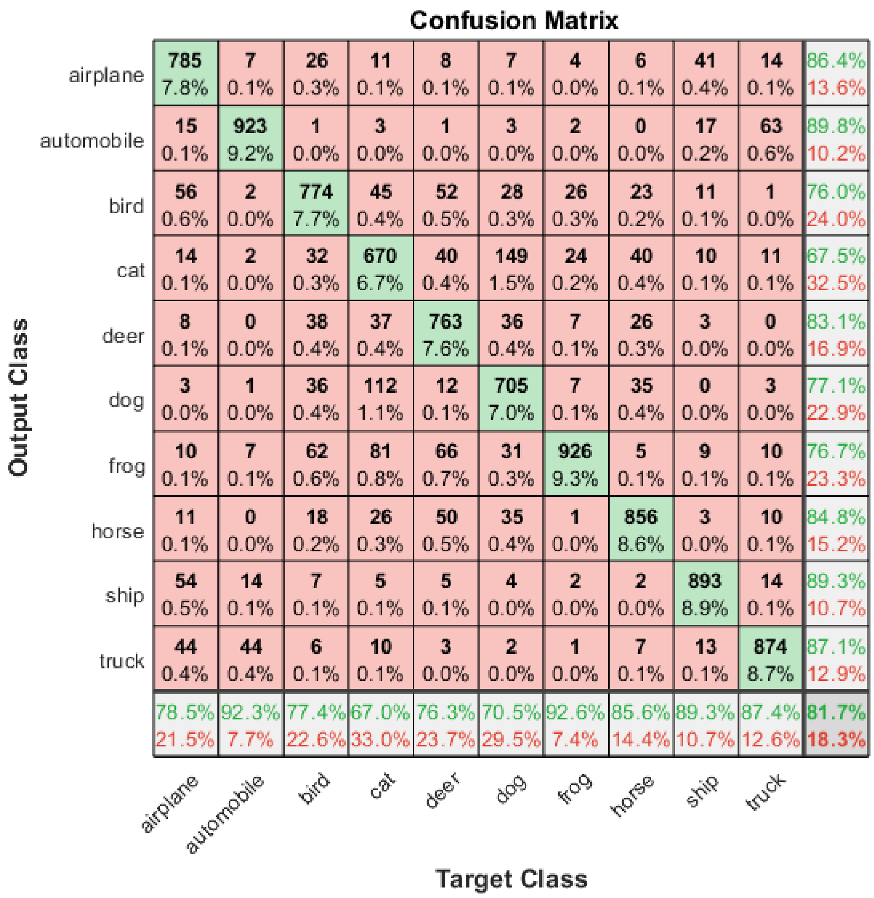
The line below will classify all images in the test dataset.

```
predicted_labels_2 = classify(trained_net_2, imds_test);
```

2.3.2 Classification Performance

As the final step of this section, we plot the confusion matrix. The final performance of the network is 81.7% over the whole test dataset.

```
plotconfusion(imds_test.Labels, predicted_labels_2);
```



Confusion Matrix
Output Class
Target Class
airplane
automobile
bird
cat
deer
dog
frog
horse
ship
truck
785 7.8% | 7 0.1% | 26 0.3% | 11 0.1% | 8 0.1% | 7 0.1% | 4 0.0% | 6 0.1% | 41 0.4% | 14 0.1% | 86.4% 13.6%
15 0.1% | 923 9.2% | 1 0.0% | 3 0.0% | 1 0.0% | 3 0.0% | 2 0.0% | 0 0.0% | 17 0.2% | 63 0.6% | 89.8% 10.2%
56 0.6% | 2 0.0% | 774 7.7% | 45 0.4% | 52 0.5% | 28 0.3% | 26 0.3% | 23 0.2% | 11 0.1% | 1 0.0% | 76.0% 24.0%
14 0.1% | 2 0.0% | 32 0.3% | 670 6.7% | 40 0.4% | 149 1.5% | 24 0.2% | 40 0.4% | 10 0.1% | 11 0.1% | 67.5% 32.5%
8 0.1% | 0 0.0% | 38 0.4% | 37 0.4% | 763 7.6% | 36 0.4% | 7 0.1% | 26 0.3% | 3 0.0% | 0 0.0% | 83.1% 16.9%
3 0.0% | 1 0.0% | 36 0.4% | 112 1.1% | 12 0.1% | 705 7.0% | 7 0.1% | 35 0.4% | 0 0.0% | 3 0.0% | 77.1% 22.9%
10 0.1% | 7 0.1% | 62 0.6% | 81 0.8% | 66 0.7% | 31 0.3% | 926 9.3% | 5 0.1% | 9 0.1% | 10 0.1% | 76.7% 23.3%
11 0.1% | 0 0.0% | 18 0.2% | 26 0.3% | 50 0.5% | 35 0.4% | 1 0.0% | 856 8.6% | 3 0.0% | 10 0.1% | 84.8% 15.2%
54 0.5% | 14 0.1% | 7 0.1% | 5 0.1% | 5 0.1% | 4 0.0% | 2 0.0% | 2 0.0% | 893 8.9% | 14 0.1% | 89.3% 10.7%
44 0.4% | 44 0.4% | 6 0.1% | 10 0.1% | 3 0.0% | 2 0.0% | 1 0.0% | 7 0.1% | 13 0.1% | 874 8.7% | 87.1% 12.9%
78.5% 21.5% | 92.3% 7.7% | 77.4% 22.6% | 67.0% 33.0% | 76.3% 23.7% | 70.5% 29.5% | 92.6% 7.4% | 85.6% 14.4% | 89.3% 10.7% | 87.4% 12.6% | 81.7% 18.3%

3. Deleting Convolutional Layer 4 with Its Max-Pooling

3.1 Defining Network Architecture

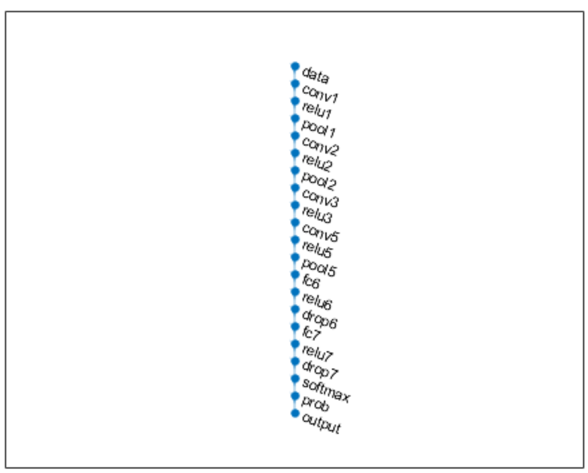
We define the layers of the network again as below. Convolutional layer 4 is deleted in comparison with question 1.

```
image_dim = [32 32 3];
kernel_dim = [3 3];
maxpool_dim = [2 2];
stride_conv_dim = [1 1];
stride_maxpool_dim = [2 2];

layers_3 = [
    imageInputLayer(image_dim, 'Name', 'data')

    convolution2dLayer(kernel_dim, 48, 'Name', 'conv1', 'BiasLearnRateFactor',
        2, 'Stride', stride_conv_dim, 'Padding', 'same')
    reluLayer('Name','relu1')
    maxPooling2dLayer(maxpool_dim, 'Name', 'pool1', 'Stride', stride_maxpool_dim
        )

    convolution2dLayer(kernel_dim, 96, 'Name', 'conv2', 'BiasLearnRateFactor',
        2, 'Stride', stride_conv_dim, 'Padding', 'same')
    reluLayer('Name','relu2')
    maxPooling2dLayer(maxpool_dim, 'Name', 'pool2', 'Stride', stride_maxpool_dim
        )

    convolution2dLayer(kernel_dim, 192, 'Name', 'conv3', 'BiasLearnRateFactor',
        2, 'Stride', stride_conv_dim, 'Padding', 'same')
    reluLayer('Name','relu3')

    convolution2dLayer(kernel_dim, 256, 'Name', 'conv5', 'BiasLearnRateFactor',
        2, 'Stride', stride_conv_dim, 'Padding', 'same')
    reluLayer('Name','relu5')
    maxPooling2dLayer(maxpool_dim, 'Name', 'pool5', 'Stride', stride_maxpool_dim
        )

    fullyConnectedLayer(512, 'Name', 'fc6', 'BiasLearnRateFactor', 2)
    reluLayer('Name', 'relu6')
    dropoutLayer(0.5,'Name','drop6')

    fullyConnectedLayer(256, 'Name', 'fc7', 'BiasLearnRateFactor', 2)
    reluLayer('Name','relu7')
    dropoutLayer(0.5,'Name','drop7')

    fullyConnectedLayer(10, 'Name', 'softmax', 'BiasLearnRateFactor', 2)
    softmaxLayer('Name','prob')
```

```
    classificationLayer('Name','output')
    ];

clear image_dim kernel_dim maxpool_dim stride_conv_dim stride_maxpool_dim

disp(layers_3);
```

```
21x1 Layer array with layers:

     1   'data'      Image Input             32x32x3 images with 'zerocenter' normalization
     2   'conv1'     Convolution             48 3x3 convolutions with stride [1  1] and padding 'same'
     3   'relu1'     ReLU                    ReLU
     4   'pool1'     Max Pooling             2x2 max pooling with stride [2  2] and padding [0  0  0  0]
     5   'conv2'     Convolution             96 3x3 convolutions with stride [1  1] and padding 'same'
     6   'relu2'     ReLU                    ReLU
     7   'pool2'     Max Pooling             2x2 max pooling with stride [2  2] and padding [0  0  0  0]
     8   'conv3'     Convolution             192 3x3 convolutions with stride [1  1] and padding 'same'
     9   'relu3'     ReLU                    ReLU
    10   'conv5'     Convolution             256 3x3 convolutions with stride [1  1] and padding 'same'
    11   'relu5'     ReLU                    ReLU
    12   'pool5'     Max Pooling             2x2 max pooling with stride [2  2] and padding [0  0  0  0]
    13   'fc6'       Fully Connected         512 fully connected layer
    14   'relu6'     ReLU                    ReLU
    15   'drop6'     Dropout                 50% dropout
    16   'fc7'       Fully Connected         256 fully connected layer
    17   'relu7'     ReLU                    ReLU
    18   'drop7'     Dropout                 50% dropout
    19   'softmax'   Fully Connected         10 fully connected layer
    20   'prob'      Softmax                 softmax
    21   'output'    Classification Output   crossentropyex
```

```
%analyzeNetwork(layers_3);
plot(layerGraph(layers_3));
```



3.2 Learning Curves and Training Process

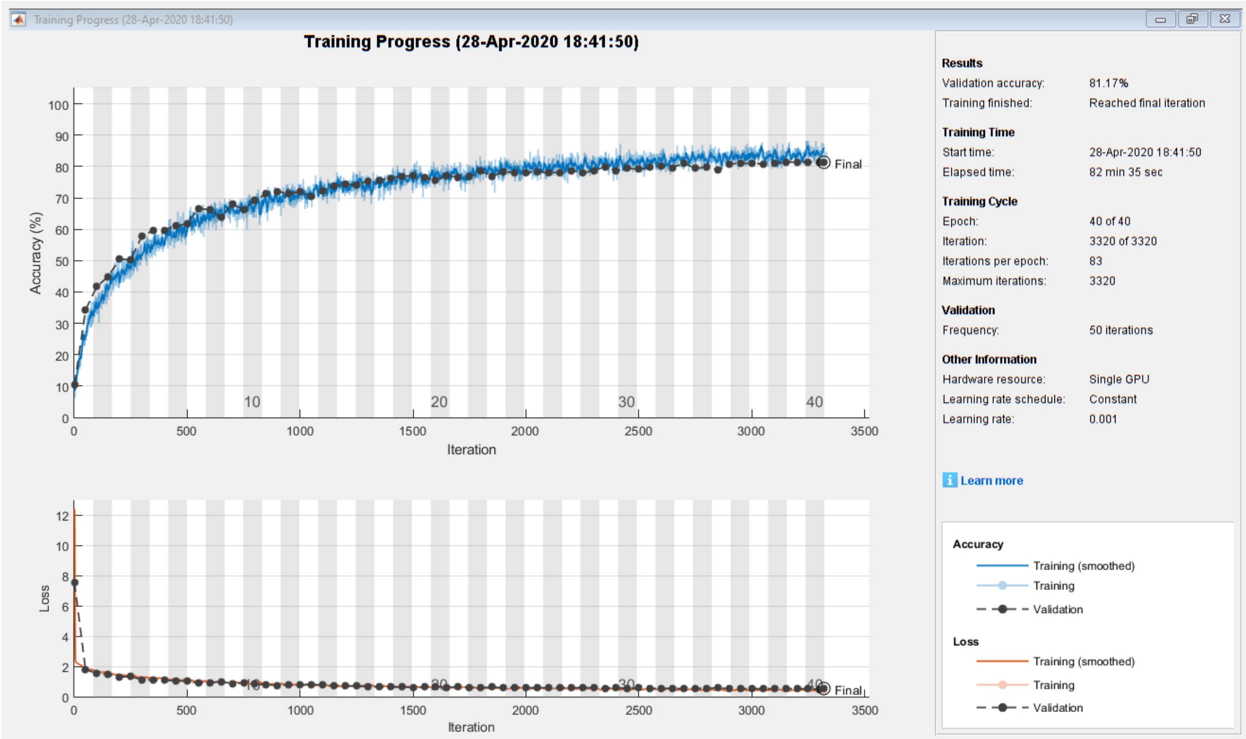
We trained the network on single GPU system nad print the results in a table every 50 iterations. Besides, the learning curves are plotted after the table. Finally the network reached 83.59% on training and 81.17%

on validation subset. The training process took about 90 minutes long.

```
trained_net_3 = trainNetwork(augimdsTrain, layers_3, opts);
```

```
Training on single GPU.
Initializing input data normalization.
|========================================================================================================================|
| Epoch | Iteration | Time Elapsed | Mini-batch | Validation | Mini-batch | Validation | Base
   Learning |
|       |           | (hh:mm:ss)   | Accuracy   | Accuracy   | Loss       | Loss       | Rate
     |
|========================================================================================================================|
|     1 |         1 |     00:00:09 |      8.40% |     10.51% |    12.4558 |     7.5910 |
   0.0010 |
|     1 |        50 |     00:01:22 |     25.98% |     34.25% |     1.9766 |     1.8403 |
   0.0010 |
|     2 |       100 |     00:02:36 |     33.20% |     41.79% |     1.7935 |     1.6030 |
   0.0010 |
|     2 |       150 |     00:03:50 |     37.50% |     44.89% |     1.7270 |     1.5264 |
   0.0010 |
|     3 |       200 |     00:05:04 |     44.34% |     50.48% |     1.5197 |     1.3583 |
   0.0010 |
|     4 |       250 |     00:06:18 |     49.61% |     50.32% |     1.4239 |     1.3820 |
   0.0010 |
|     4 |       300 |     00:07:32 |     50.00% |     57.88% |     1.3442 |     1.1852 |
   0.0010 |
|     5 |       350 |     00:08:46 |     56.45% |     59.64% |     1.2219 |     1.1483 |
   0.0010 |
|     5 |       400 |     00:10:02 |     57.03% |     59.75% |     1.2362 |     1.1274 |
   0.0010 |
|     6 |       450 |     00:11:17 |     56.64% |     61.13% |     1.2024 |     1.1178 |
   0.0010 |
|     7 |       500 |     00:12:31 |     61.91% |     61.68% |     1.1280 |     1.0773 |
   0.0010 |
|     7 |       550 |     00:13:46 |     64.06% |     66.67% |     1.0673 |     0.9591 |
   0.0010 |
|     8 |       600 |     00:15:00 |     65.04% |     66.17% |     1.0417 |     0.9873 |
   0.0010 |
|     8 |       650 |     00:16:15 |     65.63% |     63.72% |     1.0807 |     1.0454 |
   0.0010 |
|     9 |       700 |     00:17:30 |     67.19% |     68.00% |     0.9540 |     0.9266 |
   0.0010 |
|    10 |       750 |     00:18:44 |     67.19% |     66.24% |     0.9907 |     0.9674 |
   0.0010 |
|    10 |       800 |     00:19:59 |     67.19% |     69.32% |     0.9006 |     0.8895 |
   0.0010 |
|    11 |       850 |     00:21:13 |     68.55% |     71.21% |     1.0141 |     0.8429 |
   0.0010 |
|    11 |       900 |     00:22:28 |     67.19% |     72.00% |     0.9094 |     0.8113 |
   0.0010 |
|    12 |       950 |     00:23:42 |     72.07% |     71.45% |     0.7779 |     0.8314 |
   0.0010 |
|    13 |      1000 |     00:24:56 |     69.53% |     71.87% |     0.8481 |     0.8128 |
   0.0010 |
|    13 |      1050 |     00:26:11 |     71.29% |     70.47% |     0.7981 |     0.8714 |
   0.0010 |
|    14 |      1100 |     00:27:25 |     74.02% |     72.20% |     0.7570 |     0.8164 |
   0.0010 |
|    14 |      1150 |     00:28:40 |     73.24% |     73.76% |     0.7977 |     0.7711 |
   0.0010 |
|    15 |      1200 |     00:29:54 |     73.63% |     74.25% |     0.7361 |     0.7520 |
   0.0010 |
|    16 |      1250 |     00:31:08 |     77.73% |     74.15% |     0.6777 |     0.7562 |
   0.0010 |
|    16 |      1300 |     00:32:22 |     72.66% |     75.37% |     0.8078 |     0.7201 |
   0.0010 |
|    17 |      1350 |     00:33:36 |     75.59% |     75.68% |     0.7724 |     0.7068 |
   0.0010 |
|    17 |      1400 |     00:34:50 |     75.98% |     76.27% |     0.7133 |     0.7029 |
   0.0010 |
|    18 |      1450 |     00:36:04 |     75.20% |     76.87% |     0.7074 |     0.6885 |
   0.0010 |
|    19 |      1500 |     00:37:18 |     71.48% |     77.04% |     0.7779 |     0.6740 |
   0.0010 |
|    19 |      1550 |     00:38:32 |     75.98% |     76.57% |     0.6821 |     0.6965 |
   0.0010 |
|    20 |      1600 |     00:39:46 |     78.71% |     75.57% |     0.6723 |     0.7495 |
   0.0010 |
|    20 |      1650 |     00:41:00 |     76.17% |     77.03% |     0.6501 |     0.6822 |
   0.0010 |
|    21 |      1700 |     00:42:14 |     77.73% |     76.61% |     0.6755 |     0.6961 |
```

							0.0010
22	1750	00:43:29	80.47%	76.69%	0.5903	0.6787	0.0010
22	1800	00:44:43	78.71%	78.53%	0.6083	0.6350	0.0010
23	1850	00:45:57	76.76%	76.88%	0.7153	0.6905	0.0010
23	1900	00:47:11	76.56%	78.25%	0.6748	0.6467	0.0010
24	1950	00:48:25	81.84%	78.13%	0.5674	0.6835	0.0010
25	2000	00:49:39	78.71%	78.07%	0.5549	0.6560	0.0010
25	2050	00:50:53	80.86%	78.41%	0.5516	0.6459	0.0010
26	2100	00:52:08	79.69%	77.97%	0.6324	0.6510	0.0010
26	2150	00:53:22	78.32%	78.12%	0.6190	0.6611	0.0010
27	2200	00:54:36	81.64%	78.71%	0.5365	0.6301	0.0010
28	2250	00:55:51	77.73%	77.92%	0.6132	0.6678	0.0010
28	2300	00:57:05	80.66%	78.64%	0.5374	0.6289	0.0010
29	2350	00:58:19	81.05%	79.95%	0.6034	0.6107	0.0010
29	2400	00:59:34	85.74%	78.45%	0.4658	0.6574	0.0010
30	2450	01:00:48	80.66%	79.41%	0.5758	0.6080	0.0010
31	2500	01:02:03	82.81%	79.09%	0.5239	0.6284	0.0010
31	2550	01:03:17	82.42%	79.73%	0.5658	0.6017	0.0010
32	2600	01:04:31	81.05%	80.19%	0.5426	0.6025	0.0010
32	2650	01:05:46	82.03%	79.59%	0.5275	0.6171	0.0010
33	2700	01:07:00	82.81%	81.12%	0.5312	0.5785	0.0010
34	2750	01:08:15	80.47%	79.36%	0.5784	0.6150	0.0010
34	2800	01:09:29	79.69%	79.77%	0.5607	0.6057	0.0010
35	2850	01:10:43	82.42%	78.88%	0.4991	0.6532	0.0010
35	2900	01:11:58	81.45%	80.77%	0.5652	0.5843	0.0010
36	2950	01:13:12	82.03%	81.05%	0.5043	0.5763	0.0010
37	3000	01:14:26	85.16%	80.87%	0.4620	0.5881	0.0010
37	3050	01:15:40	81.84%	80.83%	0.5218	0.5819	0.0010
38	3100	01:16:56	85.35%	80.88%	0.4086	0.5834	0.0010
38	3150	01:18:10	83.79%	81.27%	0.4887	0.5780	0.0010
39	3200	01:19:25	81.25%	81.44%	0.5146	0.6004	0.0010
40	3250	01:20:40	82.03%	81.45%	0.4769	0.5755	0.0010
40	3300	01:21:54	84.38%	81.43%	0.4589	0.5587	0.0010
40	3320	01:22:28	83.59%	81.17%	0.4991	0.5806	0.0010



3.3 Evaluating the Network

Here we use the test partition of the dataset to evaluate the trained network.

3.3.1 Classifying the Test Dataset

The line below will classify all images in the test dataset.

```
predicted_labels_3 = classify(trained_net_3, imds_test);
```

3.3.2 Classification Performance

As the final step of this section, we plot the confusion matrix. The final performance of the network is 80.8% over the whole test dataset.

```
plotconfusion(imds_test.Labels, predicted_labels_3);
```

Confusion Matrix

Output Class \ Target Class	airplane	automobile	bird	cat	deer	dog	frog	horse	ship	truck	
airplane	**863** 8.6%	**4** 0.0%	**78** 0.8%	**39** 0.4%	**25** 0.3%	**16** 0.2%	**12** 0.1%	**23** 0.2%	**51** 0.5%	**14** 0.1%	76.7% 23.3%
automobile	**18** 0.2%	**926** 9.3%	**5** 0.1%	**11** 0.1%	**2** 0.0%	**7** 0.1%	**5** 0.1%	**8** 0.1%	**35** 0.4%	**77** 0.8%	84.6% 15.4%
bird	**17** 0.2%	**1** 0.0%	**680** 6.8%	**50** 0.5%	**28** 0.3%	**26** 0.3%	**13** 0.1%	**10** 0.1%	**4** 0.0%	**3** 0.0%	81.7% 18.3%
cat	**7** 0.1%	**1** 0.0%	**26** 0.3%	**549** 5.5%	**22** 0.2%	**101** 1.0%	**23** 0.2%	**20** 0.2%	**4** 0.0%	**2** 0.0%	72.7% 27.3%
deer	**7** 0.1%	**1** 0.0%	**57** 0.6%	**55** 0.5%	**774** 7.7%	**31** 0.3%	**10** 0.1%	**29** 0.3%	**2** 0.0%	**1** 0.0%	80.0% 20.0%
dog	**3** 0.0%	**2** 0.0%	**38** 0.4%	**120** 1.2%	**17** 0.2%	**739** 7.4%	**6** 0.1%	**21** 0.2%	**1** 0.0%	**1** 0.0%	78.0% 22.0%
frog	**6** 0.1%	**3** 0.0%	**69** 0.7%	**86** 0.9%	**78** 0.8%	**28** 0.3%	**923** 9.2%	**9** 0.1%	**3** 0.0%	**5** 0.1%	76.3% 23.7%
horse	**4** 0.0%	**0** 0.0%	**26** 0.3%	**33** 0.3%	**43** 0.4%	**34** 0.3%	**3** 0.0%	**867** 8.7%	**1** 0.0%	**6** 0.1%	85.3% 14.7%
ship	**42** 0.4%	**6** 0.1%	**10** 0.1%	**31** 0.3%	**6** 0.1%	**9** 0.1%	**3** 0.0%	**3** 0.0%	**880** 8.8%	**10** 0.1%	88.0% 12.0%
truck	**33** 0.3%	**56** 0.6%	**11** 0.1%	**26** 0.3%	**5** 0.1%	**9** 0.1%	**2** 0.0%	**10** 0.1%	**19** 0.2%	**881** 8.8%	83.7% 16.3%
	86.3% 13.7%	92.6% 7.4%	68.0% 32.0%	54.9% 45.1%	77.4% 22.6%	73.9% 26.1%	92.3% 7.7%	86.7% 13.3%	88.0% 12.0%	88.1% 11.9%	**80.8%** **19.2%**

4. Deleting Fully-Connected Layer 6

4.1 Defining Network Architecture

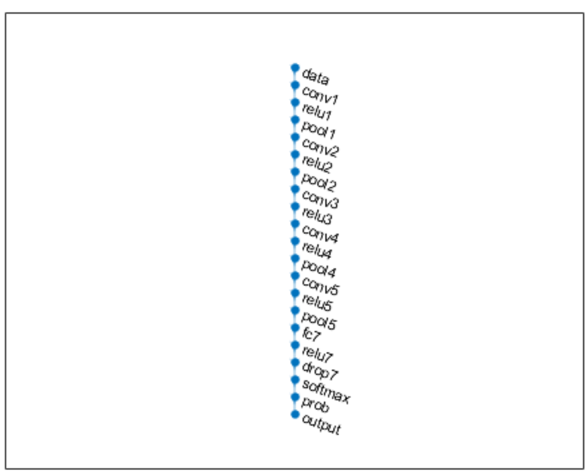
We define the layers of the network again as below. Fully-Connected layer 6 is deleted in comparison with question 1.

```
image_dim = [32 32 3];
kernel_dim = [3 3];
maxpool_dim = [2 2];
stride_conv_dim = [1 1];
stride_maxpool_dim = [2 2];

layers_4 = [
    imageInputLayer(image_dim, 'Name', 'data')

    convolution2dLayer(kernel_dim, 48, 'Name', 'conv1', 'BiasLearnRateFactor',
        2, 'Stride', stride_conv_dim, 'Padding', 'same')
    reluLayer('Name','relu1')
    maxPooling2dLayer(maxpool_dim, 'Name', 'pool1', 'Stride', stride_maxpool_dim
        )

    convolution2dLayer(kernel_dim, 96, 'Name', 'conv2', 'BiasLearnRateFactor',
        2, 'Stride', stride_conv_dim, 'Padding', 'same')
    reluLayer('Name','relu2')
    maxPooling2dLayer(maxpool_dim, 'Name', 'pool2', 'Stride', stride_maxpool_dim
        )

    convolution2dLayer(kernel_dim, 192, 'Name', 'conv3', 'BiasLearnRateFactor',
        2, 'Stride', stride_conv_dim, 'Padding', 'same')
    reluLayer('Name','relu3')

    convolution2dLayer(kernel_dim, 192, 'Name', 'conv4', 'BiasLearnRateFactor',
        2, 'Stride', stride_conv_dim, 'Padding', 'same')
    reluLayer('Name','relu4')
    maxPooling2dLayer(maxpool_dim, 'Name', 'pool4', 'Stride', stride_maxpool_dim
        )

    convolution2dLayer(kernel_dim, 256, 'Name', 'conv5', 'BiasLearnRateFactor',
        2, 'Stride', stride_conv_dim, 'Padding', 'same')
    reluLayer('Name','relu5')
    maxPooling2dLayer(maxpool_dim, 'Name', 'pool5', 'Stride', stride_maxpool_dim
        )

    fullyConnectedLayer(256, 'Name', 'fc7', 'BiasLearnRateFactor', 2)
    reluLayer('Name','relu7')
    dropoutLayer(0.5,'Name','drop7')

```

```
    fullyConnectedLayer(10, 'Name', 'softmax', 'BiasLearnRateFactor', 2)
    softmaxLayer('Name','prob')

    classificationLayer('Name','output')
    ];

clear image_dim kernel_dim maxpool_dim stride_conv_dim stride_maxpool_dim

disp(layers_4);
```

```
21x1 Layer array with layers:

     1   'data'      Image Input             32x32x3 images with 'zerocenter' normalization
     2   'conv1'     Convolution             48 3x3 convolutions with stride [1  1] and padding 'same'
     3   'relu1'     ReLU                    ReLU
     4   'pool1'     Max Pooling             2x2 max pooling with stride [2  2] and padding [0  0  0  0]
     5   'conv2'     Convolution             96 3x3 convolutions with stride [1  1] and padding 'same'
     6   'relu2'     ReLU                    ReLU
     7   'pool2'     Max Pooling             2x2 max pooling with stride [2  2] and padding [0  0  0  0]
     8   'conv3'     Convolution             192 3x3 convolutions with stride [1  1] and padding 'same'
     9   'relu3'     ReLU                    ReLU
    10   'conv4'     Convolution             192 3x3 convolutions with stride [1  1] and padding 'same'
    11   'relu4'     ReLU                    ReLU
    12   'pool4'     Max Pooling             2x2 max pooling with stride [2  2] and padding [0  0  0  0]
    13   'conv5'     Convolution             256 3x3 convolutions with stride [1  1] and padding 'same'
    14   'relu5'     ReLU                    ReLU
    15   'pool5'     Max Pooling             2x2 max pooling with stride [2  2] and padding [0  0  0  0]
    16   'fc7'       Fully Connected         256 fully connected layer
    17   'relu7'     ReLU                    ReLU
    18   'drop7'     Dropout                 50% dropout
    19   'softmax'   Fully Connected         10 fully connected layer
    20   'prob'      Softmax                 softmax
    21   'output'    Classification Output   crossentropyex
```

```
%analyzeNetwork(layers_4);
plot(layerGraph(layers_4));
```



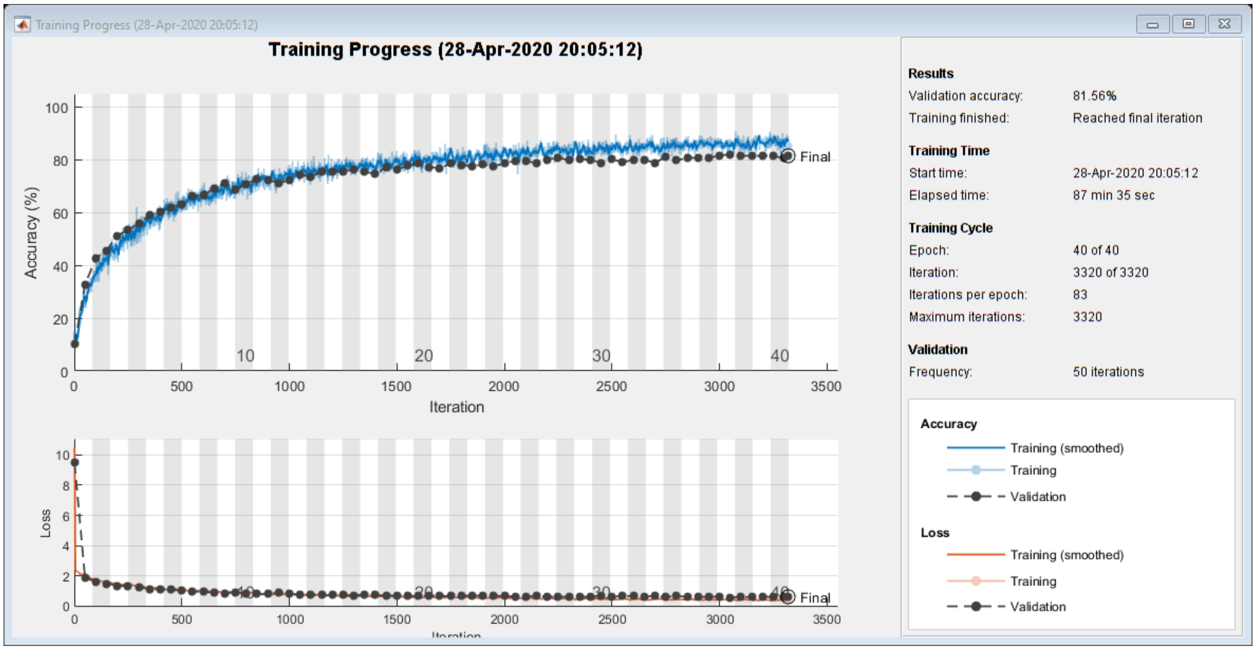
4.2 Learning Curves and Training Process

We trained the network on single GPU system nad print the results in a table every 50 iterations. Besides, the learning curves are plotted after the table. Finally the network reached 85.16% on training and 81.56% on validation subset. The training process took about 88 minutes long.

```
trained_net_4 = trainNetwork(augimdsTrain, layers_4, opts);
```

```
Training on single GPU.
Initializing input data normalization.
|======================================================================================================================|
|  Epoch  |  Iteration  |  Time Elapsed  |  Mini-batch  |  Validation  |  Mini-batch  |  Validation  |  Base
    Learning  |
|         |             |   (hh:mm:ss)   |   Accuracy   |   Accuracy   |     Loss     |     Loss     |        Rate
         |
|======================================================================================================================|
|       1 |           1 |       00:00:09 |       11.72% |       10.12% |      10.5038 |       9.4881 |
    0.0010 |
|       1 |          50 |       00:01:26 |       23.83% |       32.83% |       2.1314 |       1.8730 |
    0.0010 |
|       2 |         100 |       00:02:44 |       38.28% |       42.65% |       1.7415 |       1.5924 |
    0.0010 |
|       2 |         150 |       00:04:03 |       43.16% |       45.68% |       1.6198 |       1.4808 |
    0.0010 |
|       3 |         200 |       00:05:23 |       43.95% |       51.21% |       1.5060 |       1.3415 |
    0.0010 |
|       4 |         250 |       00:06:44 |       50.39% |       53.56% |       1.3679 |       1.3049 |
    0.0010 |
|       4 |         300 |       00:08:03 |       53.32% |       55.84% |       1.3522 |       1.2311 |
    0.0010 |
|       5 |         350 |       00:09:23 |       56.64% |       59.04% |       1.2368 |       1.1214 |
    0.0010 |
|       5 |         400 |       00:10:42 |       55.86% |       60.37% |       1.2420 |       1.0968 |
    0.0010 |
|       6 |         450 |       00:12:02 |       64.65% |       62.09% |       1.0527 |       1.0670 |
    0.0010 |
|       7 |         500 |       00:13:21 |       65.63% |       63.21% |       1.0031 |       1.0294 |
    0.0010 |
|       7 |         550 |       00:14:40 |       64.45% |       66.41% |       1.0214 |       0.9567 |
    0.0010 |
|       8 |         600 |       00:15:59 |       66.80% |       66.57% |       0.9318 |       0.9426 |
    0.0010 |
|       8 |         650 |       00:17:17 |       66.41% |       69.12% |       0.9867 |       0.8769 |
    0.0010 |
|       9 |         700 |       00:18:36 |       71.29% |       71.09% |       0.8586 |       0.8371 |
    0.0010 |
|      10 |         750 |       00:19:55 |       70.12% |       68.80% |       0.8572 |       0.8933 |
    0.0010 |
|      10 |         800 |       00:21:13 |       69.53% |       70.80% |       0.8742 |       0.8329 |
    0.0010 |
|      11 |         850 |       00:22:32 |       70.90% |       72.91% |       0.8471 |       0.7851 |
    0.0010 |
|      11 |         900 |       00:23:50 |       74.22% |       72.27% |       0.7121 |       0.7916 |
    0.0010 |
|      12 |         950 |       00:25:09 |       73.24% |       71.33% |       0.7878 |       0.8584 |
    0.0010 |
|      13 |        1000 |       00:26:27 |       77.93% |       72.17% |       0.6161 |       0.8177 |
    0.0010 |
|      13 |        1050 |       00:27:46 |       75.00% |       74.36% |       0.7175 |       0.7403 |
    0.0010 |
|      14 |        1100 |       00:29:04 |       76.17% |       73.64% |       0.7260 |       0.7520 |
    0.0010 |
|      14 |        1150 |       00:30:22 |       76.76% |       75.37% |       0.6979 |       0.7155 |
    0.0010 |
|      15 |        1200 |       00:31:40 |       76.17% |       75.59% |       0.6442 |       0.7154 |
    0.0010 |
|      16 |        1250 |       00:32:59 |       76.95% |       75.53% |       0.6579 |       0.7148 |
    0.0010 |
|      16 |        1300 |       00:34:17 |       75.78% |       76.36% |       0.7088 |       0.7086 |
    0.0010 |
|      17 |        1350 |       00:35:35 |       79.49% |       75.55% |       0.6131 |       0.7544 |
    0.0010 |
|      17 |        1400 |       00:36:53 |       75.78% |       74.63% |       0.6773 |       0.7344 |
    0.0010 |
|      18 |        1450 |       00:38:11 |       80.08% |       77.29% |       0.6093 |       0.6770 |
    0.0010 |
|      19 |        1500 |       00:39:29 |       80.66% |       76.27% |       0.5871 |       0.6974 |
    0.0010 |
```

19	1550	00:40:47	77.15%	77.79%	0.6782	0.6573	0.0010
20	1600	00:42:05	79.10%	78.64%	0.6255	0.6601	0.0010
20	1650	00:43:23	81.25%	77.33%	0.6001	0.6815	0.0010
21	1700	00:44:42	77.93%	76.87%	0.6048	0.6655	0.0010
22	1750	00:46:00	82.81%	78.67%	0.4991	0.6453	0.0010
22	1800	00:47:25	77.73%	78.15%	0.6271	0.6564	0.0010
23	1850	00:48:44	76.76%	77.64%	0.6390	0.6833	0.0010
23	1900	00:50:03	82.42%	78.17%	0.5483	0.6655	0.0010
24	1950	00:51:23	79.88%	77.65%	0.5369	0.6748	0.0010
25	2000	00:52:43	82.42%	78.63%	0.5254	0.6525	0.0010
25	2050	00:54:03	83.98%	79.60%	0.4554	0.6171	0.0010
26	2100	00:55:22	83.59%	79.52%	0.4978	0.6169	0.0010
26	2150	00:56:41	83.20%	78.80%	0.4724	0.6680	0.0010
27	2200	00:57:59	82.81%	80.08%	0.5037	0.6214	0.0010
28	2250	00:59:18	86.52%	80.93%	0.3928	0.6083	0.0010
28	2300	01:00:37	86.13%	79.84%	0.4347	0.5991	0.0010
29	2350	01:01:56	79.88%	80.29%	0.5154	0.6146	0.0010
29	2400	01:03:14	83.20%	80.00%	0.5069	0.6028	0.0010
30	2450	01:04:34	85.16%	78.81%	0.4108	0.6991	0.0010
31	2500	01:05:53	83.01%	80.20%	0.4772	0.5975	0.0010
31	2550	01:07:12	81.05%	79.15%	0.5888	0.6645	0.0010
32	2600	01:08:31	84.57%	79.93%	0.4370	0.6453	0.0010
32	2650	01:09:49	85.94%	80.13%	0.4144	0.6194	0.0010
33	2700	01:11:08	85.55%	78.76%	0.4232	0.6549	0.0010
34	2750	01:12:26	83.79%	81.27%	0.4577	0.5956	0.0010
34	2800	01:13:45	84.57%	79.92%	0.4605	0.6482	0.0010
35	2850	01:15:04	85.16%	80.64%	0.4686	0.6112	0.0010
35	2900	01:16:23	85.35%	80.91%	0.4015	0.5787	0.0010
36	2950	01:17:42	84.77%	80.65%	0.4368	0.6163	0.0010
37	3000	01:19:01	86.52%	81.67%	0.3710	0.6021	0.0010
37	3050	01:20:19	84.38%	82.09%	0.4289	0.5681	0.0010
38	3100	01:21:38	87.11%	81.64%	0.3445	0.5873	0.0010
38	3150	01:22:57	85.55%	81.47%	0.4172	0.5899	0.0010
39	3200	01:24:15	86.13%	81.55%	0.4324	0.5927	0.0010
40	3250	01:25:35	86.13%	81.41%	0.4079	0.6028	0.0010
40	3300	01:26:53	84.96%	80.73%	0.4284	0.6104	0.0010
40	3320	01:27:29	85.16%	81.56%	0.4182	0.6244	0.0010



4.3 Evaluating the Network

Here we use the test partition of the dataset to evaluate the trained network.

4.3.1 Classifying the Test Dataset

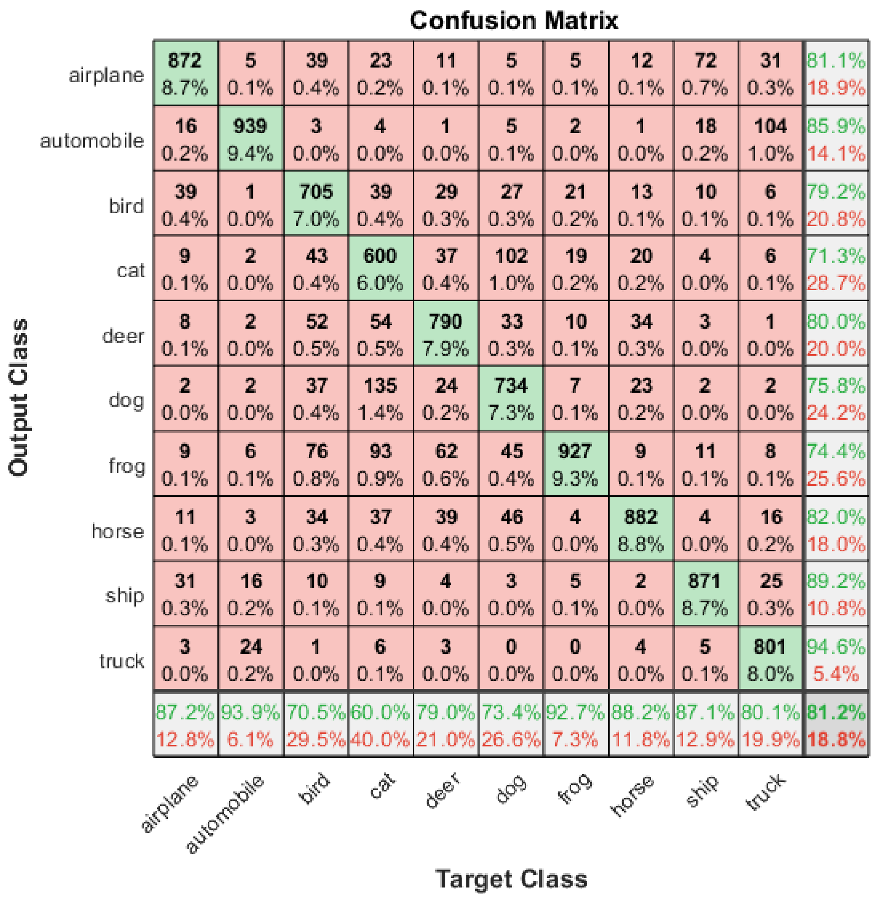
The line below will classify all images in the test dataset.

```
predicted_labels_4 = classify(trained_net_4, imds_test);
```

4.3.2 Classification Performance

As the final step of this section, we plot the confusion matrix. The final performance of the network is 81.2% over the whole test dataset.

```
plotconfusion(imds_test.Labels, predicted_labels_4);
```


Confusion Matrix
airplane 872 8.7% 5 0.1% 39 0.4% 23 0.2% 11 0.1% 5 0.1% 5 0.1% 12 0.1% 72 0.7% 31 0.3% 81.1% 18.9%
automobile 16 0.2% 939 9.4% 3 0.0% 4 0.0% 1 0.0% 5 0.1% 2 0.0% 1 0.0% 18 0.2% 104 1.0% 85.9% 14.1%
bird 39 0.4% 1 0.0% 705 7.0% 39 0.4% 29 0.3% 27 0.3% 21 0.2% 13 0.1% 10 0.1% 6 0.1% 79.2% 20.8%
cat 9 0.1% 2 0.0% 43 0.4% 600 6.0% 37 0.4% 102 1.0% 19 0.2% 20 0.2% 4 0.0% 6 0.1% 71.3% 28.7%
deer 8 0.1% 2 0.0% 52 0.5% 54 0.5% 790 7.9% 33 0.3% 10 0.1% 34 0.3% 3 0.0% 1 0.0% 80.0% 20.0%
dog 2 0.0% 2 0.0% 37 0.4% 135 1.4% 24 0.2% 734 7.3% 7 0.1% 23 0.2% 2 0.0% 2 0.0% 75.8% 24.2%
frog 9 0.1% 6 0.1% 76 0.8% 93 0.9% 62 0.6% 45 0.4% 927 9.3% 9 0.1% 11 0.1% 8 0.1% 74.4% 25.6%
horse 11 0.1% 3 0.0% 34 0.3% 37 0.4% 39 0.4% 46 0.5% 4 0.0% 882 8.8% 4 0.0% 16 0.2% 82.0% 18.0%
ship 31 0.3% 16 0.2% 10 0.1% 9 0.1% 4 0.0% 3 0.0% 5 0.1% 2 0.0% 871 8.7% 25 0.3% 89.2% 10.8%
truck 3 0.0% 24 0.2% 1 0.0% 6 0.1% 3 0.0% 0 0.0% 0 0.0% 4 0.0% 5 0.1% 801 8.0% 94.6% 5.4%
87.2% 12.8% 93.9% 6.1% 70.5% 29.5% 60.0% 40.0% 79.0% 21.0% 73.4% 26.6% 92.7% 7.3% 88.2% 11.8% 87.1% 12.9% 80.1% 19.9% 81.2% 18.8%
Output Class
airplane automobile bird cat deer dog frog horse ship truck
Target Class

Appendix

A.1 Saving Workspace Variables for Future Use

```
save('HW8_code_workspace.mat')
```

A.2 Definition of Auxiliary Functions

```
function saveCIFAR10AsFolderOfImages(inputPath, outputPath, varargin)

% Check input directories are valid
if(~isempty(inputPath))
    assert(exist(inputPath,'dir') == 7);
end
if(~isempty(outputPath))
    assert(exist(outputPath,'dir') == 7);
end

% Check if we want to save each set with the same labels to its own
% directory.
if(isempty(varargin))
    labelDirectories = false;
else
    assert(nargin == 3);
    labelDirectories = varargin{1};
end

% Set names for directories
trainDirectoryName = 'cifar10Train';
testDirectoryName = 'cifar10Test';
% Create directories for the output
mkdir(fullfile(outputPath, trainDirectoryName));
mkdir(fullfile(outputPath, testDirectoryName));

if(labelDirectories)
    labelNames = {'airplane','automobile','bird','cat','deer','dog','frog','horse','ship','truck'};
    iMakeTheseDirectories(fullfile(outputPath, trainDirectoryName), labelNames);
    iMakeTheseDirectories(fullfile(outputPath, testDirectoryName), labelNames);
    for i = 1:5
        iLoadBatchAndWriteAsImagesToLabelFolders(fullfile(inputPath,['data_batch_' num2str(i) '.mat']), fullfile(outputPath, trainDirectoryName), labelNames, (i-1)*10000);
    end
    iLoadBatchAndWriteAsImagesToLabelFolders(fullfile(inputPath,'test_batch.mat'
```

```
        ), fullfile(outputPath, testDirectoryName), labelNames, 0);
else
    for i = 1:5
        iLoadBatchAndWriteAsImages(fullfile(inputPath,['data_batch_' num2str(i) '.mat']), fullfile(outputPath, trainDirectoryName), (i-1)*10000);
    end
    iLoadBatchAndWriteAsImages(fullfile(inputPath,'test_batch.mat'), fullfile(outputPath, testDirectoryName), 0);
end
end

function iLoadBatchAndWriteAsImagesToLabelFolders(fullInputBatchPath, fullOutputDirectoryPath, labelNames, nameIndexOffset)
load(fullInputBatchPath);
data = data'; %#ok<NODEF>
data = reshape(data, 32,32,3,[]);
data = permute(data, [2 1 3 4]);
for i = 1:size(data,4)
    imwrite(data(:,:,:,i), fullfile(fullOutputDirectoryPath, labelNames{labels(i)+1}, ['image' num2str(i + nameIndexOffset) '.png']));
end
end

function iLoadBatchAndWriteAsImages(fullInputBatchPath, fullOutputDirectoryPath, nameIndexOffset)
load(fullInputBatchPath);
data = data'; %#ok<NODEF>
data = reshape(data, 32,32,3,[]);
data = permute(data, [2 1 3 4]);
for i = 1:size(data,4)
    imwrite(data(:,:,:,i), fullfile(fullOutputDirectoryPath, ['image' num2str(i + nameIndexOffset) '.png']));
end
end

function iMakeTheseDirectories(outputPath, directoryNames)
for i = 1:numel(directoryNames)
    mkdir(fullfile(outputPath, directoryNames{i}));
end
end

function h = subplottight(n,m,i)
[c,r] = ind2sub([m n], i);
ax = subplot('Position', [(c-1)/m, 1-(r)/n, 1/m, 1/n]);
if(nargout > 0)
  h = ax;
end
end
```