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# Deep Learning

# Assignment 1

## the code

In this assignment, we built a neural network “from scratch”, using formulas and instructions learned in the lecture. The code is divided into 4 parts:

* **Forward propagation-** implementation of the forward propagation methods as learned in class. We modified the method L\_model\_forward to receive a Boolean parameter (“use\_dropout”) that supports dropout operation. We also added the method “apply\_dropout” to implement the dropout.
* **Backward propagation-** implementation of the backward propagation methods.
* **Building and running the network-** implementation of the L\_layer\_model and predict methods, as well as methods for splitting the data into train & validation subsets.
* **Main-** implementation of the ‘MNIST’ data preprocessing, running L\_layer\_model to build and train the model, running evaluation and plotting the validation loss information during training.

In the following sections we will show 4 configurations of the network and their performance. Then, we will compare their performances.

## network #1 configuration

|  |  |
| --- | --- |
| **parameter** | **value** |
| Network dimensions | [784, 20, 7, 5, 10] |
| Learning rate | 0.009 |
| Validation set size | 20% |
| Stopping criteria | No improvement (or a very small one) for 100 training steps |
| Batch size | 64 |
| Batchnorm | **False** (No batch normalization) |
| Stopping criteria epsilon | **0.0000001** |
| Dropout | **False** |

* Number of iterations and epochs that were needed to train the network: 6700 training steps and 7 epochs
* Final accuracy values:
  + Train- 0.839
  + Validation- 0.836
  + Test- 0.841
* Running time 18.825 sec
* Cost value for each 100 training steps:

Chart, line chart

Description automatically generated

The graph doesn’t show convergence of the cost value. Since the network is small and the number of training steps is restricted by a stopping condition that is applied to training steps rather than epochs, the network is not yet stable. The training stopped before convergence was achieved.

## network #2 configuration

|  |  |
| --- | --- |
| **parameter** | **value** |
| Network dimensions | [784, 20, 7, 5, 10] |
| Learning rate | 0.009 |
| Validation set size | 20% |
| Stopping criteria | No improvement (or a very small one) for 100 training steps |
| Batch size | 64 |
| Batchnorm | **True** (No batch normalization) |
| Stopping criteria epsilon | **0.000001** |
| Dropout | **False** |

* Number of iterations and epochs that were needed to train the network: 12700 training steps and 13 epochs
* Final accuracy values:
* Train- 0.943
* Validation- 0.938
* Test- 0.937
* Running time: 52.0699 sec
* Cost value for each 100 training steps: Chart

  Description automatically generated

Batch normalization helps the network to reach higher stability and therefore higher accuracy rate. It performs better than without batch norm, but it takes longer to train and requires more epochs during training. The graph shows convergence around 10000 training steps, and the cost is stabilized.

## network #3 configuration

|  |  |
| --- | --- |
| **parameter** | **value** |
| Network dimensions | [784, 20, 7, 5, 10] |
| Learning rate | 0.009 |
| Validation set size | 20% |
| Stopping criteria | No improvement (or a very small one) for 100 training steps |
| Batch size | 64 |
| Batchnorm | **False** (No batch normalization) |
| Stopping criteria epsilon | **0.0000001** |
| Dropout | **True, to\_keep=0.98** |

**Note:** We had to use a high “to\_keep” probability, otherwise the network’s neurons will be zeroed quickly.

* Number of iterations and epochs that were needed to train the network: 18700 training steps and 19 epochs
* Final accuracy values:
  + Train- 0.854
  + Validation- 0.851
  + Test- 0.856
* Running time 25.668 sec
* Cost value for each 100 training steps: Chart, histogram

  Description automatically generated

We can see that with no batch normalization the network isn’t stable at all. No batch norm was applied so the accuracy was relatively low but still higher than without dropout. Moreover, the dropout rate might be still too high with respect to the network size. This network configuration took longer to fit and achieved lower accuracy than network #2

## network #4 configuration

|  |  |
| --- | --- |
| **parameter** | **value** |
| Network dimensions | [784, 20, 7, 5, 10] |
| Learning rate | 0.009 |
| Validation set size | 20% |
| Stopping criteria | No improvement (or a very small one) for 100 training steps |
| Batch size | 64 |
| Batchnorm | **True** (No batch normalization) |
| Stopping criteria epsilon | **0.0000001** |
| Dropout | **True, to\_keep=0.98** |

**Note:** We had to use a high “to\_keep” probability, otherwise the network’s neurons will be zeroed quickly.

* Number of iterations and epochs that were needed to train the network: 24700 training steps and 25 epochs
* Final accuracy values:
  + Train- 0.958
  + Validation- 0.942
  + Test- 0.943
* Running time 44.001 sec
* Cost value for each 100 training steps: Chart

  Description automatically generated

Using batch normalization and dropout together yields the best performance of all 4 configurations. The network reaches the highest accuracy rate, and the validation cost value decreases in a stable manner. It is also the configuration that took the longest to run. The graph shows convergence after around 10000 training steps, but needs more training to reach the stopping condition.

## summary- comparison of the networks

After evaluating the 4 configurations shown above (with/without batch normalization, and with/without dropout) first, we can see that none of the configurations overfit. we can clearly see the importance of batch norm and dropout regularization methods. Both promote stability of the network and help with achieving high accuracy and a faster convergence even though the network is relatively small, and the stopping criterion prevents the network’s convergence in some of the configurations.

## Values from L\_layer\_model output

### configuration #1

* Training step #0, validation data: acc - 0.09358333333333334, cost - 2.770752990611641
* Training step #100, validation data: acc - 0.10041666666666667, cost - 2.742285546053009
* Training step #200, validation data: acc - 0.106, cost - 2.715463529265504
* Training step #300, validation data: acc - 0.11783333333333333, cost - 2.668997182379666
* Training step #400, validation data: acc - 0.14991666666666667, cost - 2.6113089003770757
* Training step #500, validation data: acc - 0.172, cost - 2.558495705271219
* Training step #600, validation data: acc - 0.18641666666666667, cost - 2.5139097357678644
* Training step #700, validation data: acc - 0.17966666666666667, cost - 2.4843197922150297
* Training step #800, validation data: acc - 0.19391666666666665, cost - 2.468467335754444
* Training step #900, validation data: acc - 0.19633333333333333, cost - 2.450106594169144
* Training step #1000, validation data: acc - 0.20216666666666666, cost - 2.442034460866693
* Training step #1100, validation data: acc - 0.20375, cost - 2.4336319264943147
* Training step #1200, validation data: acc - 0.20258333333333334, cost - 2.42953106927735
* Training step #1300, validation data: acc - 0.20808333333333334, cost - 2.4214774644299597
* Training step #1400, validation data: acc - 0.21, cost - 2.4188446198840943
* Training step #1500, validation data: acc - 0.20925, cost - 2.4130776483759955
* Training step #1600, validation data: acc - 0.21116666666666667, cost - 2.4111314548343397
* Training step #1700, validation data: acc - 0.211, cost - 2.4084791643337935
* Training step #1800, validation data: acc - 0.212, cost - 2.4035540480703808
* Training step #1900, validation data: acc - 0.21225, cost - 2.399719517102925
* Training step #2000, validation data: acc - 0.21358333333333332, cost - 2.3975475749296655
* Training step #2100, validation data: acc - 0.22116666666666668, cost - 2.39102149356728
* Training step #2200, validation data: acc - 0.22325, cost - 2.389752637885486
* Training step #2300, validation data: acc - 0.22833333333333333, cost - 2.3798739338922914
* Training step #2400, validation data: acc - 0.23908333333333334, cost - 2.3693272027381145
* Training step #2500, validation data: acc - 0.24941666666666668, cost - 2.3557524025505105
* Training step #2600, validation data: acc - 0.25675, cost - 2.340909184329027
* Training step #2700, validation data: acc - 0.2569166666666667, cost - 2.3272396148115937
* Training step #2800, validation data: acc - 0.27058333333333334, cost - 2.3031432494377175
* Training step #2900, validation data: acc - 0.28325, cost - 2.283385143089069
* Training step #3000, validation data: acc - 0.29425, cost - 2.2641311979183767
* Training step #3100, validation data: acc - 0.30091666666666667, cost - 2.2459839557271026
* Training step #3200, validation data: acc - 0.3134166666666667, cost - 2.229626747755553
* Training step #3300, validation data: acc - 0.3248333333333333, cost - 2.2182361272967146
* Training step #3400, validation data: acc - 0.3418333333333333, cost - 2.2003859360919464
* Training step #3500, validation data: acc - 0.3521666666666667, cost - 2.1858114832117517
* Training step #3600, validation data: acc - 0.34408333333333335, cost - 2.1672992069688006
* Training step #3700, validation data: acc - 0.34208333333333335, cost - 2.137225050789179
* Training step #3800, validation data: acc - 0.35183333333333333, cost - 2.0917006476554443
* Training step #3900, validation data: acc - 0.35891666666666666, cost - 2.0403676007251392
* Training step #4000, validation data: acc - 0.36425, cost - 1.9929894072027987
* Training step #4100, validation data: acc - 0.3606666666666667, cost - 1.951711577718993
* Training step #4200, validation data: acc - 0.3600833333333333, cost - 1.8959924428228236
* Training step #4300, validation data: acc - 0.42441666666666666, cost - 1.8054149159824378
* Training step #4400, validation data: acc - 0.5281666666666667, cost - 1.6653635821067065
* Training step #4500, validation data: acc - 0.6211666666666666, cost - 1.3916824877029386
* Training step #4600, validation data: acc - 0.6501666666666667, cost - 1.2388181229035424
* Training step #4700, validation data: acc - 0.6828333333333333, cost - 1.1536967726658067
* Training step #4800, validation data: acc - 0.6928333333333333, cost - 1.0982592790286696
* Training step #4900, validation data: acc - 0.7184166666666667, cost - 1.024797110518452
* Training step #5000, validation data: acc - 0.7281666666666666, cost - 0.9839752087192561
* Training step #5100, validation data: acc - 0.7393333333333333, cost - 0.9469572423113226
* Training step #5200, validation data: acc - 0.7493333333333333, cost - 0.9332662762998089
* Training step #5300, validation data: acc - 0.77, cost - 0.882712695019849
* Training step #5400, validation data: acc - 0.77025, cost - 0.869255835240704
* Training step #5500, validation data: acc - 0.7740833333333333, cost - 0.8512183508588974
* Training step #5600, validation data: acc - 0.7871666666666667, cost - 0.8193762714236897
* Training step #5700, validation data: acc - 0.796, cost - 0.796551275772585
* Training step #5800, validation data: acc - 0.7983333333333333, cost - 0.7867780131464973
* Training step #5900, validation data: acc - 0.8051666666666667, cost - 0.7797767512344415
* Training step #6000, validation data: acc - 0.8095, cost - 0.7547409620727239
* Training step #6100, validation data: acc - 0.8163333333333334, cost - 0.7425385729277313
* Training step #6200, validation data: acc - 0.81375, cost - 0.7512956798972067
* Training step #6300, validation data: acc - 0.8224166666666667, cost - 0.7058916876204451
* Training step #6400, validation data: acc - 0.832, cost - 0.6922146324249715
* Training step #6500, validation data: acc - 0.832, cost - 0.6761120493529916
* Training step #6600, validation data: acc - 0.835, cost - 0.669133749393999
* Training step #6700, validation data: acc - 0.8329166666666666, cost - 0.6736240105859654

### configuration #2

* Training step #0, validation data: acc - 0.11358333333333333, cost - 3.6134010985793514
* Training step #100, validation data: acc - 0.253, cost - 2.5350251735260527
* Training step #200, validation data: acc - 0.34008333333333335, cost - 2.3602724033156655
* Training step #300, validation data: acc - 0.37975, cost - 2.238450637839736
* Training step #400, validation data: acc - 0.4103333333333333, cost - 2.124267457220185
* Training step #500, validation data: acc - 0.4349166666666667, cost - 2.022113100282431
* Training step #600, validation data: acc - 0.45566666666666666, cost - 1.9466502146352547
* Training step #700, validation data: acc - 0.4756666666666667, cost - 1.864667258231921
* Training step #800, validation data: acc - 0.49233333333333335, cost - 1.7848854171002906
* Training step #900, validation data: acc - 0.50875, cost - 1.7198031005869325
* Training step #1000, validation data: acc - 0.5310833333333334, cost - 1.6562110662212672
* Training step #1100, validation data: acc - 0.5459166666666667, cost - 1.5919407909728998
* Training step #1200, validation data: acc - 0.5659166666666666, cost - 1.5220653452718271
* Training step #1300, validation data: acc - 0.5869166666666666, cost - 1.4536221620004308
* Training step #1400, validation data: acc - 0.6208333333333333, cost - 1.3833958678279872
* Training step #1500, validation data: acc - 0.6505833333333333, cost - 1.293737174052542
* Training step #1600, validation data: acc - 0.67825, cost - 1.2047802198009372
* Training step #1700, validation data: acc - 0.70725, cost - 1.116386454813579
* Training step #1800, validation data: acc - 0.7321666666666666, cost - 1.0376163715423348
* Training step #1900, validation data: acc - 0.7598333333333334, cost - 0.951685089363194
* Training step #2000, validation data: acc - 0.7789166666666667, cost - 0.8731207423161668
* Training step #2100, validation data: acc - 0.7955833333333333, cost - 0.8109370168160891
* Training step #2200, validation data: acc - 0.8148333333333333, cost - 0.7613539882201806
* Training step #2300, validation data: acc - 0.826, cost - 0.7103954534341571
* Training step #2400, validation data: acc - 0.8381666666666666, cost - 0.673921832337762
* Training step #2500, validation data: acc - 0.8475833333333334, cost - 0.6392723912166846
* Training step #2600, validation data: acc - 0.8620833333333333, cost - 0.5975265981156235
* Training step #2700, validation data: acc - 0.8676666666666667, cost - 0.5720428808727956
* Training step #2800, validation data: acc - 0.8700833333333333, cost - 0.5556023457730336
* Training step #2900, validation data: acc - 0.8769166666666667, cost - 0.5301871348205625
* Training step #3000, validation data: acc - 0.8775833333333334, cost - 0.5248402576562721
* Training step #3100, validation data: acc - 0.8878333333333334, cost - 0.49135587005621195
* Training step #3200, validation data: acc - 0.8855833333333333, cost - 0.49004198917053554
* Training step #3300, validation data: acc - 0.8895833333333333, cost - 0.48061844128606074
* Training step #3400, validation data: acc - 0.8909166666666667, cost - 0.4756219473515058
* Training step #3500, validation data: acc - 0.8938333333333334, cost - 0.4556556868972314
* Training step #3600, validation data: acc - 0.894, cost - 0.4549412032116719
* Training step #3700, validation data: acc - 0.8950833333333333, cost - 0.4502970649118617
* Training step #3800, validation data: acc - 0.8995, cost - 0.43702168314630807
* Training step #3900, validation data: acc - 0.9001666666666667, cost - 0.4291359315000751
* Training step #4000, validation data: acc - 0.9003333333333333, cost - 0.43670486461991337
* Training step #4100, validation data: acc - 0.906, cost - 0.4136962701941846
* Training step #4200, validation data: acc - 0.90375, cost - 0.4072044968652159
* Training step #4300, validation data: acc - 0.9061666666666667, cost - 0.40718919509445123
* Training step #4400, validation data: acc - 0.9045, cost - 0.403241554916135
* Training step #4500, validation data: acc - 0.9070833333333334, cost - 0.401420706695682
* Training step #4600, validation data: acc - 0.9081666666666667, cost - 0.3939908802535636
* Training step #4700, validation data: acc - 0.9071666666666667, cost - 0.39280432722220776
* Training step #4800, validation data: acc - 0.9116666666666666, cost - 0.38557239775112534
* Training step #4900, validation data: acc - 0.9089166666666667, cost - 0.3956705607470925
* Training step #5000, validation data: acc - 0.9108333333333334, cost - 0.38607013007060365
* Training step #5100, validation data: acc - 0.9076666666666666, cost - 0.38760893457702345
* Training step #5200, validation data: acc - 0.9135, cost - 0.37723735589938895
* Training step #5300, validation data: acc - 0.9125833333333333, cost - 0.37438883967969916
* Training step #5400, validation data: acc - 0.9131666666666667, cost - 0.37901213541456663
* Training step #5500, validation data: acc - 0.90925, cost - 0.3910058048202858
* Training step #5600, validation data: acc - 0.91675, cost - 0.3591985349984816
* Training step #5700, validation data: acc - 0.9170833333333334, cost - 0.3603543606044987
* Training step #5800, validation data: acc - 0.9154166666666667, cost - 0.3629439122663774
* Training step #5900, validation data: acc - 0.9178333333333333, cost - 0.35619356413563447
* Training step #6000, validation data: acc - 0.91775, cost - 0.35492694128964064
* Training step #6100, validation data: acc - 0.9204166666666667, cost - 0.3474156288437413
* Training step #6200, validation data: acc - 0.9191666666666667, cost - 0.35550513069445616
* Training step #6300, validation data: acc - 0.9208333333333333, cost - 0.34576905518429807
* Training step #6400, validation data: acc - 0.9191666666666667, cost - 0.35463002281723816
* Training step #6500, validation data: acc - 0.91775, cost - 0.3483891570582872
* Training step #6600, validation data: acc - 0.9185, cost - 0.3486062199689771
* Training step #6700, validation data: acc - 0.9221666666666667, cost - 0.34256324277284556
* Training step #6800, validation data: acc - 0.92275, cost - 0.3336267327232764
* Training step #6900, validation data: acc - 0.9225833333333333, cost - 0.33783218898786904
* Training step #7000, validation data: acc - 0.9206666666666666, cost - 0.34983675352157556
* Training step #7100, validation data: acc - 0.92375, cost - 0.3312055564676421
* Training step #7200, validation data: acc - 0.92475, cost - 0.3280106376638113
* Training step #7300, validation data: acc - 0.9253333333333333, cost - 0.32275252819055467
* Training step #7400, validation data: acc - 0.92525, cost - 0.33064208580234977
* Training step #7500, validation data: acc - 0.924, cost - 0.3286810134038824
* Training step #7600, validation data: acc - 0.9266666666666666, cost - 0.31871121134539193
* Training step #7700, validation data: acc - 0.9239166666666667, cost - 0.3247853307896677
* Training step #7800, validation data: acc - 0.925, cost - 0.3223279482785501
* Training step #7900, validation data: acc - 0.9244166666666667, cost - 0.3263850379273164
* Training step #8000, validation data: acc - 0.9239166666666667, cost - 0.3271531022481614
* Training step #8100, validation data: acc - 0.9259166666666667, cost - 0.3228102317276493
* Training step #8200, validation data: acc - 0.9276666666666666, cost - 0.3188893047426974
* Training step #8300, validation data: acc - 0.9296666666666666, cost - 0.31087035099684407
* Training step #8400, validation data: acc - 0.9283333333333333, cost - 0.3154024793907944
* Training step #8500, validation data: acc - 0.9255, cost - 0.32386509010918607
* Training step #8600, validation data: acc - 0.9281666666666667, cost - 0.3133330775596279
* Training step #8700, validation data: acc - 0.9290833333333334, cost - 0.30569940282251207
* Training step #8800, validation data: acc - 0.9325833333333333, cost - 0.29684459066914304
* Training step #8900, validation data: acc - 0.93, cost - 0.30968561749864704
* Training step #9000, validation data: acc - 0.9319166666666666, cost - 0.3033549381741628
* Training step #9100, validation data: acc - 0.933, cost - 0.3005714179053516
* Training step #9200, validation data: acc - 0.9306666666666666, cost - 0.300404326603407
* Training step #9300, validation data: acc - 0.93175, cost - 0.2974118369032741
* Training step #9400, validation data: acc - 0.9273333333333333, cost - 0.30981517121900365
* Training step #9500, validation data: acc - 0.9306666666666666, cost - 0.3039470982410301
* Training step #9600, validation data: acc - 0.9305, cost - 0.3020659535101903
* Training step #9700, validation data: acc - 0.9325, cost - 0.2997286599753767
* Training step #9800, validation data: acc - 0.93325, cost - 0.290476581234313
* Training step #9900, validation data: acc - 0.9331666666666667, cost - 0.29051646350774624
* Training step #10000, validation data: acc - 0.9298333333333333, cost - 0.29819943129737414
* Training step #10100, validation data: acc - 0.9364166666666667, cost - 0.288801816400711
* Training step #10200, validation data: acc - 0.93575, cost - 0.28476996440047464
* Training step #10300, validation data: acc - 0.9364166666666667, cost - 0.28083959140921044
* Training step #10400, validation data: acc - 0.9345, cost - 0.2890499177107568
* Training step #10500, validation data: acc - 0.93575, cost - 0.2852365670206963
* Training step #10600, validation data: acc - 0.9348333333333333, cost - 0.29018482910833165
* Training step #10700, validation data: acc - 0.9354166666666667, cost - 0.2784668476155063
* Training step #10800, validation data: acc - 0.9355, cost - 0.28511997412857
* Training step #10900, validation data: acc - 0.9321666666666667, cost - 0.2902693062302983
* Training step #11000, validation data: acc - 0.93075, cost - 0.29854303059646886
* Training step #11100, validation data: acc - 0.9335, cost - 0.28626702942565
* Training step #11200, validation data: acc - 0.9368333333333333, cost - 0.28223727296799583
* Training step #11300, validation data: acc - 0.9359166666666666, cost - 0.2761195860490194
* Training step #11400, validation data: acc - 0.9335, cost - 0.2866510266531724
* Training step #11500, validation data: acc - 0.9340833333333334, cost - 0.28284938469367077
* Training step #11600, validation data: acc - 0.9379166666666666, cost - 0.2714660590145386
* Training step #11700, validation data: acc - 0.9364166666666667, cost - 0.26876336160067954
* Training step #11800, validation data: acc - 0.9376666666666666, cost - 0.26570336619394386
* Training step #11900, validation data: acc - 0.9361666666666667, cost - 0.27172431077255405
* Training step #12000, validation data: acc - 0.9375833333333333, cost - 0.2735170471946124
* Training step #12100, validation data: acc - 0.9375833333333333, cost - 0.2775080413058573
* Training step #12200, validation data: acc - 0.9364166666666667, cost - 0.26853745671434975
* Training step #12300, validation data: acc - 0.9368333333333333, cost - 0.2726578020165967
* Training step #12400, validation data: acc - 0.9334166666666667, cost - 0.28114985900413975
* Training step #12500, validation data: acc - 0.9308333333333333, cost - 0.2959463673461915
* Training step #12600, validation data: acc - 0.935, cost - 0.2742323520258387
* Training step #12700, validation data: acc - 0.9371666666666667, cost - 0.26632980436109016

### configuration #3

* Training step #0, validation data: acc - 0.0935, cost - 2.772072319291518
* Training step #100, validation data: acc - 0.10091666666666667, cost - 2.743182462026687
* Training step #200, validation data: acc - 0.10591666666666667, cost - 2.718053100438112
* Training step #300, validation data: acc - 0.1185, cost - 2.674846482237294
* Training step #400, validation data: acc - 0.14933333333333335, cost - 2.6240112697854725
* Training step #500, validation data: acc - 0.16941666666666666, cost - 2.5751285649670543
* Training step #600, validation data: acc - 0.18333333333333332, cost - 2.5315975429582647
* Training step #700, validation data: acc - 0.17625, cost - 2.501251183061635
* Training step #800, validation data: acc - 0.191, cost - 2.482721072141619
* Training step #900, validation data: acc - 0.1935, cost - 2.467172288966003
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* Training step #1200, validation data: acc - 0.20116666666666666, cost - 2.4465711709318088
* Training step #1300, validation data: acc - 0.2065, cost - 2.4395692606661856
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### configuration #4

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