50.039 Theory and Practice of Deep Learning HW3
Loh De Rong (1003557)

Part 1: Testing Pretrained ResNet101

The Jupyter Notebook can be found in hw3/task1/TestingPretrainedResNet.ipynb. The input test image is a beagle (a kind of dog breed), which can be found in hw3/task1/dog.jpg.

Result of the centre crop only (original code)

```
Label: tensor(162) . Confidence Score: 81.00029754638672 %
Label: tensor(168) . Confidence Score: 9.432700157165527 %
Label: tensor(208) . Confidence Score: 2.8158085346221924 %
Label: tensor(161) . Confidence Score: 1.579605221748352 %
Label: tensor(211) . Confidence Score: 1.131980538368225 %
```

Result of the five crops (edited code)

```
Label: tensor(162) . Confidence Score: 99.99964141845703 %
Label: tensor(168) . Confidence Score: 0.00034762214636430144 %
Label: tensor(161) . Confidence Score: 1.0993042451445945e-05 %
Label: tensor(164) . Confidence Score: 2.276629516018147e-07 %
Label: tensor(166) . Confidence Score: 1.4632828282401533e-09 %
```

Comparing results of centre crop and five crops

In both cases, the pretrained ResNet101 was able to successfully predict the correct class (beagle, tensor 162) based on the highest confidence score. However, the network was not as confident (81.00%) if there was only the centre crop, as compared to five crops (99.99%).

Advantages and disadvantages of data augmentation at test time

Advantages:

- The prediction relies on multiple different views of the same image, instead of only 1 raw image, so the final score is more reliable.

Disadvantages:

- Longer prediction time as each augmented image needs to be generated and processed.
- The cropped images might not always contain the object of interest, leading to incorrect predictions.

50.039 Theory and Practice of Deep Learning HW3
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Part 2: Fine-tuning Network

The Jupyter Notebook can be found in hw3/task2/FinetuningNetwork.ipynb.

Task 1

Performance of densenet169 on validation set

```
%run train.py "flowers" --gpu --epoch 5 --arch densenet169
```

```
Epoch: 1/5 -  Training Loss: 4.298 -  Validation Loss: 3.685 -  Validation Accuracy: 0.304
Epoch: 1/5 -  Training Loss: 3.306 -  Validation Loss: 2.470 -  Validation Accuracy: 0.500
Epoch: 1/5 -  Training Loss: 2.394 -  Validation Loss: 1.600 -  Validation Accuracy: 0.661
Epoch: 1/5 -  Training Loss: 1.724 -  Validation Loss: 1.158 -  Validation Accuracy: 0.755
Epoch: 1/5 -  Training Loss: 1.506 -  Validation Loss: 0.857 -  Validation Accuracy: 0.821
Epoch: 2/5 -  Training Loss: 1.128 -  Validation Loss: 0.716 -  Validation Accuracy: 0.856
Epoch: 2/5 -  Training Loss: 0.896 -  Validation Loss: 0.580 -  Validation Accuracy: 0.874
Epoch: 2/5 -  Training Loss: 0.911 -  Validation Loss: 0.564 -  Validation Accuracy: 0.881
Epoch: 2/5 -  Training Loss: 0.797 -  Validation Loss: 0.477 -  Validation Accuracy: 0.894
Epoch: 2/5 -  Training Loss: 0.707 -  Validation Loss: 0.420 -  Validation Accuracy: 0.905
Epoch: 3/5 -  Training Loss: 0.630 -  Validation Loss: 0.370 -  Validation Accuracy: 0.921
Epoch: 3/5 -  Training Loss: 0.597 -  Validation Loss: 0.368 -  Validation Accuracy: 0.911
Epoch: 3/5 -  Training Loss: 0.571 -  Validation Loss: 0.369 -  Validation Accuracy: 0.905
Epoch: 3/5 -  Training Loss: 0.532 -  Validation Loss: 0.328 -  Validation Accuracy: 0.920
Epoch: 3/5 -  Training Loss: 0.488 -  Validation Loss: 0.305 -  Validation Accuracy: 0.927
Epoch: 4/5 -  Training Loss: 0.457 -  Validation Loss: 0.281 -  Validation Accuracy: 0.928
Epoch: 4/5 -  Training Loss: 0.428 -  Validation Loss: 0.284 -  Validation Accuracy: 0.929
Epoch: 4/5 -  Training Loss: 0.424 -  Validation Loss: 0.269 -  Validation Accuracy: 0.934
Epoch: 4/5 -  Training Loss: 0.422 -  Validation Loss: 0.250 -  Validation Accuracy: 0.935
Epoch: 4/5 -  Training Loss: 0.414 -  Validation Loss: 0.282 -  Validation Accuracy: 0.925
Epoch: 5/5 -  Training Loss: 0.384 -  Validation Loss: 0.246 -  Validation Accuracy: 0.922
Epoch: 5/5 -  Training Loss: 0.363 -  Validation Loss: 0.246 -  Validation Accuracy: 0.932
Epoch: 5/5 -  Training Loss: 0.363 -  Validation Loss: 0.248 -  Validation Accuracy: 0.935
Epoch: 5/5 -  Training Loss: 0.324 -  Validation Loss: 0.225 -  Validation Accuracy: 0.940
Epoch: 5/5 -  Training Loss: 0.313 -  Validation Loss: 0.225 -  Validation Accuracy: 0.938
model: densenet169 - hidden layers: [1024] - epochs: 5 - lr: 0.001
Run time: 10.025 min
```

Performance of resnet18 on validation set

```
%run train.py "flowers" --gpu --epoch 5 --arch resnet18
```

```
Epoch: 1/5 -  Training Loss: 4.327 -  Validation Loss: 3.566 -  Validation Accuracy: 0.303
Epoch: 1/5 -  Training Loss: 3.291 -  Validation Loss: 2.461 -  Validation Accuracy: 0.497
Epoch: 1/5 -  Training Loss: 2.463 -  Validation Loss: 1.630 -  Validation Accuracy: 0.608
Epoch: 1/5 -  Training Loss: 1.787 -  Validation Loss: 1.169 -  Validation Accuracy: 0.749
Epoch: 1/5 -  Training Loss: 1.526 -  Validation Loss: 0.963 -  Validation Accuracy: 0.792
Epoch: 2/5 -  Training Loss: 1.254 -  Validation Loss: 0.794 -  Validation Accuracy: 0.824
Epoch: 2/5 -  Training Loss: 1.144 -  Validation Loss: 0.705 -  Validation Accuracy: 0.832
Epoch: 2/5 -  Training Loss: 1.031 -  Validation Loss: 0.596 -  Validation Accuracy: 0.863
Epoch: 2/5 -  Training Loss: 0.974 -  Validation Loss: 0.561 -  Validation Accuracy: 0.870
Epoch: 2/5 -  Training Loss: 0.864 -  Validation Loss: 0.519 -  Validation Accuracy: 0.888
Epoch: 3/5 -  Training Loss: 0.832 -  Validation Loss: 0.473 -  Validation Accuracy: 0.901
Epoch: 3/5 -  Training Loss: 0.773 -  Validation Loss: 0.474 -  Validation Accuracy: 0.883
Epoch: 3/5 -  Training Loss: 0.739 -  Validation Loss: 0.466 -  Validation Accuracy: 0.880
Epoch: 3/5 -  Training Loss: 0.739 -  Validation Loss: 0.430 -  Validation Accuracy: 0.903
Epoch: 3/5 -  Training Loss: 0.694 -  Validation Loss: 0.413 -  Validation Accuracy: 0.894
Epoch: 4/5 -  Training Loss: 0.629 -  Validation Loss: 0.386 -  Validation Accuracy: 0.908
Epoch: 4/5 -  Training Loss: 0.625 -  Validation Loss: 0.416 -  Validation Accuracy: 0.902
Epoch: 4/5 -  Training Loss: 0.624 -  Validation Loss: 0.374 -  Validation Accuracy: 0.909
Epoch: 4/5 -  Training Loss: 0.594 -  Validation Loss: 0.354 -  Validation Accuracy: 0.913
Epoch: 4/5 -  Training Loss: 0.602 -  Validation Loss: 0.315 -  Validation Accuracy: 0.921
Epoch: 5/5 -  Training Loss: 0.558 -  Validation Loss: 0.333 -  Validation Accuracy: 0.922
Epoch: 5/5 -  Training Loss: 0.573 -  Validation Loss: 0.328 -  Validation Accuracy: 0.913
Epoch: 5/5 -  Training Loss: 0.543 -  Validation Loss: 0.332 -  Validation Accuracy: 0.923
Epoch: 5/5 -  Training Loss: 0.532 -  Validation Loss: 0.320 -  Validation Accuracy: 0.926
Epoch: 5/5 -  Training Loss: 0.533 -  Validation Loss: 0.318 -  Validation Accuracy: 0.916
model: resnet18 - hidden layers: [1024] - epochs: 5 - lr: 0.001
Run time: 8.988 min
```

50.039 Theory and Practice of Deep Learning HW3
Loh De Rong (1003557)

Comparing performance between densenet169 model and resnet18 model

	densenet169 model	**resnet18 model**
Final validation loss	Lower (0.225)	Higher (0.318)
Final validation accuracy	Higher (0.938)	Lower (0.916)
Total runtime	Longer (10.025 min)	Shorter (8.988 min)

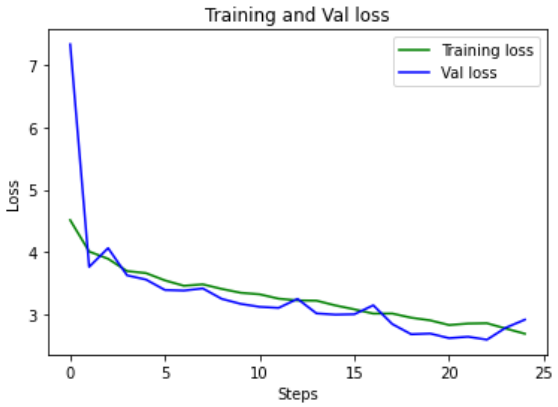
For the same number of epochs (set to 5), the densenet169 model took longer to train, but was able to yield lower validation loss and higher validation accuracy.

Task 2

Training the whole model from scratch

```
%run train.py "flowers" --gpu --epoch 5 --training_pref scratch --plot_graph True --arch densenet169
```

```
Epoch: 1/5 -  Training Loss: 4.512 -  Validation Loss: 7.336 -  Validation Accuracy: 0.075
Epoch: 1/5 -  Training Loss: 4.007 -  Validation Loss: 3.760 -  Validation Accuracy: 0.101
Epoch: 1/5 -  Training Loss: 3.890 -  Validation Loss: 4.062 -  Validation Accuracy: 0.091
Epoch: 1/5 -  Training Loss: 3.693 -  Validation Loss: 3.625 -  Validation Accuracy: 0.129
Epoch: 1/5 -  Training Loss: 3.661 -  Validation Loss: 3.557 -  Validation Accuracy: 0.139
Epoch: 2/5 -  Training Loss: 3.544 -  Validation Loss: 3.389 -  Validation Accuracy: 0.141
Epoch: 2/5 -  Training Loss: 3.457 -  Validation Loss: 3.380 -  Validation Accuracy: 0.149
Epoch: 2/5 -  Training Loss: 3.480 -  Validation Loss: 3.415 -  Validation Accuracy: 0.155
Epoch: 2/5 -  Training Loss: 3.406 -  Validation Loss: 3.247 -  Validation Accuracy: 0.169
Epoch: 2/5 -  Training Loss: 3.345 -  Validation Loss: 3.166 -  Validation Accuracy: 0.195
Epoch: 3/5 -  Training Loss: 3.320 -  Validation Loss: 3.118 -  Validation Accuracy: 0.180
Epoch: 3/5 -  Training Loss: 3.250 -  Validation Loss: 3.102 -  Validation Accuracy: 0.189
Epoch: 3/5 -  Training Loss: 3.222 -  Validation Loss: 3.247 -  Validation Accuracy: 0.179
Epoch: 3/5 -  Training Loss: 3.218 -  Validation Loss: 3.013 -  Validation Accuracy: 0.227
Epoch: 3/5 -  Training Loss: 3.141 -  Validation Loss: 2.994 -  Validation Accuracy: 0.229
Epoch: 4/5 -  Training Loss: 3.079 -  Validation Loss: 3.000 -  Validation Accuracy: 0.210
Epoch: 4/5 -  Training Loss: 3.010 -  Validation Loss: 3.144 -  Validation Accuracy: 0.232
Epoch: 4/5 -  Training Loss: 3.011 -  Validation Loss: 2.842 -  Validation Accuracy: 0.217
Epoch: 4/5 -  Training Loss: 2.944 -  Validation Loss: 2.678 -  Validation Accuracy: 0.293
Epoch: 4/5 -  Training Loss: 2.902 -  Validation Loss: 2.690 -  Validation Accuracy: 0.289
Epoch: 5/5 -  Training Loss: 2.826 -  Validation Loss: 2.616 -  Validation Accuracy: 0.292
Epoch: 5/5 -  Training Loss: 2.850 -  Validation Loss: 2.638 -  Validation Accuracy: 0.306
Epoch: 5/5 -  Training Loss: 2.855 -  Validation Loss: 2.591 -  Validation Accuracy: 0.309
Epoch: 5/5 -  Training Loss: 2.769 -  Validation Loss: 2.784 -  Validation Accuracy: 0.277
Epoch: 5/5 -  Training Loss: 2.687 -  Validation Loss: 2.912 -  Validation Accuracy: 0.301
model: densenet169 - hidden layers: [1024] - epochs: 5 - lr: 0.001
Run time: 12.442 min
```

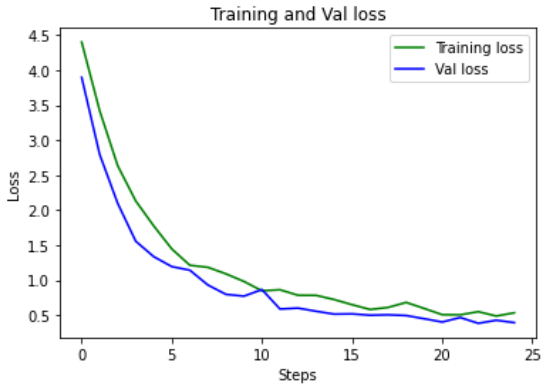


50.039 Theory and Practice of Deep Learning HW3
Loh De Rong (1003557)

Finetuning the model but only updating the top layers

```
%run train.py "flowers" --gpu --epoch 5 --training_pref finetune_top --plot_graph True --arch densenet169
```

```
Epoch: 1/5 -  Training Loss: 4.403 -  Validation Loss: 3.898 -  Validation Accuracy: 0.183
Epoch: 1/5 -  Training Loss: 3.420 -  Validation Loss: 2.796 -  Validation Accuracy: 0.355
Epoch: 1/5 -  Training Loss: 2.636 -  Validation Loss: 2.098 -  Validation Accuracy: 0.501
Epoch: 1/5 -  Training Loss: 2.132 -  Validation Loss: 1.557 -  Validation Accuracy: 0.627
Epoch: 1/5 -  Training Loss: 1.775 -  Validation Loss: 1.337 -  Validation Accuracy: 0.646
Epoch: 2/5 -  Training Loss: 1.447 -  Validation Loss: 1.195 -  Validation Accuracy: 0.688
Epoch: 2/5 -  Training Loss: 1.214 -  Validation Loss: 1.144 -  Validation Accuracy: 0.694
Epoch: 2/5 -  Training Loss: 1.185 -  Validation Loss: 0.933 -  Validation Accuracy: 0.750
Epoch: 2/5 -  Training Loss: 1.092 -  Validation Loss: 0.799 -  Validation Accuracy: 0.795
Epoch: 2/5 -  Training Loss: 0.983 -  Validation Loss: 0.772 -  Validation Accuracy: 0.812
Epoch: 3/5 -  Training Loss: 0.849 -  Validation Loss: 0.867 -  Validation Accuracy: 0.759
Epoch: 3/5 -  Training Loss: 0.864 -  Validation Loss: 0.589 -  Validation Accuracy: 0.843
Epoch: 3/5 -  Training Loss: 0.786 -  Validation Loss: 0.602 -  Validation Accuracy: 0.858
Epoch: 3/5 -  Training Loss: 0.784 -  Validation Loss: 0.557 -  Validation Accuracy: 0.850
Epoch: 3/5 -  Training Loss: 0.725 -  Validation Loss: 0.516 -  Validation Accuracy: 0.855
Epoch: 4/5 -  Training Loss: 0.651 -  Validation Loss: 0.520 -  Validation Accuracy: 0.864
Epoch: 4/5 -  Training Loss: 0.582 -  Validation Loss: 0.500 -  Validation Accuracy: 0.865
Epoch: 4/5 -  Training Loss: 0.612 -  Validation Loss: 0.506 -  Validation Accuracy: 0.863
Epoch: 4/5 -  Training Loss: 0.684 -  Validation Loss: 0.496 -  Validation Accuracy: 0.861
Epoch: 4/5 -  Training Loss: 0.597 -  Validation Loss: 0.450 -  Validation Accuracy: 0.874
Epoch: 5/5 -  Training Loss: 0.508 -  Validation Loss: 0.403 -  Validation Accuracy: 0.887
Epoch: 5/5 -  Training Loss: 0.506 -  Validation Loss: 0.467 -  Validation Accuracy: 0.886
Epoch: 5/5 -  Training Loss: 0.551 -  Validation Loss: 0.385 -  Validation Accuracy: 0.905
Epoch: 5/5 -  Training Loss: 0.489 -  Validation Loss: 0.429 -  Validation Accuracy: 0.892
Epoch: 5/5 -  Training Loss: 0.535 -  Validation Loss: 0.394 -  Validation Accuracy: 0.899
model: densenet169 - hidden layers: [1024] - epochs: 5 - lr: 0.001
Run time: 11.420 min
```



50.039 Theory and Practice of Deep Learning HW3
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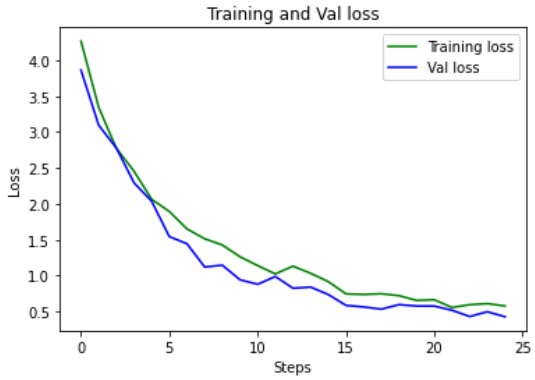
Finetuning the whole model

```
%run train.py "flowers" --gpu --epoch 5 --training_pref finetune_all --plot_graph True --arch densenet169
```

```
Epoch: 1/5 -  Training Loss: 4.266 -  Validation Loss: 3.863 -  Validation Accuracy: 0.139
Epoch: 1/5 -  Training Loss: 3.346 -  Validation Loss: 3.095 -  Validation Accuracy: 0.273
Epoch: 1/5 -  Training Loss: 2.774 -  Validation Loss: 2.778 -  Validation Accuracy: 0.333
Epoch: 1/5 -  Training Loss: 2.455 -  Validation Loss: 2.293 -  Validation Accuracy: 0.421
Epoch: 1/5 -  Training Loss: 2.064 -  Validation Loss: 2.035 -  Validation Accuracy: 0.513
Epoch: 2/5 -  Training Loss: 1.893 -  Validation Loss: 1.543 -  Validation Accuracy: 0.555
Epoch: 2/5 -  Training Loss: 1.651 -  Validation Loss: 1.443 -  Validation Accuracy: 0.596
Epoch: 2/5 -  Training Loss: 1.513 -  Validation Loss: 1.120 -  Validation Accuracy: 0.671
Epoch: 2/5 -  Training Loss: 1.426 -  Validation Loss: 1.145 -  Validation Accuracy: 0.680
Epoch: 2/5 -  Training Loss: 1.263 -  Validation Loss: 0.942 -  Validation Accuracy: 0.739
Epoch: 3/5 -  Training Loss: 1.140 -  Validation Loss: 0.879 -  Validation Accuracy: 0.746
Epoch: 3/5 -  Training Loss: 1.023 -  Validation Loss: 0.988 -  Validation Accuracy: 0.718
Epoch: 3/5 -  Training Loss: 1.132 -  Validation Loss: 0.824 -  Validation Accuracy: 0.756
Epoch: 3/5 -  Training Loss: 1.032 -  Validation Loss: 0.841 -  Validation Accuracy: 0.760
Epoch: 3/5 -  Training Loss: 0.916 -  Validation Loss: 0.736 -  Validation Accuracy: 0.797
Epoch: 4/5 -  Training Loss: 0.746 -  Validation Loss: 0.585 -  Validation Accuracy: 0.845
Epoch: 4/5 -  Training Loss: 0.738 -  Validation Loss: 0.564 -  Validation Accuracy: 0.844
Epoch: 4/5 -  Training Loss: 0.748 -  Validation Loss: 0.532 -  Validation Accuracy: 0.866
Epoch: 4/5 -  Training Loss: 0.721 -  Validation Loss: 0.596 -  Validation Accuracy: 0.829
Epoch: 4/5 -  Training Loss: 0.654 -  Validation Loss: 0.576 -  Validation Accuracy: 0.832
Epoch: 5/5 -  Training Loss: 0.664 -  Validation Loss: 0.575 -  Validation Accuracy: 0.844
Epoch: 5/5 -  Training Loss: 0.556 -  Validation Loss: 0.517 -  Validation Accuracy: 0.852
Epoch: 5/5 -  Training Loss: 0.595 -  Validation Loss: 0.430 -  Validation Accuracy: 0.878
Epoch: 5/5 -  Training Loss: 0.610 -  Validation Loss: 0.497 -  Validation Accuracy: 0.873
Epoch: 5/5 -  Training Loss: 0.577 -  Validation Loss: 0.427 -  Validation Accuracy: 0.900
model: densenet169 - hidden layers: [1024] - epochs: 5 - lr: 0.001
Run time: 12.417 min
```



Comparing training/validation loss among all 3 finetuning methods

	From scratch	Only top layers	All layers
Presence of overfitting	Training and validation loss are in sync, so there is no overfitting	Training and validation loss are in sync, so there is no overfitting	Training and validation loss are in sync, so there is no overfitting
Training and validation loss rate	Decrease very slowly (7.336 to 2.912)	Decrease very quickly, saturating near 0 (3.898 to 0.394)	Decrease very quickly, saturating near 0 (3.863 to 0.427)
Total runtime	Longer (12.442 min)	Shorter (11.420 min)	Longer (12.417 min)

When finetuning from scratch or all layers, it is expected that the total runtime is longer as the optimizer has to update more trainable parameters during gradient descent.

When finetuning from scratch, it is also not surprising that the training and validation loss rates are decreasing very slowly because the weights are initialized from scratch and have not been optimised to learn any features well. On the other hand, finetuning only the top

layers or all layers yield low loss and high accuracy very quickly with only a few epochs, meaning that the network only requires a few updates in order to reach a local minimum since the weights are already pretrained.

Task 3

Performance on testing set

```
%run evaluate.py "flowers" "modelcp.pth" --gpu
```

```
Testing Accuracy: 0.879
```

The testing accuracy is 0.879, which is slightly lower than the validation accuracy of 0.899. Hence, I believe that the model can be considered as generalizable.

50.039 Theory and Practice of Deep Learning HW3
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Task 4

Performance of CNN model (with 2 conv layers) on validation set

```
%run train.py "flowers" --gpu --epoch 10 --num_layers 2 --plot_graph True --arch custom
```

```
Epoch: 1/10 -  Training Loss: 4.311 -  Validation Loss: 3.870 -  Validation Accuracy: 0.101
Epoch: 1/10 -  Training Loss: 3.644 -  Validation Loss: 3.469 -  Validation Accuracy: 0.158
Epoch: 1/10 -  Training Loss: 3.423 -  Validation Loss: 3.262 -  Validation Accuracy: 0.186
Epoch: 1/10 -  Training Loss: 3.276 -  Validation Loss: 3.094 -  Validation Accuracy: 0.210
Epoch: 1/10 -  Training Loss: 3.145 -  Validation Loss: 2.945 -  Validation Accuracy: 0.243
Epoch: 2/10 -  Training Loss: 2.939 -  Validation Loss: 2.877 -  Validation Accuracy: 0.270
Epoch: 2/10 -  Training Loss: 2.878 -  Validation Loss: 2.813 -  Validation Accuracy: 0.254
Epoch: 2/10 -  Training Loss: 2.907 -  Validation Loss: 2.669 -  Validation Accuracy: 0.306
Epoch: 2/10 -  Training Loss: 2.695 -  Validation Loss: 2.623 -  Validation Accuracy: 0.330
Epoch: 2/10 -  Training Loss: 2.678 -  Validation Loss: 2.585 -  Validation Accuracy: 0.333
Epoch: 3/10 -  Training Loss: 2.616 -  Validation Loss: 2.561 -  Validation Accuracy: 0.337
Epoch: 3/10 -  Training Loss: 2.590 -  Validation Loss: 2.499 -  Validation Accuracy: 0.359
Epoch: 3/10 -  Training Loss: 2.544 -  Validation Loss: 2.468 -  Validation Accuracy: 0.346
Epoch: 3/10 -  Training Loss: 2.483 -  Validation Loss: 2.392 -  Validation Accuracy: 0.387
Epoch: 3/10 -  Training Loss: 2.494 -  Validation Loss: 2.395 -  Validation Accuracy: 0.369
Epoch: 4/10 -  Training Loss: 2.310 -  Validation Loss: 2.355 -  Validation Accuracy: 0.380
Epoch: 4/10 -  Training Loss: 2.353 -  Validation Loss: 2.301 -  Validation Accuracy: 0.397
Epoch: 4/10 -  Training Loss: 2.375 -  Validation Loss: 2.314 -  Validation Accuracy: 0.386
Epoch: 4/10 -  Training Loss: 2.416 -  Validation Loss: 2.263 -  Validation Accuracy: 0.382
Epoch: 4/10 -  Training Loss: 2.298 -  Validation Loss: 2.306 -  Validation Accuracy: 0.401
Epoch: 5/10 -  Training Loss: 2.249 -  Validation Loss: 2.198 -  Validation Accuracy: 0.418
Epoch: 5/10 -  Training Loss: 2.216 -  Validation Loss: 2.154 -  Validation Accuracy: 0.421
Epoch: 5/10 -  Training Loss: 2.172 -  Validation Loss: 2.095 -  Validation Accuracy: 0.453
Epoch: 5/10 -  Training Loss: 2.145 -  Validation Loss: 2.111 -  Validation Accuracy: 0.429
Epoch: 5/10 -  Training Loss: 2.112 -  Validation Loss: 2.047 -  Validation Accuracy: 0.441

Epoch: 6/10 -  Training Loss: 2.091 -  Validation Loss: 2.114 -  Validation Accuracy: 0.444
Epoch: 6/10 -  Training Loss: 2.049 -  Validation Loss: 1.981 -  Validation Accuracy: 0.472
Epoch: 6/10 -  Training Loss: 2.015 -  Validation Loss: 2.058 -  Validation Accuracy: 0.446
Epoch: 6/10 -  Training Loss: 2.111 -  Validation Loss: 2.022 -  Validation Accuracy: 0.455
Epoch: 6/10 -  Training Loss: 2.014 -  Validation Loss: 2.019 -  Validation Accuracy: 0.458
Epoch: 7/10 -  Training Loss: 1.993 -  Validation Loss: 1.961 -  Validation Accuracy: 0.479
Epoch: 7/10 -  Training Loss: 1.914 -  Validation Loss: 1.866 -  Validation Accuracy: 0.510
Epoch: 7/10 -  Training Loss: 1.901 -  Validation Loss: 1.927 -  Validation Accuracy: 0.507
Epoch: 7/10 -  Training Loss: 1.865 -  Validation Loss: 1.849 -  Validation Accuracy: 0.505
Epoch: 7/10 -  Training Loss: 1.928 -  Validation Loss: 1.820 -  Validation Accuracy: 0.517
Epoch: 8/10 -  Training Loss: 1.910 -  Validation Loss: 1.911 -  Validation Accuracy: 0.497
Epoch: 8/10 -  Training Loss: 1.768 -  Validation Loss: 1.871 -  Validation Accuracy: 0.510
Epoch: 8/10 -  Training Loss: 1.879 -  Validation Loss: 1.811 -  Validation Accuracy: 0.534
Epoch: 8/10 -  Training Loss: 1.792 -  Validation Loss: 1.798 -  Validation Accuracy: 0.505
Epoch: 8/10 -  Training Loss: 1.770 -  Validation Loss: 1.798 -  Validation Accuracy: 0.539
Epoch: 8/10 -  Training Loss: 1.758 -  Validation Loss: 1.722 -  Validation Accuracy: 0.548
Epoch: 9/10 -  Training Loss: 1.714 -  Validation Loss: 1.695 -  Validation Accuracy: 0.554
Epoch: 9/10 -  Training Loss: 1.700 -  Validation Loss: 1.688 -  Validation Accuracy: 0.552
Epoch: 9/10 -  Training Loss: 1.617 -  Validation Loss: 1.632 -  Validation Accuracy: 0.574
Epoch: 9/10 -  Training Loss: 1.682 -  Validation Loss: 1.695 -  Validation Accuracy: 0.533
Epoch: 9/10 -  Training Loss: 1.726 -  Validation Loss: 1.616 -  Validation Accuracy: 0.568
Epoch: 10/10 -  Training Loss: 1.689 -  Validation Loss: 1.791 -  Validation Accuracy: 0.535
Epoch: 10/10 -  Training Loss: 1.518 -  Validation Loss: 1.615 -  Validation Accuracy: 0.563
Epoch: 10/10 -  Training Loss: 1.577 -  Validation Loss: 1.712 -  Validation Accuracy: 0.536
Epoch: 10/10 -  Training Loss: 1.627 -  Validation Loss: 1.567 -  Validation Accuracy: 0.588
Epoch: 10/10 -  Training Loss: 1.660 -  Validation Loss: 1.566 -  Validation Accuracy: 0.574
model: custom - hidden layers: [1024] - epochs: 10 - lr: 0.001
Run time: 18.960 min
```

50.039 Theory and Practice of Deep Learning HW3
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Performance of CNN model (with 3 conv layers) on validation set

```
%run train.py "flowers" --gpu --epoch 10 --num_layers 3 --plot_graph True --arch custom
```

```
Epoch: 1/10 -  Training Loss: 4.287 -  Validation Loss: 3.993 -  Validation Accuracy: 0.106
Epoch: 1/10 -  Training Loss: 3.718 -  Validation Loss: 3.375 -  Validation Accuracy: 0.155
Epoch: 1/10 -  Training Loss: 3.335 -  Validation Loss: 3.202 -  Validation Accuracy: 0.196
Epoch: 1/10 -  Training Loss: 3.166 -  Validation Loss: 3.009 -  Validation Accuracy: 0.229
Epoch: 1/10 -  Training Loss: 3.045 -  Validation Loss: 2.927 -  Validation Accuracy: 0.253
Epoch: 2/10 -  Training Loss: 2.900 -  Validation Loss: 2.741 -  Validation Accuracy: 0.269
Epoch: 2/10 -  Training Loss: 2.774 -  Validation Loss: 2.733 -  Validation Accuracy: 0.274
Epoch: 2/10 -  Training Loss: 2.690 -  Validation Loss: 2.648 -  Validation Accuracy: 0.295
Epoch: 2/10 -  Training Loss: 2.639 -  Validation Loss: 2.624 -  Validation Accuracy: 0.302
Epoch: 2/10 -  Training Loss: 2.706 -  Validation Loss: 2.491 -  Validation Accuracy: 0.340
Epoch: 3/10 -  Training Loss: 2.572 -  Validation Loss: 2.519 -  Validation Accuracy: 0.334
Epoch: 3/10 -  Training Loss: 2.444 -  Validation Loss: 2.422 -  Validation Accuracy: 0.370
Epoch: 3/10 -  Training Loss: 2.357 -  Validation Loss: 2.287 -  Validation Accuracy: 0.372
Epoch: 3/10 -  Training Loss: 2.405 -  Validation Loss: 2.267 -  Validation Accuracy: 0.388
Epoch: 3/10 -  Training Loss: 2.411 -  Validation Loss: 2.253 -  Validation Accuracy: 0.392
Epoch: 4/10 -  Training Loss: 2.225 -  Validation Loss: 2.172 -  Validation Accuracy: 0.404
Epoch: 4/10 -  Training Loss: 2.176 -  Validation Loss: 2.111 -  Validation Accuracy: 0.441
Epoch: 4/10 -  Training Loss: 2.198 -  Validation Loss: 2.106 -  Validation Accuracy: 0.437
Epoch: 4/10 -  Training Loss: 2.164 -  Validation Loss: 2.029 -  Validation Accuracy: 0.447
Epoch: 4/10 -  Training Loss: 2.110 -  Validation Loss: 2.031 -  Validation Accuracy: 0.444
Epoch: 5/10 -  Training Loss: 2.135 -  Validation Loss: 1.857 -  Validation Accuracy: 0.484
Epoch: 5/10 -  Training Loss: 2.073 -  Validation Loss: 1.912 -  Validation Accuracy: 0.495
Epoch: 5/10 -  Training Loss: 1.977 -  Validation Loss: 1.999 -  Validation Accuracy: 0.487
Epoch: 5/10 -  Training Loss: 1.979 -  Validation Loss: 1.918 -  Validation Accuracy: 0.493
Epoch: 5/10 -  Training Loss: 1.986 -  Validation Loss: 1.812 -  Validation Accuracy: 0.534

Epoch: 6/10 -  Training Loss: 1.912 -  Validation Loss: 1.881 -  Validation Accuracy: 0.488
Epoch: 6/10 -  Training Loss: 1.905 -  Validation Loss: 1.896 -  Validation Accuracy: 0.487
Epoch: 6/10 -  Training Loss: 1.804 -  Validation Loss: 1.795 -  Validation Accuracy: 0.521
Epoch: 6/10 -  Training Loss: 1.840 -  Validation Loss: 1.851 -  Validation Accuracy: 0.520
Epoch: 6/10 -  Training Loss: 1.880 -  Validation Loss: 1.758 -  Validation Accuracy: 0.547
Epoch: 7/10 -  Training Loss: 1.770 -  Validation Loss: 1.692 -  Validation Accuracy: 0.543
Epoch: 7/10 -  Training Loss: 1.716 -  Validation Loss: 1.769 -  Validation Accuracy: 0.532
Epoch: 7/10 -  Training Loss: 1.707 -  Validation Loss: 1.653 -  Validation Accuracy: 0.565
Epoch: 7/10 -  Training Loss: 1.675 -  Validation Loss: 1.736 -  Validation Accuracy: 0.520
Epoch: 7/10 -  Training Loss: 1.733 -  Validation Loss: 1.699 -  Validation Accuracy: 0.558
Epoch: 8/10 -  Training Loss: 1.740 -  Validation Loss: 1.636 -  Validation Accuracy: 0.560
Epoch: 8/10 -  Training Loss: 1.594 -  Validation Loss: 1.553 -  Validation Accuracy: 0.579
Epoch: 8/10 -  Training Loss: 1.562 -  Validation Loss: 1.607 -  Validation Accuracy: 0.571
Epoch: 8/10 -  Training Loss: 1.654 -  Validation Loss: 1.625 -  Validation Accuracy: 0.559
Epoch: 8/10 -  Training Loss: 1.664 -  Validation Loss: 1.539 -  Validation Accuracy: 0.588
Epoch: 8/10 -  Training Loss: 1.603 -  Validation Loss: 1.654 -  Validation Accuracy: 0.555
Epoch: 9/10 -  Training Loss: 1.446 -  Validation Loss: 1.450 -  Validation Accuracy: 0.595
Epoch: 9/10 -  Training Loss: 1.508 -  Validation Loss: 1.438 -  Validation Accuracy: 0.627
Epoch: 9/10 -  Training Loss: 1.472 -  Validation Loss: 1.399 -  Validation Accuracy: 0.616
Epoch: 10/10 -  Training Loss: 1.384 -  Validation Loss: 1.349 -  Validation Accuracy: 0.629
Epoch: 10/10 -  Training Loss: 1.394 -  Validation Loss: 1.422 -  Validation Accuracy: 0.624
Epoch: 10/10 -  Training Loss: 1.411 -  Validation Loss: 1.474 -  Validation Accuracy: 0.599
Epoch: 10/10 -  Training Loss: 1.464 -  Validation Loss: 1.343 -  Validation Accuracy: 0.642
Epoch: 10/10 -  Training Loss: 1.460 -  Validation Loss: 1.378 -  Validation Accuracy: 0.620
model: custom - hidden layers: [1024] - epochs: 10 - lr: 0.001
Run time: 19.040 min
```

50.039 Theory and Practice of Deep Learning HW3
Loh De Rong (1003557)

Performance of CNN model (with 4 conv layers) on validation set

```
%run train.py "flowers" --gpu --epoch 10 --num_layers 4 --plot_graph True --arch custom
```

```
Epoch: 1/10 -  Training Loss: 4.288 -  Validation Loss: 3.887 -  Validation Accuracy: 0.105
Epoch: 1/10 -  Training Loss: 3.731 -  Validation Loss: 3.509 -  Validation Accuracy: 0.144
Epoch: 1/10 -  Training Loss: 3.289 -  Validation Loss: 3.309 -  Validation Accuracy: 0.188
Epoch: 1/10 -  Training Loss: 3.120 -  Validation Loss: 3.047 -  Validation Accuracy: 0.245
Epoch: 1/10 -  Training Loss: 2.998 -  Validation Loss: 2.946 -  Validation Accuracy: 0.255
Epoch: 2/10 -  Training Loss: 2.855 -  Validation Loss: 2.935 -  Validation Accuracy: 0.245
Epoch: 2/10 -  Training Loss: 2.801 -  Validation Loss: 2.747 -  Validation Accuracy: 0.277
Epoch: 2/10 -  Training Loss: 2.722 -  Validation Loss: 2.609 -  Validation Accuracy: 0.313
Epoch: 2/10 -  Training Loss: 2.580 -  Validation Loss: 2.466 -  Validation Accuracy: 0.351
Epoch: 2/10 -  Training Loss: 2.568 -  Validation Loss: 2.394 -  Validation Accuracy: 0.367
Epoch: 3/10 -  Training Loss: 2.417 -  Validation Loss: 2.452 -  Validation Accuracy: 0.337
Epoch: 3/10 -  Training Loss: 2.448 -  Validation Loss: 2.170 -  Validation Accuracy: 0.411
Epoch: 3/10 -  Training Loss: 2.310 -  Validation Loss: 2.196 -  Validation Accuracy: 0.389
Epoch: 3/10 -  Training Loss: 2.339 -  Validation Loss: 2.207 -  Validation Accuracy: 0.394
Epoch: 3/10 -  Training Loss: 2.198 -  Validation Loss: 2.131 -  Validation Accuracy: 0.429
Epoch: 4/10 -  Training Loss: 2.159 -  Validation Loss: 2.110 -  Validation Accuracy: 0.424
Epoch: 4/10 -  Training Loss: 2.113 -  Validation Loss: 2.099 -  Validation Accuracy: 0.445
Epoch: 4/10 -  Training Loss: 2.087 -  Validation Loss: 1.986 -  Validation Accuracy: 0.462
Epoch: 4/10 -  Training Loss: 2.054 -  Validation Loss: 1.965 -  Validation Accuracy: 0.472
Epoch: 4/10 -  Training Loss: 2.014 -  Validation Loss: 1.927 -  Validation Accuracy: 0.480
Epoch: 5/10 -  Training Loss: 2.069 -  Validation Loss: 1.854 -  Validation Accuracy: 0.512
Epoch: 5/10 -  Training Loss: 1.943 -  Validation Loss: 1.800 -  Validation Accuracy: 0.510
Epoch: 5/10 -  Training Loss: 1.925 -  Validation Loss: 1.811 -  Validation Accuracy: 0.514
Epoch: 5/10 -  Training Loss: 1.833 -  Validation Loss: 1.863 -  Validation Accuracy: 0.507
Epoch: 5/10 -  Training Loss: 1.830 -  Validation Loss: 1.699 -  Validation Accuracy: 0.565

Epoch: 6/10 -  Training Loss: 1.807 -  Validation Loss: 1.868 -  Validation Accuracy: 0.513
Epoch: 6/10 -  Training Loss: 1.696 -  Validation Loss: 1.725 -  Validation Accuracy: 0.525
Epoch: 6/10 -  Training Loss: 1.731 -  Validation Loss: 1.583 -  Validation Accuracy: 0.586
Epoch: 6/10 -  Training Loss: 1.677 -  Validation Loss: 1.558 -  Validation Accuracy: 0.566
Epoch: 6/10 -  Training Loss: 1.672 -  Validation Loss: 1.563 -  Validation Accuracy: 0.580
Epoch: 7/10 -  Training Loss: 1.636 -  Validation Loss: 1.626 -  Validation Accuracy: 0.573
Epoch: 7/10 -  Training Loss: 1.527 -  Validation Loss: 1.498 -  Validation Accuracy: 0.600
Epoch: 7/10 -  Training Loss: 1.556 -  Validation Loss: 1.526 -  Validation Accuracy: 0.595
Epoch: 7/10 -  Training Loss: 1.605 -  Validation Loss: 1.497 -  Validation Accuracy: 0.606
Epoch: 7/10 -  Training Loss: 1.508 -  Validation Loss: 1.479 -  Validation Accuracy: 0.590
Epoch: 8/10 -  Training Loss: 1.557 -  Validation Loss: 1.563 -  Validation Accuracy: 0.566
Epoch: 8/10 -  Training Loss: 1.421 -  Validation Loss: 1.389 -  Validation Accuracy: 0.627
Epoch: 8/10 -  Training Loss: 1.471 -  Validation Loss: 1.509 -  Validation Accuracy: 0.593
Epoch: 8/10 -  Training Loss: 1.375 -  Validation Loss: 1.340 -  Validation Accuracy: 0.645
Epoch: 8/10 -  Training Loss: 1.396 -  Validation Loss: 1.526 -  Validation Accuracy: 0.592
Epoch: 8/10 -  Training Loss: 1.496 -  Validation Loss: 1.392 -  Validation Accuracy: 0.644
Epoch: 9/10 -  Training Loss: 1.358 -  Validation Loss: 1.368 -  Validation Accuracy: 0.631
Epoch: 9/10 -  Training Loss: 1.320 -  Validation Loss: 1.331 -  Validation Accuracy: 0.628
Epoch: 9/10 -  Training Loss: 1.366 -  Validation Loss: 1.277 -  Validation Accuracy: 0.653
Epoch: 9/10 -  Training Loss: 1.360 -  Validation Loss: 1.288 -  Validation Accuracy: 0.639
Epoch: 9/10 -  Training Loss: 1.300 -  Validation Loss: 1.430 -  Validation Accuracy: 0.608
Epoch: 10/10 -  Training Loss: 1.332 -  Validation Loss: 1.256 -  Validation Accuracy: 0.673
Epoch: 10/10 -  Training Loss: 1.299 -  Validation Loss: 1.179 -  Validation Accuracy: 0.686
Epoch: 10/10 -  Training Loss: 1.229 -  Validation Loss: 1.193 -  Validation Accuracy: 0.676
Epoch: 10/10 -  Training Loss: 1.243 -  Validation Loss: 1.283 -  Validation Accuracy: 0.660
Epoch: 10/10 -  Training Loss: 1.247 -  Validation Loss: 1.172 -  Validation Accuracy: 0.682
model: custom - hidden layers: [1024] - epochs: 10 - lr: 0.001
Run time: 19.043 min
```

50.039 Theory and Practice of Deep Learning HW3
Loh De Rong (1003557)

Comparing performance among all different number of convolutional layers

	2 layers	**3 layers**	**4 layers**
Presence of overfitting	Training and validation loss are in sync, so there is no overfitting	Training and validation loss are in sync, so there is no overfitting	Training and validation loss are in sync, so there is no overfitting
Training and validation loss rate	Decrease most slowly (3.870 to 1.566)	Decrease more slowly (3.993 to 1.378)	Decrease least slowly (3.887 to 1.172)
Training and validation accuracy rate	Increase most slowly (0.101 to 0.574)	Increase more slowly (0.106 to 0.620)	Increase least slowly (0.105 to 0.682)
Total runtime	About the same (18.960 min)	About the same (19.040 min)	About the same (19.043 min)

The model performance is better when there are more convolutional layers. The training and validation loss rates decrease more quickly, resulting in a faster improvement in the training and validation accuracy scores. This is likely because the network is deeper with more activation maps that could better detect higher dimensional features for the class represented by each input image.

An increase in the number of convolutional layers increases the total runtime slightly only because the total number of parameters in each extra layer according to what I defined was not a significantly large number, so the difference in computation time was not very noticeable.