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, hence it will be more robust.

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.

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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: 4.324 -  Validation Loss: 3.689 -  Validation Accuracy: 0.250
Epoch: 1/5 -  Training Loss: 3.278 -  Validation Loss: 2.479 -  Validation Accuracy: 0.499
Epoch: 1/5 -  Training Loss: 2.447 -  Validation Loss: 1.610 -  Validation Accuracy: 0.674
Epoch: 1/5 -  Training Loss: 1.696 -  Validation Loss: 1.098 -  Validation Accuracy: 0.764
Epoch: 1/5 -  Training Loss: 1.285 -  Validation Loss: 0.851 -  Validation Accuracy: 0.813
Epoch: 2/5 -  Training Loss: 1.098 -  Validation Loss: 0.689 -  Validation Accuracy: 0.848
Epoch: 2/5 -  Training Loss: 0.932 -  Validation Loss: 0.606 -  Validation Accuracy: 0.862
Epoch: 2/5 -  Training Loss: 0.858 -  Validation Loss: 0.517 -  Validation Accuracy: 0.891
Epoch: 2/5 -  Training Loss: 0.743 -  Validation Loss: 0.438 -  Validation Accuracy: 0.908
Epoch: 2/5 -  Training Loss: 0.706 -  Validation Loss: 0.441 -  Validation Accuracy: 0.910
Epoch: 3/5 -  Training Loss: 0.676 -  Validation Loss: 0.382 -  Validation Accuracy: 0.905
Epoch: 3/5 -  Training Loss: 0.572 -  Validation Loss: 0.369 -  Validation Accuracy: 0.926
Epoch: 3/5 -  Training Loss: 0.548 -  Validation Loss: 0.342 -  Validation Accuracy: 0.919
Epoch: 3/5 -  Training Loss: 0.495 -  Validation Loss: 0.307 -  Validation Accuracy: 0.933
Epoch: 3/5 -  Training Loss: 0.480 -  Validation Loss: 0.310 -  Validation Accuracy: 0.923
Epoch: 4/5 -  Training Loss: 0.433 -  Validation Loss: 0.293 -  Validation Accuracy: 0.927
Epoch: 4/5 -  Training Loss: 0.383 -  Validation Loss: 0.289 -  Validation Accuracy: 0.928
Epoch: 4/5 -  Training Loss: 0.425 -  Validation Loss: 0.259 -  Validation Accuracy: 0.937
Epoch: 4/5 -  Training Loss: 0.434 -  Validation Loss: 0.271 -  Validation Accuracy: 0.940
Epoch: 4/5 -  Training Loss: 0.389 -  Validation Loss: 0.235 -  Validation Accuracy: 0.947
Epoch: 5/5 -  Training Loss: 0.336 -  Validation Loss: 0.254 -  Validation Accuracy: 0.943
Epoch: 5/5 -  Training Loss: 0.367 -  Validation Loss: 0.260 -  Validation Accuracy: 0.937
Epoch: 5/5 -  Training Loss: 0.332 -  Validation Loss: 0.237 -  Validation Accuracy: 0.935
Epoch: 5/5 -  Training Loss: 0.347 -  Validation Loss: 0.231 -  Validation Accuracy: 0.940
Epoch: 5/5 -  Training Loss: 0.375 -  Validation Loss: 0.237 -  Validation Accuracy: 0.933
model: densenet169 - hidden layers: [1024] - epochs: 5 - lr: 0.001
Run time: 10.228 min
```

Performance of resnet18 on validation set

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

```
Epoch: 1/5 -  Training Loss: 4.342 -  Validation Loss: 3.582 -  Validation Accuracy: 0.323
Epoch: 1/5 -  Training Loss: 3.233 -  Validation Loss: 2.394 -  Validation Accuracy: 0.480
Epoch: 1/5 -  Training Loss: 2.328 -  Validation Loss: 1.638 -  Validation Accuracy: 0.641
Epoch: 1/5 -  Training Loss: 1.874 -  Validation Loss: 1.224 -  Validation Accuracy: 0.715
Epoch: 1/5 -  Training Loss: 1.527 -  Validation Loss: 0.975 -  Validation Accuracy: 0.802
Epoch: 2/5 -  Training Loss: 1.237 -  Validation Loss: 0.785 -  Validation Accuracy: 0.823
Epoch: 2/5 -  Training Loss: 1.103 -  Validation Loss: 0.692 -  Validation Accuracy: 0.837
Epoch: 2/5 -  Training Loss: 0.983 -  Validation Loss: 0.618 -  Validation Accuracy: 0.857
Epoch: 2/5 -  Training Loss: 0.963 -  Validation Loss: 0.599 -  Validation Accuracy: 0.851
Epoch: 2/5 -  Training Loss: 0.898 -  Validation Loss: 0.530 -  Validation Accuracy: 0.886
Epoch: 3/5 -  Training Loss: 0.777 -  Validation Loss: 0.477 -  Validation Accuracy: 0.883
Epoch: 3/5 -  Training Loss: 0.765 -  Validation Loss: 0.484 -  Validation Accuracy: 0.879
Epoch: 3/5 -  Training Loss: 0.748 -  Validation Loss: 0.435 -  Validation Accuracy: 0.899
Epoch: 3/5 -  Training Loss: 0.740 -  Validation Loss: 0.402 -  Validation Accuracy: 0.911
Epoch: 3/5 -  Training Loss: 0.615 -  Validation Loss: 0.403 -  Validation Accuracy: 0.903
Epoch: 4/5 -  Training Loss: 0.661 -  Validation Loss: 0.410 -  Validation Accuracy: 0.890
Epoch: 4/5 -  Training Loss: 0.581 -  Validation Loss: 0.367 -  Validation Accuracy: 0.910
Epoch: 4/5 -  Training Loss: 0.604 -  Validation Loss: 0.402 -  Validation Accuracy: 0.893
Epoch: 4/5 -  Training Loss: 0.586 -  Validation Loss: 0.375 -  Validation Accuracy: 0.902
Epoch: 4/5 -  Training Loss: 0.626 -  Validation Loss: 0.338 -  Validation Accuracy: 0.920
Epoch: 5/5 -  Training Loss: 0.622 -  Validation Loss: 0.356 -  Validation Accuracy: 0.900
Epoch: 5/5 -  Training Loss: 0.543 -  Validation Loss: 0.328 -  Validation Accuracy: 0.914
Epoch: 5/5 -  Training Loss: 0.556 -  Validation Loss: 0.337 -  Validation Accuracy: 0.909
Epoch: 5/5 -  Training Loss: 0.577 -  Validation Loss: 0.342 -  Validation Accuracy: 0.919
Epoch: 5/5 -  Training Loss: 0.513 -  Validation Loss: 0.330 -  Validation Accuracy: 0.921
model: resnet18 - hidden layers: [1024] - epochs: 5 - lr: 0.001
Run time: 9.028 min
```

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Comparing performance between densenet169 model and resnet18 model

	densenet169	**resnet18**
Final validation loss	Lower (0.237)	Higher (0.330)
Final validation accuracy	Higher (0.933)	Lower (0.921)
Total runtime	Longer (10.228 min)	Shorter (9.028 min)

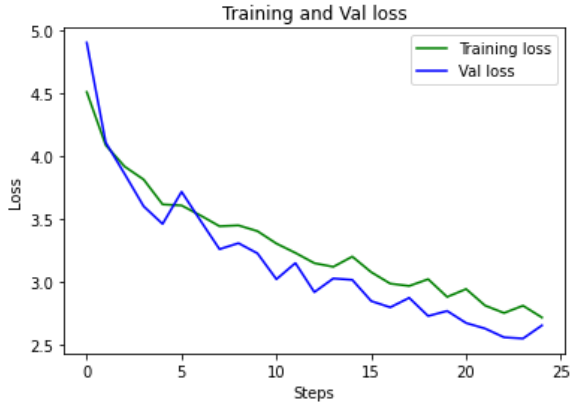
For the same number of epochs (set to 5), the densenet169 model took longer to train, but was able to yield lower validation loss and higher validation accuracy. This is because densenet169 is like “resnet18 to the extreme”, with even more skip connections, which help with improving gradient flow at the expense of an extra small computation cost.

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: 4.508 -  Validation Loss: 4.899 -  Validation Accuracy: 0.071
Epoch: 1/5 -  Training Loss: 4.085 -  Validation Loss: 4.107 -  Validation Accuracy: 0.114
Epoch: 1/5 -  Training Loss: 3.916 -  Validation Loss: 3.857 -  Validation Accuracy: 0.105
Epoch: 1/5 -  Training Loss: 3.813 -  Validation Loss: 3.600 -  Validation Accuracy: 0.115
Epoch: 1/5 -  Training Loss: 3.616 -  Validation Loss: 3.460 -  Validation Accuracy: 0.170
Epoch: 2/5 -  Training Loss: 3.607 -  Validation Loss: 3.716 -  Validation Accuracy: 0.113
Epoch: 2/5 -  Training Loss: 3.528 -  Validation Loss: 3.486 -  Validation Accuracy: 0.135
Epoch: 2/5 -  Training Loss: 3.442 -  Validation Loss: 3.260 -  Validation Accuracy: 0.170
Epoch: 2/5 -  Training Loss: 3.449 -  Validation Loss: 3.308 -  Validation Accuracy: 0.174
Epoch: 2/5 -  Training Loss: 3.403 -  Validation Loss: 3.227 -  Validation Accuracy: 0.173
Epoch: 3/5 -  Training Loss: 3.305 -  Validation Loss: 3.022 -  Validation Accuracy: 0.209
Epoch: 3/5 -  Training Loss: 3.231 -  Validation Loss: 3.150 -  Validation Accuracy: 0.205
Epoch: 3/5 -  Training Loss: 3.149 -  Validation Loss: 2.919 -  Validation Accuracy: 0.236
Epoch: 3/5 -  Training Loss: 3.120 -  Validation Loss: 3.028 -  Validation Accuracy: 0.225
Epoch: 3/5 -  Training Loss: 3.201 -  Validation Loss: 3.017 -  Validation Accuracy: 0.202
Epoch: 4/5 -  Training Loss: 3.078 -  Validation Loss: 2.848 -  Validation Accuracy: 0.246
Epoch: 4/5 -  Training Loss: 2.987 -  Validation Loss: 2.798 -  Validation Accuracy: 0.275
Epoch: 4/5 -  Training Loss: 2.968 -  Validation Loss: 2.874 -  Validation Accuracy: 0.244
Epoch: 4/5 -  Training Loss: 3.022 -  Validation Loss: 2.730 -  Validation Accuracy: 0.278
Epoch: 4/5 -  Training Loss: 2.881 -  Validation Loss: 2.770 -  Validation Accuracy: 0.276
Epoch: 5/5 -  Training Loss: 2.944 -  Validation Loss: 2.674 -  Validation Accuracy: 0.283
Epoch: 5/5 -  Training Loss: 2.813 -  Validation Loss: 2.630 -  Validation Accuracy: 0.289
Epoch: 5/5 -  Training Loss: 2.754 -  Validation Loss: 2.561 -  Validation Accuracy: 0.323
Epoch: 5/5 -  Training Loss: 2.812 -  Validation Loss: 2.551 -  Validation Accuracy: 0.341
Epoch: 5/5 -  Training Loss: 2.718 -  Validation Loss: 2.655 -  Validation Accuracy: 0.292
model: densenet169 - hidden layers: [1024] - epochs: 5 - lr: 0.001
Run time: 12.456 min
```



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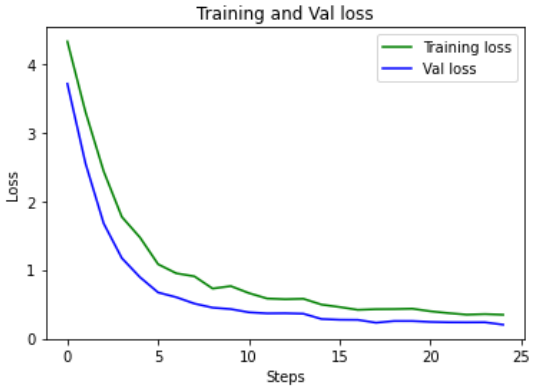
Finetuning the model but only updating the top layers

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

```
Epoch: 1/5 -  Training Loss: 4.324 -  Validation Loss: 3.709 -  Validation Accuracy: 0.279
Epoch: 1/5 -  Training Loss: 3.297 -  Validation Loss: 2.549 -  Validation Accuracy: 0.465
Epoch: 1/5 -  Training Loss: 2.434 -  Validation Loss: 1.676 -  Validation Accuracy: 0.639
Epoch: 1/5 -  Training Loss: 1.771 -  Validation Loss: 1.170 -  Validation Accuracy: 0.752
Epoch: 1/5 -  Training Loss: 1.471 -  Validation Loss: 0.892 -  Validation Accuracy: 0.827
Epoch: 2/5 -  Training Loss: 1.081 -  Validation Loss: 0.670 -  Validation Accuracy: 0.869
Epoch: 2/5 -  Training Loss: 0.949 -  Validation Loss: 0.601 -  Validation Accuracy: 0.871
Epoch: 2/5 -  Training Loss: 0.905 -  Validation Loss: 0.508 -  Validation Accuracy: 0.896
Epoch: 2/5 -  Training Loss: 0.727 -  Validation Loss: 0.449 -  Validation Accuracy: 0.903
Epoch: 2/5 -  Training Loss: 0.763 -  Validation Loss: 0.429 -  Validation Accuracy: 0.901
Epoch: 3/5 -  Training Loss: 0.661 -  Validation Loss: 0.381 -  Validation Accuracy: 0.904
Epoch: 3/5 -  Training Loss: 0.582 -  Validation Loss: 0.366 -  Validation Accuracy: 0.916
Epoch: 3/5 -  Training Loss: 0.572 -  Validation Loss: 0.368 -  Validation Accuracy: 0.919
Epoch: 3/5 -  Training Loss: 0.579 -  Validation Loss: 0.361 -  Validation Accuracy: 0.914
Epoch: 3/5 -  Training Loss: 0.494 -  Validation Loss: 0.284 -  Validation Accuracy: 0.935
Epoch: 4/5 -  Training Loss: 0.458 -  Validation Loss: 0.273 -  Validation Accuracy: 0.940
Epoch: 4/5 -  Training Loss: 0.418 -  Validation Loss: 0.272 -  Validation Accuracy: 0.933
Epoch: 4/5 -  Training Loss: 0.427 -  Validation Loss: 0.230 -  Validation Accuracy: 0.947
Epoch: 4/5 -  Training Loss: 0.429 -  Validation Loss: 0.255 -  Validation Accuracy: 0.940
Epoch: 4/5 -  Training Loss: 0.434 -  Validation Loss: 0.255 -  Validation Accuracy: 0.944
Epoch: 5/5 -  Training Loss: 0.397 -  Validation Loss: 0.242 -  Validation Accuracy: 0.940
Epoch: 5/5 -  Training Loss: 0.370 -  Validation Loss: 0.236 -  Validation Accuracy: 0.940
Epoch: 5/5 -  Training Loss: 0.348 -  Validation Loss: 0.235 -  Validation Accuracy: 0.943
Epoch: 5/5 -  Training Loss: 0.355 -  Validation Loss: 0.236 -  Validation Accuracy: 0.936
Epoch: 5/5 -  Training Loss: 0.346 -  Validation Loss: 0.202 -  Validation Accuracy: 0.950
model: densenet169 - hidden layers: [1024] - epochs: 5 - lr: 0.001
Run time: 10.030 min
```



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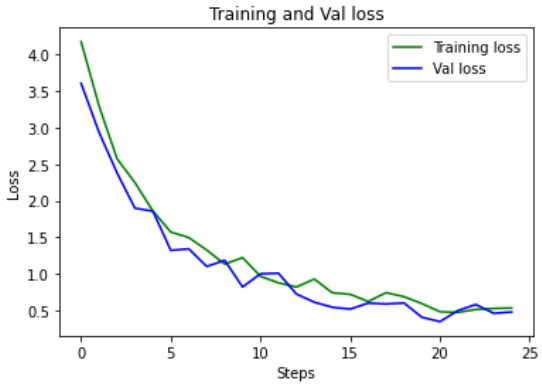
Finetuning the whole model

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

```
Epoch: 1/5 -  Training Loss: 4.172 -  Validation Loss: 3.604 -  Validation Accuracy: 0.194
Epoch: 1/5 -  Training Loss: 3.296 -  Validation Loss: 2.934 -  Validation Accuracy: 0.281
Epoch: 1/5 -  Training Loss: 2.576 -  Validation Loss: 2.383 -  Validation Accuracy: 0.379
Epoch: 1/5 -  Training Loss: 2.248 -  Validation Loss: 1.900 -  Validation Accuracy: 0.474
Epoch: 1/5 -  Training Loss: 1.862 -  Validation Loss: 1.858 -  Validation Accuracy: 0.530
Epoch: 2/5 -  Training Loss: 1.574 -  Validation Loss: 1.324 -  Validation Accuracy: 0.618
Epoch: 2/5 -  Training Loss: 1.500 -  Validation Loss: 1.345 -  Validation Accuracy: 0.620
Epoch: 2/5 -  Training Loss: 1.328 -  Validation Loss: 1.105 -  Validation Accuracy: 0.694
Epoch: 2/5 -  Training Loss: 1.137 -  Validation Loss: 1.189 -  Validation Accuracy: 0.692
Epoch: 2/5 -  Training Loss: 1.224 -  Validation Loss: 0.825 -  Validation Accuracy: 0.760
Epoch: 3/5 -  Training Loss: 0.969 -  Validation Loss: 1.005 -  Validation Accuracy: 0.733
Epoch: 3/5 -  Training Loss: 0.881 -  Validation Loss: 1.012 -  Validation Accuracy: 0.721
Epoch: 3/5 -  Training Loss: 0.824 -  Validation Loss: 0.728 -  Validation Accuracy: 0.796
Epoch: 3/5 -  Training Loss: 0.932 -  Validation Loss: 0.617 -  Validation Accuracy: 0.826
Epoch: 3/5 -  Training Loss: 0.746 -  Validation Loss: 0.548 -  Validation Accuracy: 0.860
Epoch: 4/5 -  Training Loss: 0.724 -  Validation Loss: 0.523 -  Validation Accuracy: 0.850
Epoch: 4/5 -  Training Loss: 0.626 -  Validation Loss: 0.605 -  Validation Accuracy: 0.847
Epoch: 4/5 -  Training Loss: 0.746 -  Validation Loss: 0.593 -  Validation Accuracy: 0.829
Epoch: 4/5 -  Training Loss: 0.692 -  Validation Loss: 0.606 -  Validation Accuracy: 0.830
Epoch: 4/5 -  Training Loss: 0.597 -  Validation Loss: 0.410 -  Validation Accuracy: 0.892
Epoch: 5/5 -  Training Loss: 0.487 -  Validation Loss: 0.351 -  Validation Accuracy: 0.908
Epoch: 5/5 -  Training Loss: 0.477 -  Validation Loss: 0.503 -  Validation Accuracy: 0.883
Epoch: 5/5 -  Training Loss: 0.517 -  Validation Loss: 0.585 -  Validation Accuracy: 0.861
Epoch: 5/5 -  Training Loss: 0.532 -  Validation Loss: 0.465 -  Validation Accuracy: 0.878
Epoch: 5/5 -  Training Loss: 0.538 -  Validation Loss: 0.484 -  Validation Accuracy: 0.867
model: densenet169 - hidden layers: [1024] - epochs: 5 - lr: 0.001
Run time: 12.322 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 (4.899 to 2.655)	Decrease very quickly, saturating near 0 (3.709 to 0.202)	Decrease very quickly, saturating near 0 (3.604 to 0.484)
Total runtime	Longer (12.456 min)	Shorter (10.030 min)	Longer (12.322 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 very quickly with only a few epochs, meaning that the network only requires a few updates to converge since the weights are already pretrained.

Task 3

Performance on testing set

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

```
Testing Accuracy: 0.927
```

The testing accuracy is 0.927, which is about the same as the validation accuracy of 0.950, as found in Task 2. Hence, I believe that the model can be considered as generalizable.

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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: 4.300 -  Validation Loss: 3.896 -  Validation Accuracy: 0.113
Epoch: 1/10 -  Training Loss: 3.683 -  Validation Loss: 3.439 -  Validation Accuracy: 0.148
Epoch: 1/10 -  Training Loss: 3.450 -  Validation Loss: 3.210 -  Validation Accuracy: 0.190
Epoch: 1/10 -  Training Loss: 3.183 -  Validation Loss: 3.023 -  Validation Accuracy: 0.232
Epoch: 1/10 -  Training Loss: 2.988 -  Validation Loss: 2.960 -  Validation Accuracy: 0.213
Epoch: 2/10 -  Training Loss: 2.957 -  Validation Loss: 2.835 -  Validation Accuracy: 0.271
Epoch: 2/10 -  Training Loss: 2.922 -  Validation Loss: 2.736 -  Validation Accuracy: 0.275
Epoch: 2/10 -  Training Loss: 2.819 -  Validation Loss: 2.642 -  Validation Accuracy: 0.319
Epoch: 2/10 -  Training Loss: 2.648 -  Validation Loss: 2.572 -  Validation Accuracy: 0.321
Epoch: 2/10 -  Training Loss: 2.650 -  Validation Loss: 2.554 -  Validation Accuracy: 0.318
Epoch: 3/10 -  Training Loss: 2.634 -  Validation Loss: 2.550 -  Validation Accuracy: 0.313
Epoch: 3/10 -  Training Loss: 2.513 -  Validation Loss: 2.492 -  Validation Accuracy: 0.337
Epoch: 3/10 -  Training Loss: 2.495 -  Validation Loss: 2.457 -  Validation Accuracy: 0.350
Epoch: 3/10 -  Training Loss: 2.490 -  Validation Loss: 2.450 -  Validation Accuracy: 0.353
Epoch: 3/10 -  Training Loss: 2.528 -  Validation Loss: 2.393 -  Validation Accuracy: 0.372
Epoch: 4/10 -  Training Loss: 2.364 -  Validation Loss: 2.357 -  Validation Accuracy: 0.371
Epoch: 4/10 -  Training Loss: 2.446 -  Validation Loss: 2.323 -  Validation Accuracy: 0.391
Epoch: 4/10 -  Training Loss: 2.447 -  Validation Loss: 2.301 -  Validation Accuracy: 0.394
Epoch: 4/10 -  Training Loss: 2.282 -  Validation Loss: 2.380 -  Validation Accuracy: 0.368
Epoch: 4/10 -  Training Loss: 2.238 -  Validation Loss: 2.181 -  Validation Accuracy: 0.409
Epoch: 5/10 -  Training Loss: 2.200 -  Validation Loss: 2.282 -  Validation Accuracy: 0.385
Epoch: 5/10 -  Training Loss: 2.233 -  Validation Loss: 2.149 -  Validation Accuracy: 0.423
Epoch: 5/10 -  Training Loss: 2.146 -  Validation Loss: 2.185 -  Validation Accuracy: 0.430
Epoch: 5/10 -  Training Loss: 2.178 -  Validation Loss: 2.149 -  Validation Accuracy: 0.408
Epoch: 5/10 -  Training Loss: 2.180 -  Validation Loss: 2.136 -  Validation Accuracy: 0.447
Epoch: 6/10 -  Training Loss: 2.122 -  Validation Loss: 2.062 -  Validation Accuracy: 0.449
Epoch: 6/10 -  Training Loss: 2.065 -  Validation Loss: 2.047 -  Validation Accuracy: 0.463
Epoch: 6/10 -  Training Loss: 2.073 -  Validation Loss: 2.001 -  Validation Accuracy: 0.473
Epoch: 6/10 -  Training Loss: 1.995 -  Validation Loss: 2.023 -  Validation Accuracy: 0.454
Epoch: 6/10 -  Training Loss: 2.119 -  Validation Loss: 1.972 -  Validation Accuracy: 0.480
Epoch: 7/10 -  Training Loss: 2.064 -  Validation Loss: 2.058 -  Validation Accuracy: 0.451
Epoch: 7/10 -  Training Loss: 1.926 -  Validation Loss: 1.967 -  Validation Accuracy: 0.459
Epoch: 7/10 -  Training Loss: 1.924 -  Validation Loss: 1.993 -  Validation Accuracy: 0.472
Epoch: 7/10 -  Training Loss: 1.937 -  Validation Loss: 1.937 -  Validation Accuracy: 0.476
Epoch: 7/10 -  Training Loss: 1.900 -  Validation Loss: 1.925 -  Validation Accuracy: 0.502
Epoch: 8/10 -  Training Loss: 1.926 -  Validation Loss: 1.905 -  Validation Accuracy: 0.488
Epoch: 8/10 -  Training Loss: 1.839 -  Validation Loss: 1.852 -  Validation Accuracy: 0.506
Epoch: 8/10 -  Training Loss: 1.834 -  Validation Loss: 1.912 -  Validation Accuracy: 0.493
Epoch: 8/10 -  Training Loss: 1.911 -  Validation Loss: 1.855 -  Validation Accuracy: 0.526
Epoch: 8/10 -  Training Loss: 1.783 -  Validation Loss: 1.775 -  Validation Accuracy: 0.516
Epoch: 8/10 -  Training Loss: 1.774 -  Validation Loss: 1.807 -  Validation Accuracy: 0.528
Epoch: 9/10 -  Training Loss: 1.709 -  Validation Loss: 1.762 -  Validation Accuracy: 0.538
Epoch: 9/10 -  Training Loss: 1.666 -  Validation Loss: 1.746 -  Validation Accuracy: 0.540
Epoch: 9/10 -  Training Loss: 1.809 -  Validation Loss: 1.755 -  Validation Accuracy: 0.547
Epoch: 9/10 -  Training Loss: 1.738 -  Validation Loss: 1.772 -  Validation Accuracy: 0.543
Epoch: 9/10 -  Training Loss: 1.682 -  Validation Loss: 1.744 -  Validation Accuracy: 0.540
Epoch: 10/10 -  Training Loss: 1.705 -  Validation Loss: 1.753 -  Validation Accuracy: 0.547
Epoch: 10/10 -  Training Loss: 1.697 -  Validation Loss: 1.721 -  Validation Accuracy: 0.523
Epoch: 10/10 -  Training Loss: 1.642 -  Validation Loss: 1.643 -  Validation Accuracy: 0.572
Epoch: 10/10 -  Training Loss: 1.537 -  Validation Loss: 1.581 -  Validation Accuracy: 0.592
Epoch: 10/10 -  Training Loss: 1.655 -  Validation Loss: 1.648 -  Validation Accuracy: 0.572
model: custom - hidden layers: [1024] - epochs: 10 - lr: 0.001
Run time: 18.891 min
```

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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: 4.286 -  Validation Loss: 3.886 -  Validation Accuracy: 0.097
Epoch: 1/10 -  Training Loss: 3.644 -  Validation Loss: 3.438 -  Validation Accuracy: 0.149
Epoch: 1/10 -  Training Loss: 3.337 -  Validation Loss: 3.289 -  Validation Accuracy: 0.190
Epoch: 1/10 -  Training Loss: 3.133 -  Validation Loss: 3.001 -  Validation Accuracy: 0.213
Epoch: 1/10 -  Training Loss: 3.099 -  Validation Loss: 2.922 -  Validation Accuracy: 0.247
Epoch: 2/10 -  Training Loss: 2.881 -  Validation Loss: 2.805 -  Validation Accuracy: 0.260
Epoch: 2/10 -  Training Loss: 2.795 -  Validation Loss: 2.715 -  Validation Accuracy: 0.276
Epoch: 2/10 -  Training Loss: 2.784 -  Validation Loss: 2.660 -  Validation Accuracy: 0.312
Epoch: 2/10 -  Training Loss: 2.706 -  Validation Loss: 2.613 -  Validation Accuracy: 0.277
Epoch: 2/10 -  Training Loss: 2.543 -  Validation Loss: 2.529 -  Validation Accuracy: 0.320
Epoch: 3/10 -  Training Loss: 2.574 -  Validation Loss: 2.450 -  Validation Accuracy: 0.346
Epoch: 3/10 -  Training Loss: 2.456 -  Validation Loss: 2.413 -  Validation Accuracy: 0.358
Epoch: 3/10 -  Training Loss: 2.386 -  Validation Loss: 2.336 -  Validation Accuracy: 0.376
Epoch: 3/10 -  Training Loss: 2.419 -  Validation Loss: 2.388 -  Validation Accuracy: 0.378
Epoch: 3/10 -  Training Loss: 2.409 -  Validation Loss: 2.309 -  Validation Accuracy: 0.403
Epoch: 4/10 -  Training Loss: 2.348 -  Validation Loss: 2.200 -  Validation Accuracy: 0.428
Epoch: 4/10 -  Training Loss: 2.248 -  Validation Loss: 2.230 -  Validation Accuracy: 0.413
Epoch: 4/10 -  Training Loss: 2.212 -  Validation Loss: 2.213 -  Validation Accuracy: 0.406
Epoch: 4/10 -  Training Loss: 2.254 -  Validation Loss: 2.095 -  Validation Accuracy: 0.446
Epoch: 4/10 -  Training Loss: 2.122 -  Validation Loss: 2.050 -  Validation Accuracy: 0.481
Epoch: 5/10 -  Training Loss: 2.117 -  Validation Loss: 2.011 -  Validation Accuracy: 0.449
Epoch: 5/10 -  Training Loss: 2.060 -  Validation Loss: 1.964 -  Validation Accuracy: 0.479
Epoch: 5/10 -  Training Loss: 2.028 -  Validation Loss: 2.045 -  Validation Accuracy: 0.462
Epoch: 5/10 -  Training Loss: 1.969 -  Validation Loss: 1.928 -  Validation Accuracy: 0.500
Epoch: 5/10 -  Training Loss: 2.015 -  Validation Loss: 1.866 -  Validation Accuracy: 0.519
Epoch: 6/10 -  Training Loss: 1.940 -  Validation Loss: 1.818 -  Validation Accuracy: 0.497
Epoch: 6/10 -  Training Loss: 1.839 -  Validation Loss: 1.908 -  Validation Accuracy: 0.498
Epoch: 6/10 -  Training Loss: 1.911 -  Validation Loss: 1.831 -  Validation Accuracy: 0.512
Epoch: 6/10 -  Training Loss: 1.901 -  Validation Loss: 1.757 -  Validation Accuracy: 0.534
Epoch: 6/10 -  Training Loss: 1.873 -  Validation Loss: 1.789 -  Validation Accuracy: 0.513
Epoch: 7/10 -  Training Loss: 1.755 -  Validation Loss: 1.722 -  Validation Accuracy: 0.530
Epoch: 7/10 -  Training Loss: 1.821 -  Validation Loss: 1.828 -  Validation Accuracy: 0.517
Epoch: 7/10 -  Training Loss: 1.764 -  Validation Loss: 1.656 -  Validation Accuracy: 0.561
Epoch: 7/10 -  Training Loss: 1.719 -  Validation Loss: 1.680 -  Validation Accuracy: 0.553
Epoch: 7/10 -  Training Loss: 1.745 -  Validation Loss: 1.690 -  Validation Accuracy: 0.551
Epoch: 8/10 -  Training Loss: 1.758 -  Validation Loss: 1.562 -  Validation Accuracy: 0.576
Epoch: 8/10 -  Training Loss: 1.677 -  Validation Loss: 1.663 -  Validation Accuracy: 0.543
Epoch: 8/10 -  Training Loss: 1.590 -  Validation Loss: 1.518 -  Validation Accuracy: 0.580
Epoch: 8/10 -  Training Loss: 1.629 -  Validation Loss: 1.719 -  Validation Accuracy: 0.527
Epoch: 8/10 -  Training Loss: 1.580 -  Validation Loss: 1.620 -  Validation Accuracy: 0.583
Epoch: 8/10 -  Training Loss: 1.606 -  Validation Loss: 1.493 -  Validation Accuracy: 0.583
Epoch: 9/10 -  Training Loss: 1.388 -  Validation Loss: 1.505 -  Validation Accuracy: 0.580
Epoch: 9/10 -  Training Loss: 1.592 -  Validation Loss: 1.557 -  Validation Accuracy: 0.586
Epoch: 9/10 -  Training Loss: 1.526 -  Validation Loss: 1.474 -  Validation Accuracy: 0.623
Epoch: 9/10 -  Training Loss: 1.593 -  Validation Loss: 1.561 -  Validation Accuracy: 0.585
Epoch: 9/10 -  Training Loss: 1.515 -  Validation Loss: 1.457 -  Validation Accuracy: 0.620
Epoch: 10/10 -  Training Loss: 1.462 -  Validation Loss: 1.400 -  Validation Accuracy: 0.637
Epoch: 10/10 -  Training Loss: 1.389 -  Validation Loss: 1.459 -  Validation Accuracy: 0.627
Epoch: 10/10 -  Training Loss: 1.434 -  Validation Loss: 1.496 -  Validation Accuracy: 0.593
Epoch: 10/10 -  Training Loss: 1.449 -  Validation Loss: 1.466 -  Validation Accuracy: 0.602
Epoch: 10/10 -  Training Loss: 1.461 -  Validation Loss: 1.527 -  Validation Accuracy: 0.584
model: custom - hidden layers: [1024] - epochs: 10 - lr: 0.001
Run time: 18.831 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: 4.248 -  Validation Loss: 3.790 -  Validation Accuracy: 0.106
Epoch: 1/10 -  Training Loss: 3.676 -  Validation Loss: 3.355 -  Validation Accuracy: 0.182
Epoch: 1/10 -  Training Loss: 3.356 -  Validation Loss: 3.113 -  Validation Accuracy: 0.203
Epoch: 1/10 -  Training Loss: 3.245 -  Validation Loss: 3.086 -  Validation Accuracy: 0.206
Epoch: 1/10 -  Training Loss: 3.034 -  Validation Loss: 2.939 -  Validation Accuracy: 0.234
Epoch: 2/10 -  Training Loss: 2.733 -  Validation Loss: 2.710 -  Validation Accuracy: 0.292
Epoch: 2/10 -  Training Loss: 2.736 -  Validation Loss: 2.620 -  Validation Accuracy: 0.314
Epoch: 2/10 -  Training Loss: 2.704 -  Validation Loss: 2.744 -  Validation Accuracy: 0.273
Epoch: 2/10 -  Training Loss: 2.653 -  Validation Loss: 2.511 -  Validation Accuracy: 0.341
Epoch: 2/10 -  Training Loss: 2.550 -  Validation Loss: 2.298 -  Validation Accuracy: 0.374
Epoch: 3/10 -  Training Loss: 2.444 -  Validation Loss: 2.470 -  Validation Accuracy: 0.371
Epoch: 3/10 -  Training Loss: 2.369 -  Validation Loss: 2.199 -  Validation Accuracy: 0.434
Epoch: 3/10 -  Training Loss: 2.365 -  Validation Loss: 2.156 -  Validation Accuracy: 0.412
Epoch: 3/10 -  Training Loss: 2.253 -  Validation Loss: 2.120 -  Validation Accuracy: 0.438
Epoch: 3/10 -  Training Loss: 2.253 -  Validation Loss: 2.284 -  Validation Accuracy: 0.385
Epoch: 4/10 -  Training Loss: 2.218 -  Validation Loss: 1.980 -  Validation Accuracy: 0.492
Epoch: 4/10 -  Training Loss: 2.073 -  Validation Loss: 2.134 -  Validation Accuracy: 0.432
Epoch: 4/10 -  Training Loss: 2.025 -  Validation Loss: 2.074 -  Validation Accuracy: 0.453
Epoch: 4/10 -  Training Loss: 2.057 -  Validation Loss: 1.915 -  Validation Accuracy: 0.483
Epoch: 4/10 -  Training Loss: 1.951 -  Validation Loss: 1.866 -  Validation Accuracy: 0.485
Epoch: 5/10 -  Training Loss: 1.877 -  Validation Loss: 1.872 -  Validation Accuracy: 0.504
Epoch: 5/10 -  Training Loss: 1.892 -  Validation Loss: 1.760 -  Validation Accuracy: 0.540
Epoch: 5/10 -  Training Loss: 1.913 -  Validation Loss: 1.756 -  Validation Accuracy: 0.515
Epoch: 5/10 -  Training Loss: 1.856 -  Validation Loss: 1.749 -  Validation Accuracy: 0.501
Epoch: 5/10 -  Training Loss: 1.818 -  Validation Loss: 1.742 -  Validation Accuracy: 0.512
Epoch: 6/10 -  Training Loss: 1.719 -  Validation Loss: 1.618 -  Validation Accuracy: 0.568
Epoch: 6/10 -  Training Loss: 1.682 -  Validation Loss: 1.620 -  Validation Accuracy: 0.561
Epoch: 6/10 -  Training Loss: 1.723 -  Validation Loss: 1.645 -  Validation Accuracy: 0.552
Epoch: 6/10 -  Training Loss: 1.713 -  Validation Loss: 1.709 -  Validation Accuracy: 0.549
Epoch: 6/10 -  Training Loss: 1.654 -  Validation Loss: 1.707 -  Validation Accuracy: 0.550
Epoch: 7/10 -  Training Loss: 1.580 -  Validation Loss: 1.500 -  Validation Accuracy: 0.583
Epoch: 7/10 -  Training Loss: 1.483 -  Validation Loss: 1.699 -  Validation Accuracy: 0.567
Epoch: 7/10 -  Training Loss: 1.586 -  Validation Loss: 1.652 -  Validation Accuracy: 0.549
Epoch: 7/10 -  Training Loss: 1.619 -  Validation Loss: 1.508 -  Validation Accuracy: 0.585
Epoch: 7/10 -  Training Loss: 1.497 -  Validation Loss: 1.610 -  Validation Accuracy: 0.562
Epoch: 8/10 -  Training Loss: 1.546 -  Validation Loss: 1.464 -  Validation Accuracy: 0.614
Epoch: 8/10 -  Training Loss: 1.439 -  Validation Loss: 1.492 -  Validation Accuracy: 0.598
Epoch: 8/10 -  Training Loss: 1.410 -  Validation Loss: 1.355 -  Validation Accuracy: 0.630
Epoch: 8/10 -  Training Loss: 1.469 -  Validation Loss: 1.426 -  Validation Accuracy: 0.619
Epoch: 8/10 -  Training Loss: 1.431 -  Validation Loss: 1.318 -  Validation Accuracy: 0.639
Epoch: 8/10 -  Training Loss: 1.441 -  Validation Loss: 1.355 -  Validation Accuracy: 0.626
Epoch: 9/10 -  Training Loss: 1.304 -  Validation Loss: 1.256 -  Validation Accuracy: 0.652
Epoch: 9/10 -  Training Loss: 1.313 -  Validation Loss: 1.295 -  Validation Accuracy: 0.640
Epoch: 9/10 -  Training Loss: 1.297 -  Validation Loss: 1.339 -  Validation Accuracy: 0.642
Epoch: 9/10 -  Training Loss: 1.294 -  Validation Loss: 1.349 -  Validation Accuracy: 0.638
Epoch: 9/10 -  Training Loss: 1.447 -  Validation Loss: 1.391 -  Validation Accuracy: 0.608
Epoch: 10/10 -  Training Loss: 1.281 -  Validation Loss: 1.366 -  Validation Accuracy: 0.605
Epoch: 10/10 -  Training Loss: 1.148 -  Validation Loss: 1.215 -  Validation Accuracy: 0.683
Epoch: 10/10 -  Training Loss: 1.212 -  Validation Loss: 1.316 -  Validation Accuracy: 0.637
Epoch: 10/10 -  Training Loss: 1.239 -  Validation Loss: 1.217 -  Validation Accuracy: 0.661
Epoch: 10/10 -  Training Loss: 1.225 -  Validation Loss: 1.237 -  Validation Accuracy: 0.655
model: custom - hidden layers: [1024] - epochs: 10 - lr: 0.001
Run time: 18.842 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 (3.896 to 1.648)	Decrease more slowly (3.886 to 1.527)	Decrease least slowly (3.790 to 1.237)
Training and validation accuracy rate	Increase most slowly (0.113 to 0.572)	Increase more slowly (0.097 to 0.584)	Increase least slowly (0.106 to 0.655)
Total runtime	About the same (18.891 min)	About the same (18.831 min)	About the same (18.842 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 have larger receptive field and hence could better detect neighbouring parts and higher dimensional features for the class represented by each input image.

An increase in the number of convolutional layers does not appear to influence the total runtime because the total number of parameters in each extra layer according to what I defined is not a significantly large number. Furthermore, most of the model parameters are largely dominated by fully connected layers, so the difference in computation time due to extra convolutional layers will not be very noticeable.