Lab 1. PyTorch and ANNs

This lab is a warm up to get you used to the PyTorch programming environment used in the course, and also to help you review and renew your knowledge of Python and relevant Python libraries. The lab must be done individually. Please recall that the University of Toronto plagarism rules apply.

By the end of this lab, you should be able to:

1. Be able to perform basic PyTorch tensor operations.
2. Be able to load data into PyTorch
3. Be able to configure an Artificial Neural Network (ANN) using PyTorch
4. Be able to train ANNs using PyTorch
5. Be able to evaluate different ANN configuations

You will need to use numpy and PyTorch documentations for this assignment:

- https://docs.scipy.org/doc/numpy/reference/
- https://pytorch.org/docs/stable/torch.html

You can also reference Python API documentations freely.

What to submit

Submit a PDF file containing all your code, outputs, and write-up from parts 1-5. You can produce a PDF of your Google Colab file by going to `File -> Print` and then save as PDF. The Colab instructions has more information.

Do not submit any other files produced by your code.

Include a link to your colab file in your submission.

Please use Google Colab to complete this assignment. If you want to use Jupyter Notebook, please complete the assignment and upload your Jupyter Notebook file to Google Colab for submission.

Adjust the scaling to ensure that the text is not cutoff at the margins.

Colab Link

Submit make sure to include a link to your colab file here

Colab Link: https://colab.research.google.com/drive/1IKVgAzUwmi91bLcUrRjHmfCnEnjEBfcx?usp=sharing

Part 1. Python Basics [3 pt]

The purpose of this section is to get you used to the basics of Python, including working with functions, numbers, lists, and strings.

Note that we **will** be checking your code for clarity and efficiency.

If you have trouble with this part of the assignment, please review http://cs231n.github.io/python-numpy-tutorial/

Part (a) -- 1pt

Write a function `sum_of_cubes` that computes the sum of cubes up to `n`. If the input to `sum_of_cubes` invalid (e.g. negative or non-integer `n`), the function should print out `"Invalid input"` and return `-1`.

In [ ]:
```
def sum_of_cubes(n):
    if n < 0 or isinstance(n, int) == False:
        print("Invalid input")
        return -1
    else:
        total = 0
        for i in range(n,0,-1):
            sum = i**3
            total = total + sum
    return total

print(sum_of_cubes(3))
print(sum_of_cubes(9.9))
print(sum_of_cubes(-3))
```

```
36
Invalid input
-1
Invalid input
-1
```

Part (b) -- 1pt

Write a function `word_lengths` that takes a sentence (string), computes the length of each word in that sentence, and returns the length of each word in a list. You can assume that words are always separated by a space character `" "`.

Hint: recall the `str.split` function in Python. If you arenot sure how this function works, try typing `help(str.split)` into a Python shell, or check out https://docs.python.org/3.6/library/stdtypes.html#str.split

In [ ]:
```
help(str.split)
```

```
Help on method_descriptor:

split(self, /, sep=None, maxsplit=-1)
    Return a list of the substrings in the string, using sep as the separator strin
g.

      sep
        The separator used to split the string.

        When set to None (the default value), will split on any whitespace
        character (including \\n \\r \\t \\f and spaces) and will discard
        empty strings from the result.
      maxsplit
        Maximum number of splits (starting from the left).
        -1 (the default value) means no limit.

    Note, str.split() is mainly useful for data that has been intentionally
    delimited.  With natural text that includes punctuation, consider using
    the regular expression module.
```

In [ ]:
```
def word_lengths(sentence):
    sentence_list = sentence.split()
    length_list = []

    for i in range(len(sentence_list)):
      length_list.append(len(sentence_list[i]))

    return length_list
    """Return a list containing the length of each word in
    sentence.


    >>> word_lengths("welcome to APS360!")
    [7, 2, 7]
    >>> word_lengths("machine learning is so cool")
    [7, 8, 2, 2, 4]
    """

word_lengths("machine learning is so cool")
```

Out[ ]:
```
[7, 8, 2, 2, 4]
```

Part (c) -- 1pt

Write a function `all_same_length` that takes a sentence (string), and checks whether every word in the string is the same length. You should call the function `word_lengths` in the body of this new function.

In [ ]:
```
def all_same_length(sentence):
    word_list = sentence.split()
    length = len(word_list[0])
    for i in range(len(word_list)):
        if length != len(word_list[i]):
          return False
    return True

    """Return True if every word in sentence has the same
    length, and False otherwise.

    >>> all_same_length("all same length")
    False
    >>> word_lengths("hello world")
    True
    """
all_same_length("yap yap yap yap")
```

Out[ ]:
```
True
```

Part 2. NumPy Exercises [5 pt]

In this part of the assignment, you'll be manipulating arrays usign NumPy. Normally, we use the shorter name `np` to represent the package `numpy`.

In [ ]:
```
import numpy as np
```

Part (a) -- 1pt

The below variables `matrix` and `vector` are numpy arrays. Explain what you think `<NumpyArray>.size` and `<NumpyArray>.shape` represent.

In [ ]:
```
matrix = np.array([[1., 2., 3., 0.5],
                   [4., 5., 0., 0.],
                   [-1., -2., 1., 1.]])
vector = np.array([2., 0., 1., -2.])
```

In [ ]:
```
matrix.size
```

Out[ ]:
```
12
```

In [ ]:
```
matrix.shape
```

Out[ ]:
```
(3, 4)
```

```
In [ ]: vector.size
```

```
Out[ ]: 4
```

```
In [ ]: vector.shape
```

```
Out[ ]: (4,)
```

NumpyArray.size represents the total number of elements in the array.

NumpyArray.shape represents column and row size of an array in a tuple.

Part (b) -- 1pt

Perform matrix multiplication `output = matrix x vector` by using for loops to iterate through the columns and rows. Do not use any builtin NumPy functions. Cast your output into a NumPy array, if it isn't one already.

Hint: be mindful of the dimension of output

```
In [ ]: output = []

        for j in range(len(matrix)): # row size 3
          value = 0
          total = 0
          for i in range(len(matrix[0])): # column size 4
            value = matrix[j][i] * vector[i]
            total += value
          output.append(total)
```

```
In [ ]: print(output)
```

```
[4.0, 8.0, -3.0]
```

Part (c) -- 1pt

Perform matrix multiplication `output2 = matrix x vector` by using the function `numpy.dot`.

We will never actually write code as in part(c), not only because `numpy.dot` is more concise and easier to read/write, but also performance-wise `numpy.dot` is much faster (it is written in C and highly optimized). In general, we will avoid for loops in our code.

```
In [ ]: output2 = None
```

```
In [ ]: output2 = np.dot(matrix, vector)
        print(output2)
```

```
[ 4.  8. -3.]
```

Part (d) -- 1pt

As a way to test for consistency, show that the two outputs match.

In [ ]:
```
for i in range(len(output)):
  if output[i] == output2[i]:
      true = 1
  else:
    true = 0

if(true):
    print("The two outputs match")

else:
  print("The two outputs are different")
```

```
The two outputs match
```

Part (e) -- 1pt

Show that using `np.dot` is faster than using your code from part (c).

You may find the below code snippit helpful:

In [ ]:
```
# @title
import time

# record the time before running code
start_time = time.time()

# place code to run here
for i in range(10000):
    99*99

# record the time after the code is run
end_time = time.time()

# compute the difference
diff = end_time - start_time
```

In [ ]:
```
import time

# without numpy
# record the time before running code
start_time_no_numpy = time.time()

# place code to run here
output = []
for j in range(len(matrix)): # row size 3
  value = 0
  total = 0
  for i in range(len(matrix[0])): # column size 4
    value = matrix[j][i] * vector[i]
    total += value
  output.append(total)
# record the time after the code is run
end_time_no_numpy = time.time()

# with numpy
# record the time before running code
start_time_numpy = time.time()

# place code to run here
output2 = []
output2 = np.dot(matrix, vector)
# record the time after the code is run
end_time_numpy = time.time()

# compute the difference
diff_no_numpy = end_time_no_numpy - start_time_no_numpy
diff_with_numpy = end_time_numpy - start_time_numpy

print('The time without using Numpy is: ' + str(diff_no_numpy) + '. The time using
```

```
The time without using Numpy is: 0.0002930164337158203. The time using Numpy is: 0.0
0018668174743652344
```

Part 3. Images [6 pt]

A picture or image can be represented as a NumPy array of "pixels", with dimensions H × W × C, where H is the height of the image, W is the width of the image, and C is the number of colour channels. Typically we will use an image with channels that give the the Red, Green, and Blue "level" of each pixel, which is referred to with the short form RGB.

You will write Python code to load an image, and perform several array manipulations to the image and visualize their effects.

In [ ]:
```
import matplotlib.pyplot as plt
```

Part (a) -- 1 pt

This is a photograph of a dog whose name is Mochi.

alt text

Load the image from its url (https://drive.google.com/uc?export=view&id=1oaLVR2hr1_qzpKQ47i9rVUIklwbDcews) into the variable `img` using the `plt.imread` function.

Hint: You can enter the URL directly into the `plt.imread` function as a Python string.

In [ ]:
```
import urllib.request
from PIL import Image
```

```
urllib.request.urlretrieve(
  'https://drive.google.com/uc?export=view&id=1oaLVR2hr1_qzpKQ47i9rVUIklwbDcews',
   "mochi.png")

img = Image.open("mochi.png")
```

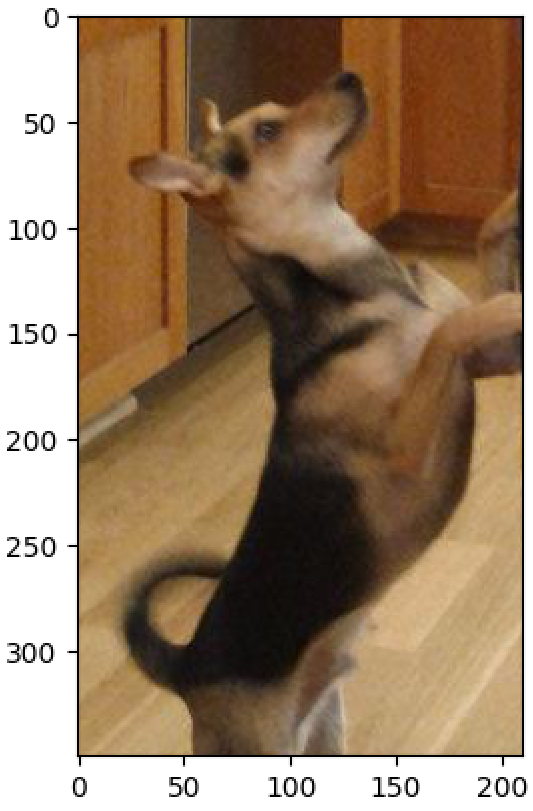
Part (b) -- 1pt

Use the function `plt.imshow` to visualize `img`.

This function will also show the coordinate system used to identify pixels. The origin is at the top left corner, and the first dimension indicates the Y (row) direction, and the second dimension indicates the X (column) dimension.

In [ ]:
```
plt.imshow(img)
```

Out[ ]:
```
<matplotlib.image.AxesImage at 0x7b95b43425f0>
```

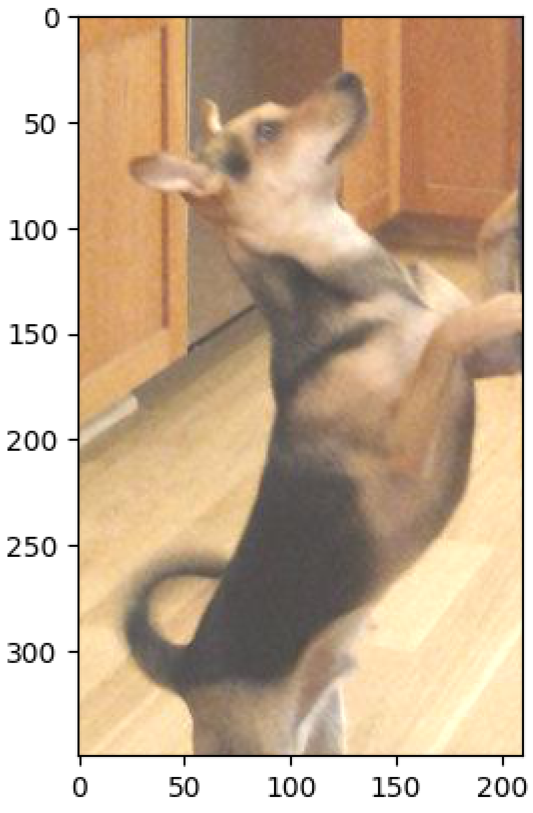


Part (c) -- 2pt

Modify the image by adding a constant value of 0.25 to each pixel in the `img` and store the result in the variable `img_add`. Note that, since the range for the pixels needs to be between [0, 1], you will also need to clip img_add to be in the range [0, 1] using `numpy.clip`. Clipping sets any value that is outside of the desired range to the closest endpoint. Display the image using `plt.imshow`.

In [ ]:
```python
img_add = None

# converts mochi_img to array
mochi_array = np.array(img)

# changes pixel range to [0,1]
mochi_array  = np.dot(mochi_array, 1/255)

# add 0.25
img_add_array = np.add(mochi_array, 0.25)

# clip pixel to valid range
img_add = np.clip(img_add_array, 0, 1)

plt.imshow(img_add)
```

Out[ ]:
```
<matplotlib.image.AxesImage at 0x7b95b424d600>
```



Part (d) -- 2pt

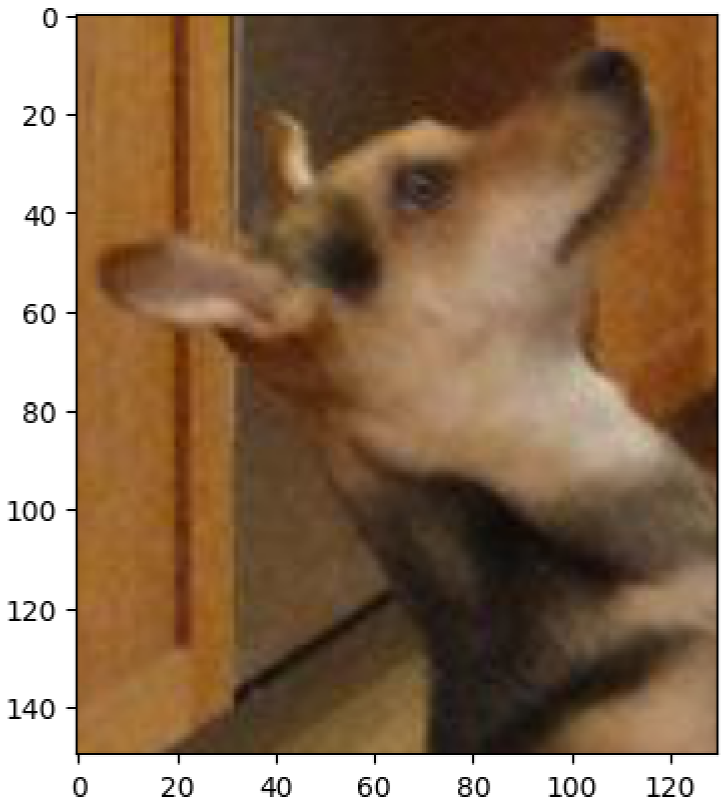
Crop the **original** image (`img` variable) to a 130 x 150 image including Mochi's face. Discard the alpha colour channel (i.e. resulting `img_cropped` should **only have RGB channels**)

Display the image.

In [ ]:
```python
img = np.array(img)
img_cropped = img[20:170, 20:150, :3]
```

```
plt.imshow(img_cropped)
```

```
Out[ ]: <matplotlib.image.AxesImage at 0x7b95b42ca590>
```



Part 4. Basics of PyTorch [6 pt]

PyTorch is a Python-based neural networks package. Along with tensorflow, PyTorch is currently one of the most popular machine learning libraries.

PyTorch, at its core, is similar to Numpy in a sense that they both try to make it easier to write codes for scientific computing achieve improved performance over vanilla Python by leveraging highly optimized C back-end. However, compare to Numpy, PyTorch offers much better GPU support and provides many high-level features for machine learning. Technically, Numpy can be used to perform almost every thing PyTorch does. However, Numpy would be a lot slower than PyTorch, especially with CUDA GPU, and it would take more effort to write machine learning related code compared to using PyTorch.

```
In [ ]: import torch
```

Part (a) -- 1 pt

Use the function `torch.from_numpy` to convert the numpy array `img_cropped` into a PyTorch tensor. Save the result in a variable called `img_torch`.

```
In [ ]: img_torch = None
        img_torch = torch.from_numpy(img_cropped)
```

Part (b) -- 1pt

Use the method `<Tensor>.shape` to find the shape (dimension and size) of `img_torch`.

```
In [ ]: import tensorflow as tf
        tf.shape(img_torch)

Out[ ]: <tf.Tensor: shape=(3,), dtype=int32, numpy=array([150, 130,   3], dtype=int32)>
```

Part (c) -- 1pt

How many floating-point numbers are stored in the tensor `img_torch`?

```
In [ ]: print(img_torch.nelement())

58500
```

Part (d) -- 1 pt

What does the code `img_torch.transpose(0,2)` do? What does the expression return? Is the original variable `img_torch` updated? Explain.

```
In [ ]: img_torch.transpose(0,2)
        tf.shape(img_torch.transpose(0,2))
        print(tf.shape(img_torch))
        # this expression returns the transposed verion of img_torch, where diemensions 0 a
        # so instead of [Width Length Channel] it's now [Channel Length Width]
        # the expression returns [3, 130, 150]
        # the original expression returns [150, 130, 3]
        # the original vaiable img_torch is not updated

tf.Tensor([150 130   3], shape=(3,), dtype=int32)
```

Part (e) -- 1 pt

What does the code `img_torch.unsqueeze(0)` do? What does the expression return? Is the original variable `img_torch` updated? Explain.

```
In [ ]: print(tf.shape(img_torch.unsqueeze(0)))
        print(tf.shape(img_torch))

        # An additional dimension has been added to the tensor at the zeroeth dimension
        # the original img_torch is not updated

tf.Tensor([  1 150 130   3], shape=(4,), dtype=int32)
tf.Tensor([150 130   3], shape=(3,), dtype=int32)
```

Part (f) -- 1 pt

Find the maximum value of `img_torch` along each colour channel? Your output should be a one-dimensional PyTorch tensor with exactly three values.

Hint: lookup the function `torch.max`.

In [ ]:
```
max_values = img_torch.max(dim=0).values.max(dim=0).values
print(max_values)
```

```
tensor([228, 201, 172], dtype=torch.uint8)
```

Part 5. Training an ANN [10 pt]

The sample code provided below is a 2-layer ANN trained on the MNIST dataset to identify digits less than 3 or greater than and equal to 3. Modify the code by changing any of the following and observe how the accuracy and error are affected:

- number of training iterations
- number of hidden units
- numbers of layers
- types of activation functions
- learning rate

Please select at least three different options from the list above. For each option, please select two to three different parameters and provide a table.

In [ ]:
```
import torch
import torch.nn as nn
import torch.nn.functional as F
from torchvision import datasets, transforms
import matplotlib.pyplot as plt # for plotting
import torch.optim as optim

torch.manual_seed(1) # set the random seed

# define a 2-layer artificial neural network
class Pigeon(nn.Module):
    def __init__(self):
        super(Pigeon, self).__init__()
        self.layer1 = nn.Linear(28 * 28, 30) # used 300 and 3000 for second paramet
        self.layer2 = nn.Linear(30, 1)
    def forward(self, img):
        flattened = img.view(-1, 28 * 28)
        activation1 = self.layer1(flattened)
        activation1 = F.relu(activation1) # used softplus and silu
        activation2 = self.layer2(activation1)
        return activation2

pigeon = Pigeon()
```

```python
# load the data
mnist_data = datasets.MNIST('data', train=True, download=True)
mnist_data = list(mnist_data)
mnist_train = mnist_data[:1000]
mnist_val   = mnist_data[1000:2000]
img_to_tensor = transforms.ToTensor()


# simplified training code to train `pigeon` on the "small digit recognition" task
criterion = nn.BCEWithLogitsLoss()
optimizer = optim.SGD(pigeon.parameters(), lr=0.005, momentum=0.9)

for i in range(0,3): # increases training iteration
  for (image, label) in mnist_train:
      # actual ground truth: is the digit less than 3?
      actual = torch.tensor(label < 3).reshape([1,1]).type(torch.FloatTensor)
      # pigeon prediction
      out = pigeon(img_to_tensor(image)) # step 1-2
      # update the parameters based on the loss
      loss = criterion(out, actual)      # step 3
      loss.backward()                    # step 4 (compute the updates for each par
      optimizer.step()                   # step 4 (make the updates for each parame
      optimizer.zero_grad()              # a clean up step for PyTorch

# computing the error and accuracy on the training set
error = 0
for (image, label) in mnist_train:
    prob = torch.sigmoid(pigeon(img_to_tensor(image)))
    if (prob < 0.5 and label < 3) or (prob >= 0.5 and label >= 3):
        error += 1
print("Training Error Rate:", error/len(mnist_train))
print("Training Accuracy:", 1 - error/len(mnist_train))


# computing the error and accuracy on a test set
error = 0
for (image, label) in mnist_val:
    prob = torch.sigmoid(pigeon(img_to_tensor(image)))
    if (prob < 0.5 and label < 3) or (prob >= 0.5 and label >= 3):
        error += 1
print("Test Error Rate:", error/len(mnist_val))
print("Test Accuracy:", 1 - error/len(mnist_val))
```

```
Downloading http://yann.lecun.com/exdb/mnist/train-images-idx3-ubyte.gz
Failed to download (trying next):
HTTP Error 403: Forbidden

Downloading https://ossci-datasets.s3.amazonaws.com/mnist/train-images-idx3-ubyte.gz
Downloading https://ossci-datasets.s3.amazonaws.com/mnist/train-images-idx3-ubyte.gz
to data/MNIST/raw/train-images-idx3-ubyte.gz
100%|██████████| 9912422/9912422 [00:00<00:00, 51321512.50it/s]
```

```
Extracting data/MNIST/raw/train-images-idx3-ubyte.gz to data/MNIST/raw

Downloading http://yann.lecun.com/exdb/mnist/train-labels-idx1-ubyte.gz
Failed to download (trying next):
HTTP Error 403: Forbidden

Downloading https://ossci-datasets.s3.amazonaws.com/mnist/train-labels-idx1-ubyte.gz
Downloading https://ossci-datasets.s3.amazonaws.com/mnist/train-labels-idx1-ubyte.gz
to data/MNIST/raw/train-labels-idx1-ubyte.gz
100%|██████████| 28881/28881 [00:00<00:00, 1765594.80it/s]
Extracting data/MNIST/raw/train-labels-idx1-ubyte.gz to data/MNIST/raw

Downloading http://yann.lecun.com/exdb/mnist/t10k-images-idx3-ubyte.gz
Failed to download (trying next):
HTTP Error 403: Forbidden

Downloading https://ossci-datasets.s3.amazonaws.com/mnist/t10k-images-idx3-ubyte.gz
Downloading https://ossci-datasets.s3.amazonaws.com/mnist/t10k-images-idx3-ubyte.gz
to data/MNIST/raw/t10k-images-idx3-ubyte.gz
100%|██████████| 1648877/1648877 [00:00<00:00, 14378391.73it/s]
Extracting data/MNIST/raw/t10k-images-idx3-ubyte.gz to data/MNIST/raw

Downloading http://yann.lecun.com/exdb/mnist/t10k-labels-idx1-ubyte.gz
Failed to download (trying next):
HTTP Error 403: Forbidden

Downloading https://ossci-datasets.s3.amazonaws.com/mnist/t10k-labels-idx1-ubyte.gz
Downloading https://ossci-datasets.s3.amazonaws.com/mnist/t10k-labels-idx1-ubyte.gz
to data/MNIST/raw/t10k-labels-idx1-ubyte.gz
100%|██████████| 4542/4542 [00:00<00:00, 2271164.61it/s]
Extracting data/MNIST/raw/t10k-labels-idx1-ubyte.gz to data/MNIST/raw

Training Error Rate: 0.014
Training Accuracy: 0.986
Test Error Rate: 0.069
Test Accuracy: 0.931
```

Number of Hidden Layers	Training Error Rate	Training Accuracy	Test Error Rate	Test Accuracy
30	0.036	0.964	0.079	0.921
300	0.023	0.977	0.071	0.929
3000	0.015	0.985	0.062	0.938

Changing Activation Functions	Training Error Rate	Training Accuracy	Test Error Rate	Test Accuracy
ReLU	0.036	0.964	0.079	0.921
SoftPlus	0.056	0.944	0.116	0.884
SiLU	0.04	0.96	0.085	0.915

Training Iterations	Training Error Rate	Training Accuracy	Test Error Rate	Test Accuracy
1	0.036	0.964	0.079	0.921
2	0.016	0.984	0.057	0.943
3	0.014	0.986	0.069	0.931

Part (a) -- 3 pt

Comment on which of the above changes resulted in the best accuracy on training data? What accuracy were you able to achieve?

By changing the number of training iterations to 3 instead of 1, I was able to achieve a training accuracy of 0.986

Part (b) -- 3 pt

Comment on which of the above changes resulted in the best accuracy on testing data? What accuracy were you able to achieve?

By changing the number of training iterations, the testing data accuracy increased, the best accuracy is 0.943 during the second iteration

Part (c) -- 4 pt

Which model hyperparameters should you use, the ones from (a) or (b)?

Since both of my results show that the number of iterations improve both training and testing accuracy the most, I would stick to changing the number of training iterations if it's the only parameter that I can change.