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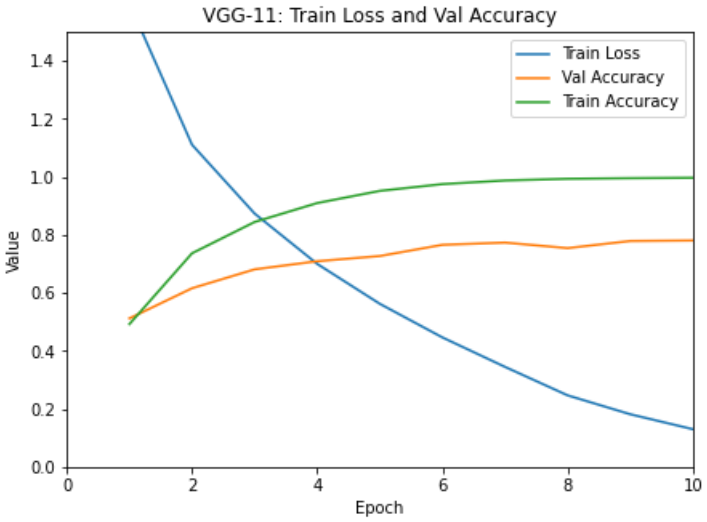
HW3

Github Link: https://github.com/jacintomart/4106/tree/main/HW3

Problem 1:

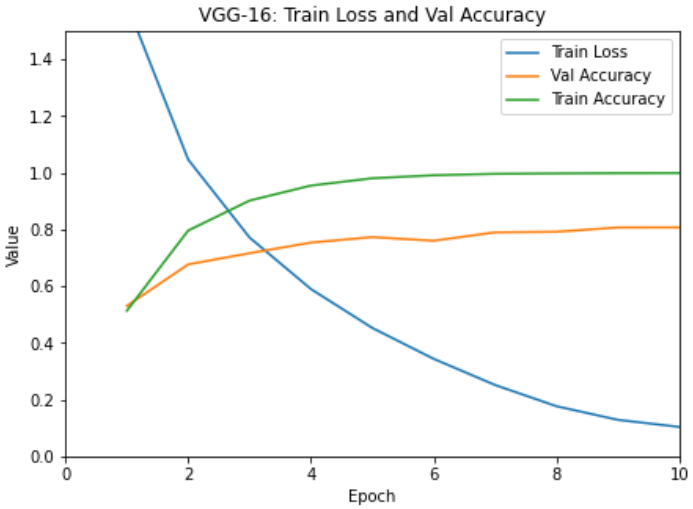
VGG-11:




```
Epoch 7
loss: 0.3252418637275696
loss: 0.3342866897583008
loss: 0.3068305253982544
loss: 0.2835935652256012
Training Accuracy:  98.74000000000001     Training Loss:  0.3446421988327485
Validation Accuracy: 77.32     Validation Loss:  0.7261034318163425

Epoch 8
loss: 0.22867552936077118
loss: 0.2970028519630432
loss: 0.20768484473228455
loss: 0.27622395753860474
Training Accuracy:  99.32     Training Loss:  0.24649672507477538
Validation Accuracy: 75.42     Validation Loss:  0.8427747205088411

Epoch 9
loss: 0.26739972829818726
loss: 0.1905825287103653
loss: 0.2787529528141022
loss: 0.09876351803541183
Training Accuracy:  99.532     Training Loss:  0.18137390120788607
Validation Accuracy: 77.86999999999999     Validation Loss:  0.7751829186572304

Epoch 10
loss: 0.2703735828399658
loss: 0.06612680107355118
loss: 0.10197493433952332
loss: 0.23051315546035767
Training Accuracy:  99.664     Training Loss:  0.129865981533628
Validation Accuracy: 78.05     Validation Loss:  0.8045465218115456
```

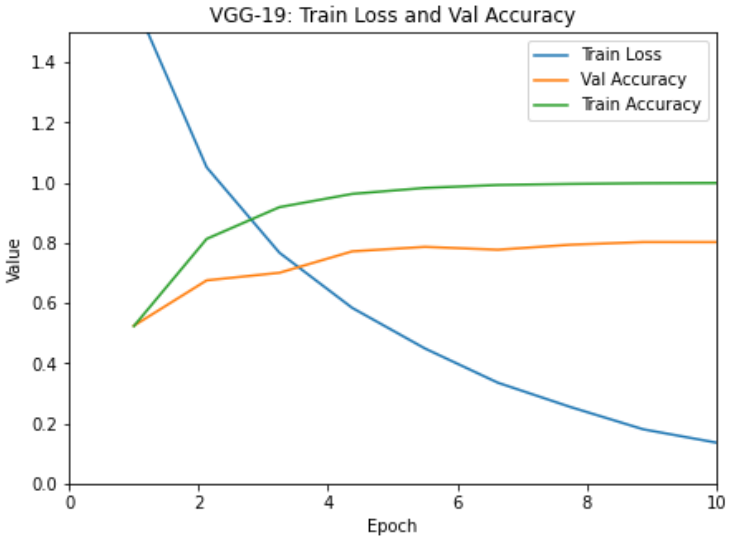
The VGG-11 model was trained on 64x64 images from the CIFAR-10 dataset. The model achieved a training loss of 0.129, training accuracy of 99.66%, and displayed some subtle dips in performance until reaching a final validation accuracy of 78.05%.

VGG-16:




```
Epoch 7
loss: 0.3063439428806305
loss: 0.224542498588562
loss: 0.21085478365421295
loss: 0.30594658851623535
Training Accuracy:  99.61     Training Loss:  0.2512144137678854
Validation Accuracy: 78.97     Validation Loss:  0.689447547816023

Epoch 8
loss: 0.2563817501068115
loss: 0.1132490485906601
loss: 0.23413074016571045
loss: 0.23023918271064758
Training Accuracy:  99.752     Training Loss:  0.17632066239328945
Validation Accuracy: 79.17     Validation Loss:  0.716099568182909

Epoch 9
loss: 0.20530660450458527
loss: 0.1152021586894989
loss: 0.13534468412399292
loss: 0.12362498790025711
Training Accuracy:  99.85000000000001     Training Loss:  0.12841168850126777
Validation Accuracy: 80.69     Validation Loss:  0.720429743392558

Epoch 10
loss: 0.05386313423514366
loss: 0.13676169514656067
loss: 0.06648583710193634
loss: 0.10550615936517715
Training Accuracy:  99.866     Training Loss:  0.10345476229324975
Validation Accuracy: 80.72     Validation Loss:  0.753635081686551
```

VGG-19:




```
Epoch 7
loss: 0.26394909620285034
loss: 0.2867668867111206
loss: 0.32079559564590454
loss: 0.3416512906551361
Training Accuracy:  99.58200000000001     Training Loss:  0.2542842682784476
Validation Accuracy: 79.36999999999999     Validation Loss:  0.6789268756969066

Epoch 8
loss: 0.2204064577817917
loss: 0.19845499098300934
loss: 0.1552555412054062
loss: 0.13485829532146454
Training Accuracy:  99.798     Training Loss:  0.18023010173721996
Validation Accuracy: 80.25999999999999     Validation Loss:  0.6903623685806612

Epoch 9
loss: 0.09689150005578995
loss: 0.11360768973827362
loss: 0.09631191194057465
loss: 0.2283611297607422
Training Accuracy:  99.878     Training Loss:  0.1361897181757652
Validation Accuracy: 80.25     Validation Loss:  0.7412889343273791

Epoch 10
loss: 0.1488541066646576
loss: 0.08853688091039658
```

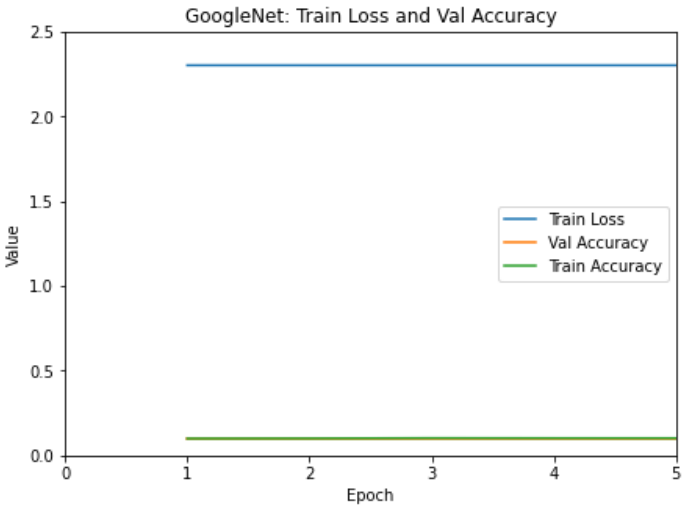
Note: I was unable to train this model for a full 10 epochs due to time constraints but the values at the end of epoch 9 were used for this report. A full training session of 10 epochs will be needed in the future for a fair comparison between the VGG variants.

Model	Parameters	Operations	Accuracy
VGG-11	19.72 M	624.48 M	78.05%
VGG-16	25.22 M	1.27 G	80.72%
VGG-19	30.53 M	1.61 G	80.25%

As seen in the table above, the number of computational complexity/operations quickly grew to a significantly large amount as the VGG variants expanded in depth. The size differences between VGG-11 and VGG-16 were more pronounced than with VGG-19 and also showed a more noticeable increase in validation accuracy of 78.05% and 80.72%, respectively. The performance of VGG-19 demonstrated a diminishing return in performance vs. network depth, seeing a comparable validation accuracy to VGG-16 despite requiring roughly 340M more MACs and 5M more parameters.

Problem 2:

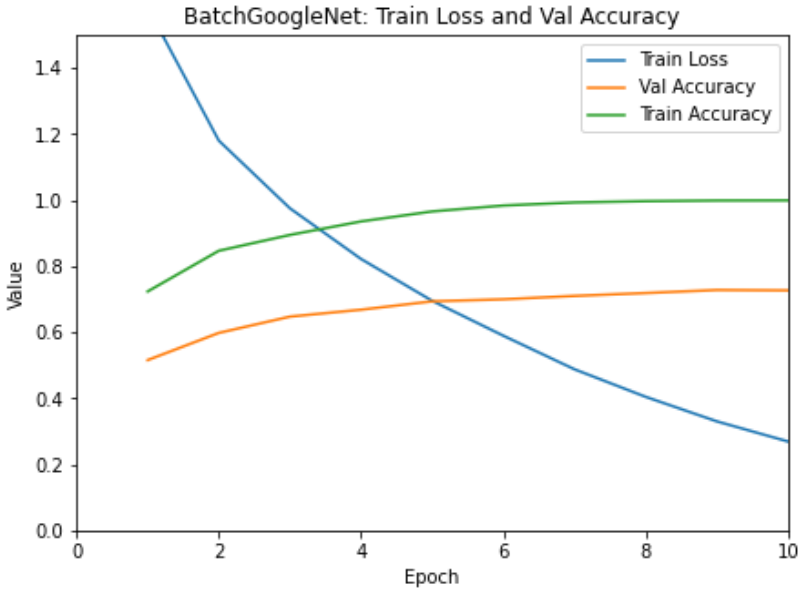
Baseline GoogleNet:




```
Epoch 2
loss: 2.3016629219055176
loss: 2.3033292293548584
loss: 2.302647590637207
loss: 2.302816152572632
Training Accuracy:  10.07     Training Loss:  2.302648488213034
Validation Accuracy: 10.0     Validation Loss:  2.3026042165635507

Epoch 3
loss: 2.302588939666748
loss: 2.3023459911346436
loss: 2.3028881549835205
loss: 2.303091526031494
Training Accuracy:  10.25     Training Loss:  2.3026394051359134
Validation Accuracy: 10.0     Validation Loss:  2.302596753156638

Epoch 4
loss: 2.302618980407715
loss: 2.3027374744415283
loss: 2.3028383255004883
loss: 2.302997350692749
Training Accuracy:  10.209999999999999     Training Loss:  2.302632306847731
Validation Accuracy: 10.0     Validation Loss:  2.3025873974908757

Epoch 5
loss: 2.3026015758514404
loss: 2.3025219440460205
loss: 2.3024256229400635
loss: 2.302746295928955
Training Accuracy:  10.198     Training Loss:  2.3026275384761488
Validation Accuracy: 10.0     Validation Loss:  2.30258980582032
```

The baseline GoogleNet model was unable to properly train, displaying no noticeable improvement in performance during training. The model appeared to simply guess, resulting in a validation accuracy of 10% and a near constant loss of ~2.3. I wasn't able to figure out the cause of this unusual behavior, but the GoogleNet architecture is all correct and present in the model constructed for this problem.

GoogleNet w/ Batch Normalization:

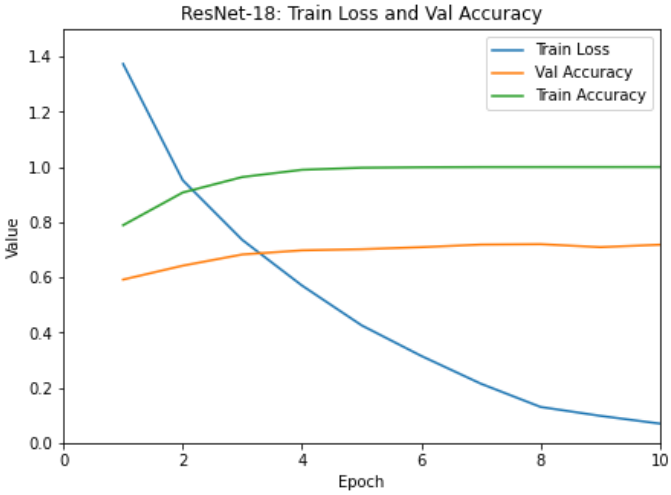



```
Epoch 7
loss: 0.3940551280975342
loss: 0.32410064339637756
loss: 0.5813966393470764
loss: 0.5567288398742676
Training Accuracy:  99.278     Training Loss:  0.48764182044112164
Validation Accuracy: 70.98     Validation Loss:  0.9099403778208962

Epoch 8
loss: 0.4223775863647461
loss: 0.5032692551612854
loss: 0.41108882427215576
loss: 0.44687962532043457
Training Accuracy:  99.664     Training Loss:  0.40428711218602215
Validation Accuracy: 71.85000000000001     Validation Loss:  0.8919230737263644

Epoch 9
loss: 0.30680426955223083
loss: 0.2765175700187683
loss: 0.46522948145866394
loss: 0.3755722641944885
Training Accuracy:  99.856     Training Loss:  0.3300665570875568
Validation Accuracy: 72.77     Validation Loss:  0.9000150500973568

Epoch 10
loss: 0.28192389011383057
loss: 0.2751345932483673
loss: 0.2120654284954071
loss: 0.21147401630878448
Training Accuracy:  99.9     Training Loss:  0.26910821962005954
Validation Accuracy: 72.66     Validation Loss:  0.9544999976701374
```

Unlike the baseline GoogleNet model, the BatchGoogleNet model did train successfully. The model was constructed by integrating batchnorm2d layers after every conv2d layer in the baseline GoogleNet model and reached a training loss of 0.27, training accuracy of 99.9%, and validation accuracy of 72.66%.

Problem 3:

ResNet-18:

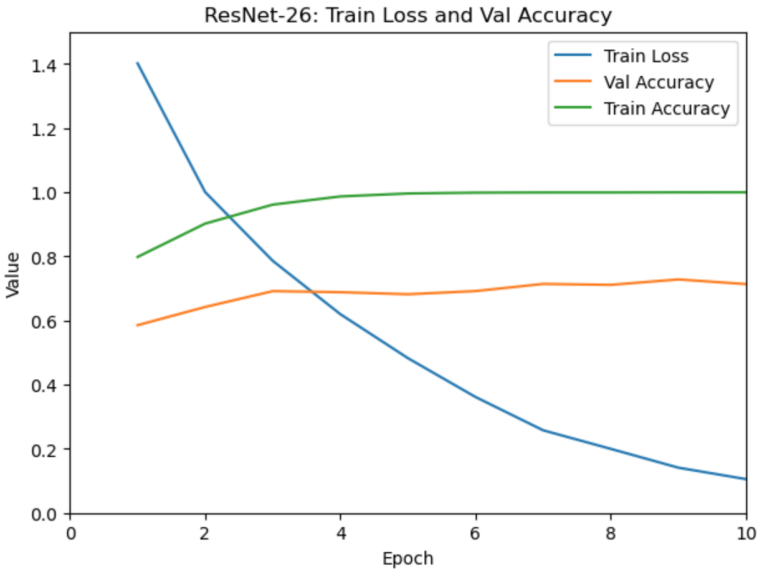



```
Epoch 7
loss: 0.13786502182483673
loss: 0.2778322994709015
loss: 0.20755711197853088
loss: 0.27415210008621216
Training Accuracy:  99.96000000000001     Training Loss:  0.21426948436233392
Validation Accuracy: 71.86     Validation Loss:  1.0094171053246608

Epoch 8
loss: 0.18470793962478638
loss: 0.12318746000528336
loss: 0.19871483743190765
loss: 0.18515336513519287
Training Accuracy:  99.97399999999999     Training Loss:  0.13010384603534514
Validation Accuracy: 72.00999999999999     Validation Loss:  1.0689714105823371

Epoch 9
loss: 0.1592712253332138
loss: 0.05907793343067169
loss: 0.14718875288963318
loss: 0.10887660831212997
Training Accuracy:  99.976     Training Loss:  0.09785724740446833
Validation Accuracy: 70.93     Validation Loss:  1.1867564562000805

Epoch 10
loss: 0.21967542171478271
loss: 0.07099102437496185
loss: 0.08001641184091568
loss: 0.03691113740205765
Training Accuracy:  99.98599999999999     Training Loss:  0.06972898281110293
Validation Accuracy: 71.81     Validation Loss:  1.2231912348843827
```

The baseline ResNet-18 model yielded a validation accuracy of 71.81%, lower than VGG-11's 78.05%, but almost reaching BatchGoogleNet's 72.66%. The training time, size, and computational complexity of each of the three models are compared in the table below:

Model	Training Time	Size (Parameters)	Complexity (MACs)
VGG-11	1hr 43mins	19.72 M	624.48 M
BatchGoogleNet	45mins	6 M	130.28 M
ResNet-18	32mins	11.18 M	148.76 M

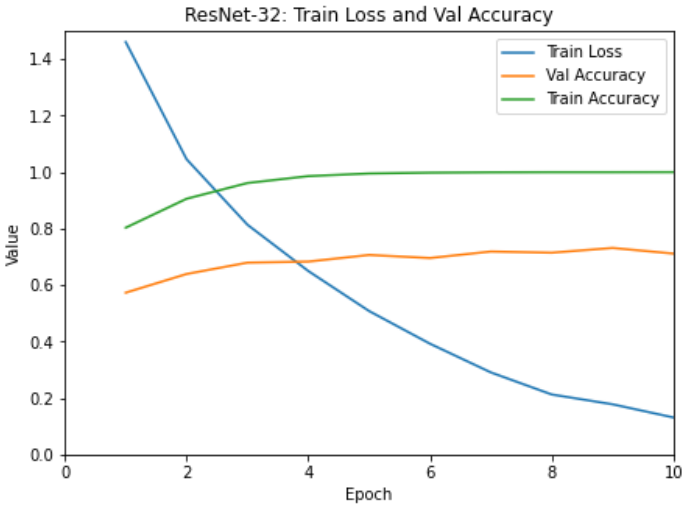
Resnet 26:




```
Epoch 7
loss: 0.4060518145561218
loss: 0.30143043398857117
loss: 0.27606508135795593
loss: 0.3078552484512329
Training Accuracy:  99.926     Training Loss:  0.25766140805638355
Validation Accuracy: 71.41     Validation Loss:  0.9698203915282141

Epoch 8
loss: 0.22760169208049774
loss: 0.13227973878383636
loss: 0.2172379493713379
loss: 0.17700572311878204
Training Accuracy:  99.928     Training Loss:  0.19978978067560269
Validation Accuracy: 71.12     Validation Loss:  1.055658839925935

Epoch 9
loss: 0.15198272466659546
loss: 0.16485220193862915
loss: 0.06377767026424408
loss: 0.19376257061958313
Training Accuracy:  99.964     Training Loss:  0.14111633908451365
Validation Accuracy: 72.81     Validation Loss:  1.06619703618786

Epoch 10
loss: 0.1364363133907318
loss: 0.08847086876630783
loss: 0.0878872498869896
loss: 0.08473409712314606
Training Accuracy:  99.976     Training Loss:  0.1054236834435283
Validation Accuracy: 71.36     Validation Loss:  1.1931136024149158
```

Note: I initially trained ResNet-26 on a Kaggle notebook to test the Kaggle GPU speed but ultimately decided to keep the results instead of re-running the entire training in Colab, which explains the different appearance of the training outputs above. The Kaggle notebook I used for this training is also included in the linked GitHub repository.

ResNet-32:



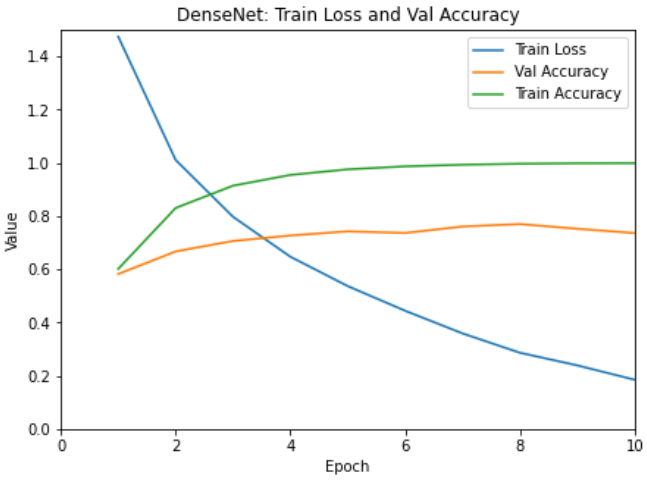

```
Epoch 7
loss: 0.43339353799819946
loss: 0.19347110390663147
loss: 0.2977222204208374
loss: 0.4343850016593933
Training Accuracy:  99.90599999999999     Training Loss:  0.2905266760179149
Validation Accuracy: 71.86     Validation Loss:  0.9686806730077236

Epoch 8
loss: 0.17181630432605743
loss: 0.1988162398338318
loss: 0.17788703739643097
loss: 0.30840954184532166
Training Accuracy:  99.94800000000001     Training Loss:  0.21237409197727738
Validation Accuracy: 71.44     Validation Loss:  1.0706723626655867

Epoch 9
loss: 0.24500755965709686
loss: 0.20261642336845398
loss: 0.1468559056520462
loss: 0.18641404807567596
Training Accuracy:  99.94800000000001     Training Loss:  0.17761448602123028
Validation Accuracy: 73.11999999999999     Validation Loss:  1.0381930334658562

Epoch 10
loss: 0.09995867311954498
loss: 0.12257780879735947
loss: 0.15950791537761688
loss: 0.1627320647239685
Training Accuracy:  99.97200000000001     Training Loss:  0.13097810363182633
Validation Accuracy: 71.13000000000001     Validation Loss:  1.1898945917057087
```

The three ResNet model variants all demonstrated a similar performance during training, with each of the models achieving a validation accuracy of approximately 71%. Although the validation accuracies remained similar across the three models, the model sizes and complexities grew noticeably from ResNet-18 to ResNet-26 to ResNet-32. The table below demonstrates this

steady complexity growth as the baseline model was modified to create the larger ResNet variants.

Model	Complexity (MACs)	Size (Parameters)	Accuracy
ResNet-18	148.76 M	11.18 M	71.81%
ResNet-26	205.49 M	13.84 M	71.36%
ResNet-32	300.07 M	21.3 M	71.13%

Extra Credit:



```
Epoch 7
loss: 0.3975030183792114
loss: 0.3060373067855835
loss: 0.3046684265136719
loss: 0.4185643494129181
Training Accuracy:  99.28200000000001     Training Loss:  0.3589277767464328
Validation Accuracy: 76.06     Validation Loss:  0.7428525852251656

Epoch 8
loss: 0.3421012759208679
loss: 0.24105846881866455
loss: 0.23136299848556519
loss: 0.27629151940345764
Training Accuracy:  99.646     Training Loss:  0.28623457489263676
Validation Accuracy: 76.98     Validation Loss:  0.7413115429727337

Epoch 9
loss: 0.23472537100315094
loss: 0.18735474348068237
loss: 0.2592465877532959
loss: 0.27361223101615906
Training Accuracy:  99.822     Training Loss:  0.2387881857697921
Validation Accuracy: 75.21     Validation Loss:  0.8242324326611772

Epoch 10
loss: 0.17829659581184387
loss: 0.12568531930446625
loss: 0.15204043686389923
loss: 0.25462886691093445
Training Accuracy:  99.864     Training Loss:  0.1846945375261252
Validation Accuracy: 73.6     Validation Loss:  0.9259455939636955
```

The DenseNet model was constructed in order to match the size and computational complexity of ResNet-18 as closely as possible. Although the DenseNet model took almost twice as long to train than ResNet, the model reached a final validation accuracy of 73.6%, almost 2% higher than ResNet-18. Thus, making DenseNet slightly better in performance for this dataset.

Model	Size (Parameters)	Complexity (MACs)	Accuracy
ResNet-18	11.18 M	148.76 M	71.81%
DenseNet	11.17 M	199.44 M	73.6%