In [1]:
```
import numpy as np
import matplotlib.pyplot as plt
import pandas as pd
from numpy import random
import time
from sklearn import *
```

In [2]:
```
from mnist import MNIST

mndata = MNIST(r"C:\Users\kalya\OneDrive - University of Illinois at Chicago\!UIC\!Semesters\2nd Sem\Courses
\CS 559 NN\Homeworks\HW2\Q2\data\t")

xtrain, ytrain = mndata.load_training()
xtest, ytest = mndata.load_testing()
xtrain = np.reshape(xtrain,(60000,784))
xtest = np.reshape(xtest,(10000,784))
ytrain = np.reshape(ytrain,(60000,1))
ytest = np.reshape(ytest,(10000,1))
xtrain = (xtrain)/255
xtest = (xtest)/255
xtrain.shape
```

Out[2]:
```
(60000, 784)
```

In [3]:
```
x_train = []
x_test = []
for i in range(len(xtrain)):
    x_train.append(np.append(xtrain[i],1))

for i in range(len(xtest)):
    x_test.append(np.append(xtest[i],1))
x_train = np.asarray(x_train)
x_test = np.asarray(x_test)
```

In [4]:
```
# x_test1 = pd.DataFrame(data = x_test.reshape(len(x_test),785))
# ytest1 = pd.DataFrame(data = ytest.reshape(len(ytest),1))
```

In [5]:
```
# x_test1.head()
```

In [6]:
```
# x=[1,1]
# np.linalg.norm(x)
```

In [7]:
```
ytrain
```

Out[7]:
```
array([[5],
       [0],
       [4],
       ...,
       [5],
       [6],
       [8]], dtype=uint8)
```

In [20]:
```
# x =[[0,1, 1],[1,0, 0],[1,1, 0], [0,0, 0]]
# y=[4,1,2,3]
# x = np.asarray(x)
# y = np.asarray(y)

d = np.zeros(shape = (len(xtrain),10))

for i in range(len(ytrain)):
    d[i][ytrain[i]] = 1

dt = np.zeros(shape = (len(xtest),10))
for i in range(len(ytest)):
    dt[i][ytest[i]] = 1

# d = np.zeros(shape = (len(x),10))
# for i in range(len(y)):
#     d[i][y[i]] = 1
# xtrain = x
# xtrain
d[0]
```

Out[20]:
```
array([0., 0., 0., 0., 0., 1., 0., 0., 0., 0.])
```

In [21]:
```
# # # d = np.zeros(shape = (len(xtrain),10))
# # # for i in range(len(ytrain)):
# # #     d[i][ytrain[i]] = 1

# # # dt = np.zeros(shape = (len(xtest),10))
# # # for i in range(len(ytest)):
# # #     dt[i][ytest[i]] = 1

# # #w = random.normal(size = (10,784))

# d = np.zeros(shape = (len(xtrain)))
# for i in range(len(ytrain)):
#     d[i] = ytrain[i][0]

# dt = np.zeros(shape = (len(xtest)))
# for i in range(len(ytest)):
#     dt[i] = ytest[i][0]
```

In [22]:
```
d
```

Out[22]:
```
array([[0., 0., 0., ..., 0., 0., 0.],
       [1., 0., 0., ..., 0., 0., 0.],
       [0., 0., 0., ..., 0., 0., 0.],
       ...,
       [0., 0., 0., ..., 0., 0., 0.],
       [0., 0., 0., ..., 0., 0., 0.],
       [0., 0., 0., ..., 0., 1., 0.]])
```

In [23]:
```
a = [[1.5, 2.5], [2.6, 3.3]]
np.around(a)
```

Out[23]:
```
array([[2., 2.],
       [3., 3.]])
```

In [24]:
```
# weights = np.random.uniform(low =-2, high = 2, size = (784, 60000))
# np.matmul(weights, x_train)
```

In [25]:
```
d
```

Out[25]:
```
array([[0., 0., 0., ..., 0., 0., 0.],
       [1., 0., 0., ..., 0., 0., 0.],
       [0., 0., 0., ..., 0., 0., 0.],
       ...,
       [0., 0., 0., ..., 0., 0., 0.],
       [0., 0., 0., ..., 0., 0., 0.],
       [0., 0., 0., ..., 0., 1., 0.]])
```

In [26]:
```
# t = np.asarray([1,2,3])*(np.asarray([4,5,6]))
# t
```

In [232]:
```
a=np.asarray([[1,2,3], [4,5,6]])
print(a[:-1])
c = np.asarray([[7,8,9]])
b =np.append(a,c, axis=0)
b
```

```
[[1 2 3]]
```

Out[232]:
```
array([[1, 2, 3],
       [4, 5, 6],
       [7, 8, 9]])
```

In [427]:
```
class Neural_Network():

    def __init__(self, x=[[]], y=[], p=[[]], q=[], nHiddenLayers = 0, nHiddenNodes =0, numOutputs = 0, eta =
1, iter = 0, prec = 0):
        self.data = x
        self.labels = y
        self.test = p
        self.testlabels = q
        self.nInputNodes = x.shape[1]
        self.nHiddenLayers = nHiddenLayers
        self.nHiddenNodes = nHiddenNodes
        self.numOutputs = numOutputs
        self.eta = eta
        self.maxIt = iter
        self.prec = prec
        self.weights=[np.random.uniform(low = -2, high = 2, size = (self.nHiddenNodes, self.nInputNodes))]
        for i in range(self.nHiddenLayers-1):
            self.weights.append(np.random.uniform(low =-2, high = 2, size =(self.nHiddenNodes, self.nHiddenNo
des+1)))
        self.weights.append(np.random.uniform(low =-2, high = 2, size = (self.numOutputs, self.nHiddenNodes+1
)))

    # Tanh activation function for all layers except the output layer
    def tanh(self, s):
        return np.tanh(s)

    # Derivative of tanh for all layers
    def tanhPrime(self, s):
        return (1 - s**2)

    # Activation function for all the input data
    def af_predict(self,t):
#         t = np.tanh(t)
        p =[]
        for i in range(len(t)):
            max = np.argmax(t[i])
            y = np.zeros(len(t[i]))
            y[max] = 1
            p.append(y)
        return np.asarray(p)

    # Activation function for the output layer of the feedforward graph
```

```
    def af(self,t):
#         t = np.tanh(t)
        max = np.argmax(t[0])
        y = np.zeros(self.numOutputs)
        y[max] = 1
#         temp = np.asarray(y).reshape(1,self.numOutputs)
        return np.asarray(y)

#     # Derivative of sigmoid for the output layer
#     def sigmoidPrime(self, s):
#         return s * (1 - s)

#     def decision_A(self,x):
#         out =[]
# #         print(x.shape)
# #         print(f)
#         for i in range(x.shape[0]):
#             s =np.zeros(x.shape[1])
#             max = np.argmax(x[i])
#             #print(max)
#             s[max] = 1
#             out.append(s)
#         out = np.asarray(out)
#         print(out.shape)
#         print(f)
#         return out

    def misclassifications(self, x,y):
        count = 0
        for i in range(y.shape[0]):
            if np.any(x[i]-y[i]):
                count += 1
        return count

    def predict(self, data=[]):
        prev = data.T

        for i in range(len(self.weights)-1):
            temp = (np.matmul(self.weights[i], prev))
            temp2 = self.tanh(temp)
            y=[np.ones(temp2.shape[1])]
            prev = np.append(y, temp2, axis = 0)
#             print(prev.shape)
```

```
#             print(f)
        temp_f = np.matmul(self.weights[self.nHiddenLayers], prev)
        temp4 = self.af_predict(np.transpose(temp_f))
        return temp4

    def feedforward(self, x):
#         print(x)
        self.r = []
        self.r.append(x)
#         print(self.r)
#         print(f)
        prev = x.T
        for i in range(len(self.weights)-1):
#             print(self.weights[i])
#             print(prev)
            temp = np.matmul(self.weights[i], prev)
#             print(temp)
            temp2 = self.tanh(temp)
            prev = np.append([[1]], temp2).reshape(temp2.shape[0]+1,1)
#             print(prev.shape)
#             print(f)
            self.r.append(prev)
#             print(self.r)
#             print('\n')

#         print(self.weights[self.nHiddenLayers])
#         print(prev)
        temp_f = np.matmul(self.weights[self.nHiddenLayers], prev)
        temp4 =self.af(temp_f.T)
        return temp4

    def backward(self, x, y):
        self.gradient=[]
#         print(x)
#         print(y)
#         print(f)
        o = self.feedforward(x)
#         print(o)
        self.out_error = y - o
#         print(self.out_error)
#         print(f)

        for i in reversed(range(len(self.weights))):
```

```
            if i == 0 and i != len(self.weights)-1:
                temp2 = temp.T.dot(self.weights[i+1]).T
#                 print(self.sigmoidPrime(self.r[i+1]))
                temp3 = temp2*self.tanhPrime(self.r[i+1])
                temp4 = (temp3.dot(self.r[i]))*2/len(self.data)
#                 print('w')
#                 print(self.weights[i])
#                 print((self.eta*temp4*2)/len(self.data))
                self.gradient.append(self.eta*2*temp4[1:])

            elif i > 0 and i<len(self.weights)-1:
                temp2 = temp.T.dot(self.weights[i+1]).T

#                 print(self.sigmoidPrime(self.r[i+1]))
                temp3 = temp2*self.tanhPrime(self.r[i+1])
#                 print(temp3.shape)
                temp4 = (temp3.dot(self.r[i].T))*2/len(self.data)
#                 print('w')
#                 print(self.weights[i])
#                 print((self.eta*temp4*2)/len(self.data))
                self.gradient.append(self.eta*2*temp4[1:])
                temp = temp3[1:]

            elif i == len(self.weights)-1:
#                 print(self.weights)
#                 print(self.out_error)
#                 print(o)
#                 print(self.af_derivative(o).T)
                temp = self.out_error.reshape(self.numOutputs,1)
#                 temp = (self.out_error*self.tanhPrime(o)).reshape(self.numOutputs,1)
#                 print(temp.shape)
#                 print(f)
#                 print(self.weights[i])
                temp2 = self.r[i].dot(temp.T)*2/len(self.data)
                self.gradient.append(self.eta*temp2.T)
#                 print(self.weights[i])
#                 print('\n')

        self.gradient = self.gradient[::-1]

        for i in range(len(self.weights)):
            self.weights[i] += self.gradient[i]
#         print(self.weights)
```

```
#         print(f)

    def train (self):
        #print(self.eta)
#         print(self.weights[0].shape)
#         print(f)
        e = 0
        obj_training =[]
        obj_testing = []
        epoch = []
        mis_training = []
        mis_testing =[]
        epoch.append(e)
        pred_train = self.predict(self.data)
        pred_test = self.predict(self.test)
        obj_training.append(((np.linalg.norm(self.labels - pred_train))**2)/len(self.data))
        obj_testing.append(((np.linalg.norm(self.testlabels - pred_test))**2)/len(self.test))
        mis_training.append(self.misclassifications(self.labels, pred_train))
        mis_testing.append(self.misclassifications(self.testlabels, pred_test))
        mse = 100000000000
#         while e <= self.maxIt and mse >= self.prec:
        while e <= self.maxIt:
            prev = mse
#             print(prev)
#             print(f)
            e += 1
            for i in range(len(self.data)):
                self.backward(self.data[i].reshape(1,self.nInputNodes), self.labels[i])
#                 print(self.delta)
#             print(self.weights)
#             print(f)
#             print('after')
#             print(self.weights)
            pred_train = self.predict(self.data)
            pred_test = self.predict(self.test)
            mse = ((np.linalg.norm(self.labels - pred_train))**2)/len(self.data)
            mse_test = ((np.linalg.norm(self.testlabels - pred_test))**2)/len(self.test)
#             print(mse)
#             print(f)
            obj_training.append(mse)
            obj_testing.append(mse_test)
            epoch.append(e)
            mis_training.append(self.misclassifications(self.labels, pred_train))
```

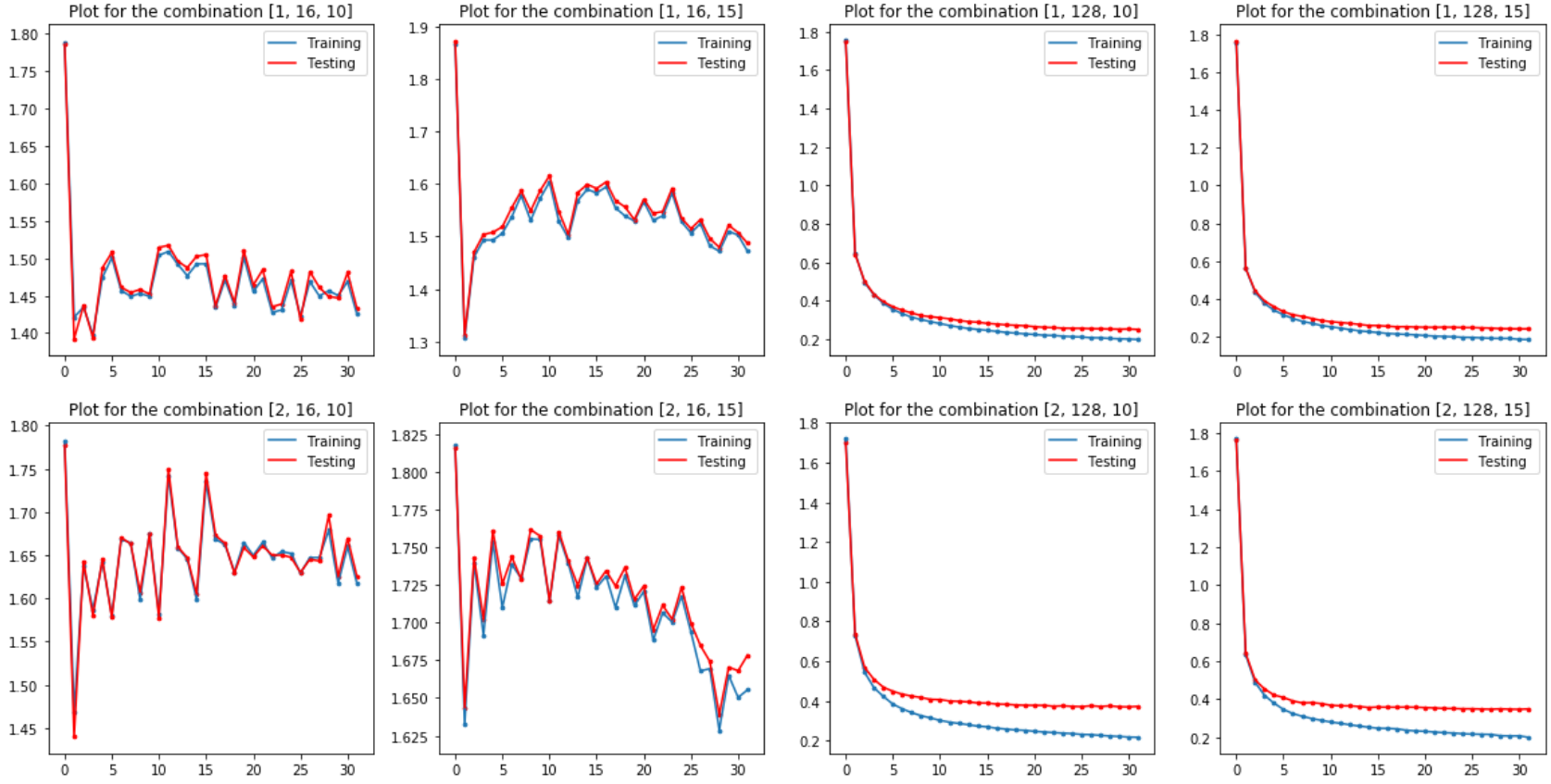
```
            mis_testing.append(self.misclassifications(self.testlabels, pred_test))
            if mse >= prev:
                self.eta = 0.7*self.eta
            prev = mse
        return self.weights, epoch, obj_training, mis_training, obj_testing, mis_testing
```

Hyperparameter Selection

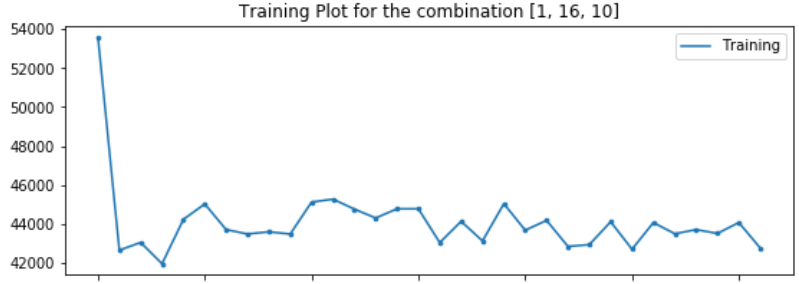
In [417]:
```
# nHiddenLayers = 1
# nHiddenNodes =2
# numOutputs = 10
# eta = 1
# iter = 100
# prec = 1.6
#print(xtrain.shape)

hid = [1,2]
hidnodes= [16,128]
lrate = [10, 15]
a =[]
b =[]
c =[]
q =[]

weights =[]
u =[]
iter = 30
numOutputs = 10
prec = 0.2
for i in range(len(hid)):
    for j in range(len(hidnodes)):
        for k in range(len(lrate)):
            u.append([hid[i],hidnodes[j],lrate[k]])
            print([hid[i],hidnodes[j],lrate[k]])
            NN = Neural_Network(x_train, d, x_test, dt, hid[i], hidnodes[j], numOutputs, lrate[k], iter, prec
)
            w, epoch, obj_training, mis_training, obj_testing, mis_testing = NN.train()
            weights.append(w)
            a.append(obj_training)
            b.append(mis_training)
            c.append(obj_testing)
            q.append(mis_testing)
```

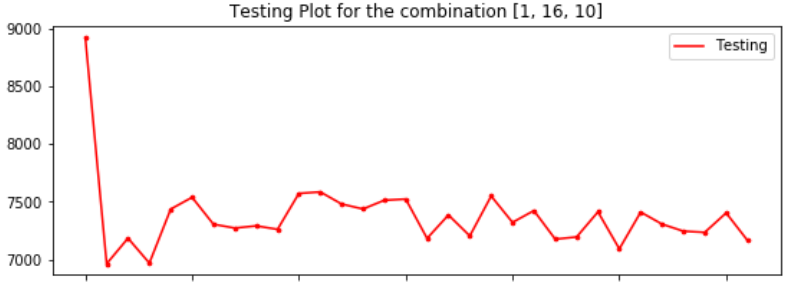
```
[1, 16, 10]
[1, 16, 15]
[1, 128, 10]
[1, 128, 15]
[2, 16, 10]
[2, 16, 15]
[2, 128, 10]
[2, 128, 15]
```

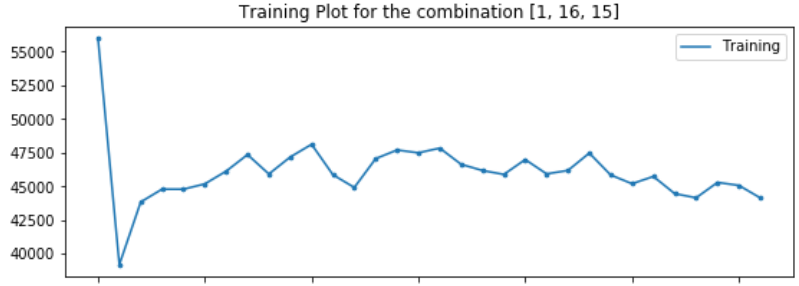
In [418]:
```
fig, ax = plt.subplots(2,4,figsize = (20,10))

# for i in range(len(hid)):
#     for j in range(len(hidnodes)):
#         for k in range(len(lta)):
k = 0
for i in range(2):
    for j in range(4):
        ax[i,j].scatter(epoch,a[k], s  = 7)
        ax[i,j].plot(epoch,a[k], label='Training')
        ax[i,j].scatter(epoch,c[k], s  = 7, c ='r')
        ax[i,j].plot(epoch, c[k], c='r',label='Testing')
        ax[i,j].legend()
        ax[i,j].title.set_text('Plot for the combination ' + str(u[k]))
        k += 1
```

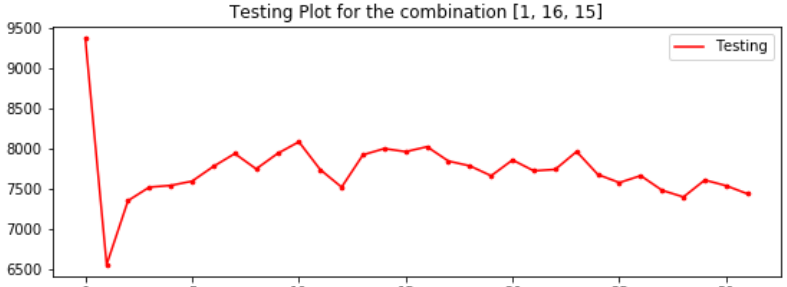


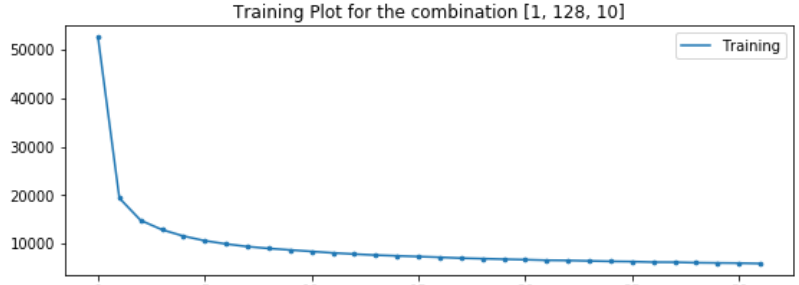
In [419]:
```
fig, ax = plt.subplots(8,2,figsize = (20,30))
k = 0
i = 0
p=0
while i < 8:
    ax[i,0].scatter(epoch,b[k], s  = 7)
    ax[i,0].plot(epoch,b[k], label='Training')
    ax[i,0].legend()
    ax[i,0].title.set_text('Training Plot for the combination ' + str(u[k]))

    ax[i,1].scatter(epoch,q[k], s  = 7, c ='r')
    ax[i,1].plot(epoch, q[k], c='r',label='Testing')
    ax[i,1].legend()
    ax[i,1].title.set_text('Testing Plot for the combination ' + str(u[k]))
    i += 1
    k += 1
```

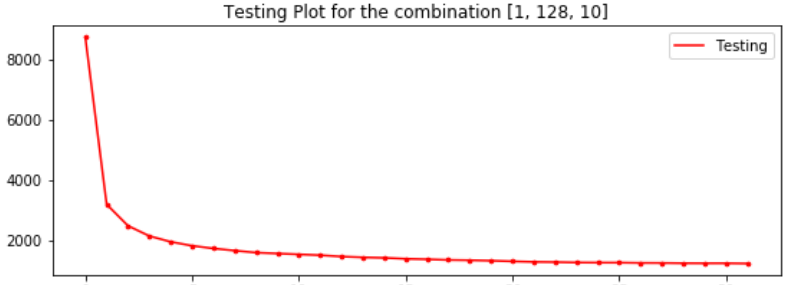

Training Plot for the combination [1, 16, 10]
Training

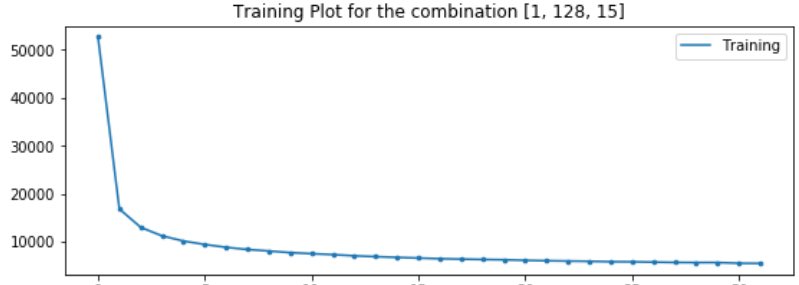

Testing Plot for the combination [1, 16, 10]
Testing

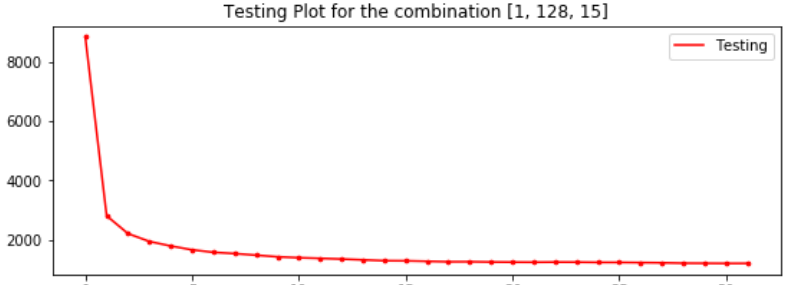

Training Plot for the combination [1, 16, 15]
Training

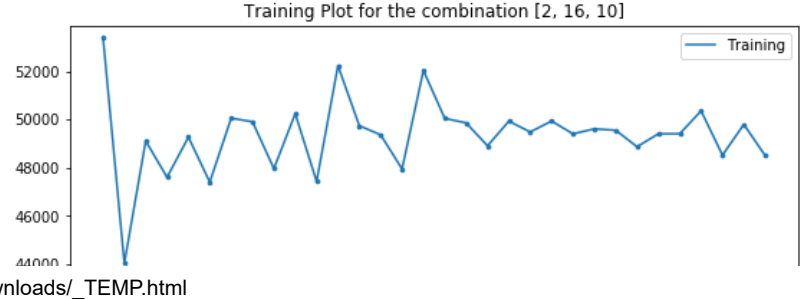

Testing Plot for the combination [1, 16, 15]
Testing

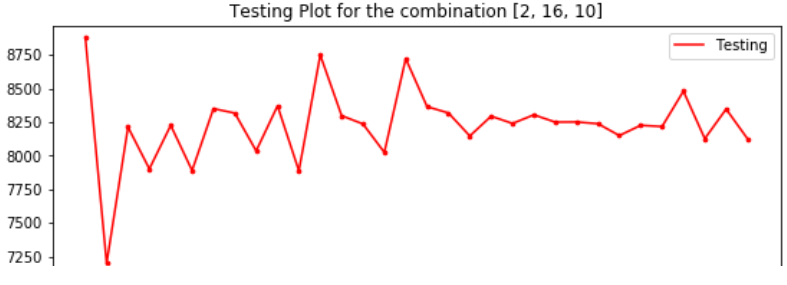

Training Plot for the combination [1, 128, 10]
Training

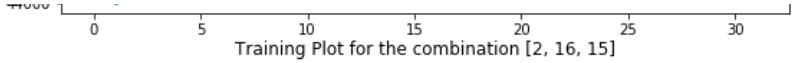

Testing Plot for the combination [1, 128, 10]
Testing

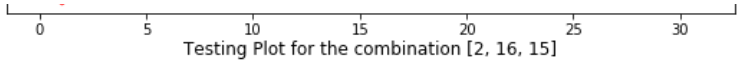

Training Plot for the combination [1, 128, 15]
Training

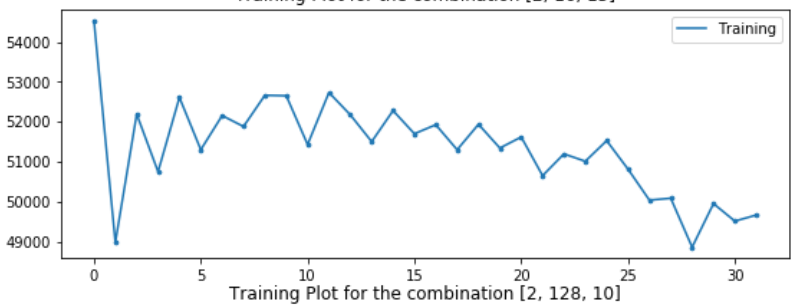

Testing Plot for the combination [1, 128, 15]
Testing

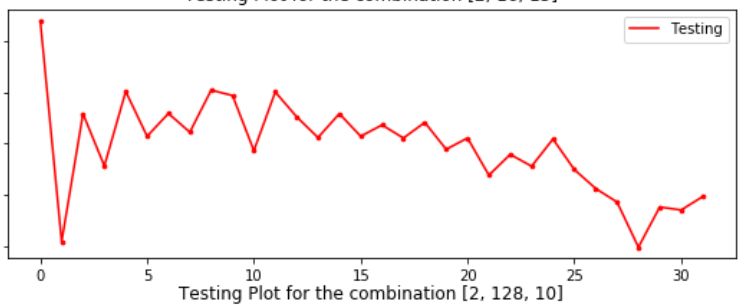

Training Plot for the combination [2, 16, 10]
Training

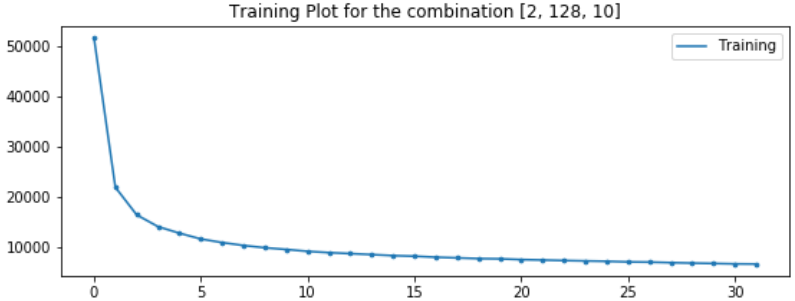

Testing Plot for the combination [2, 16, 10]
Testing

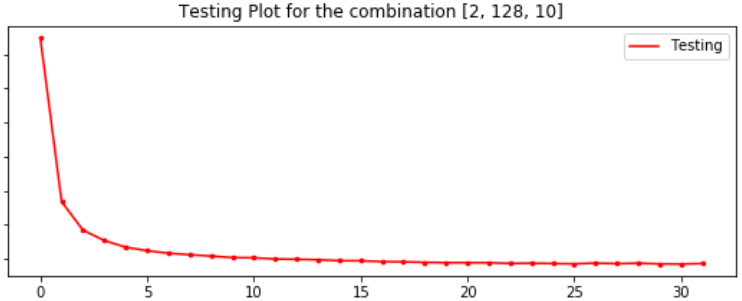


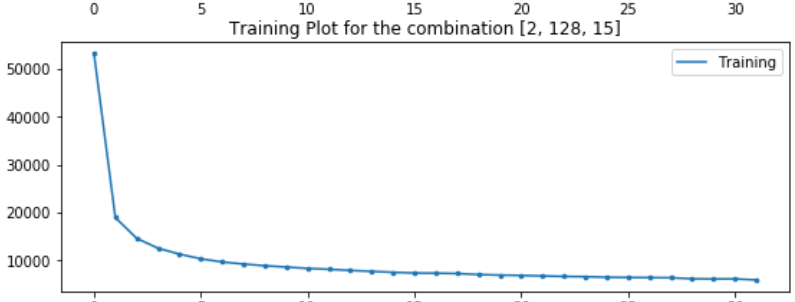


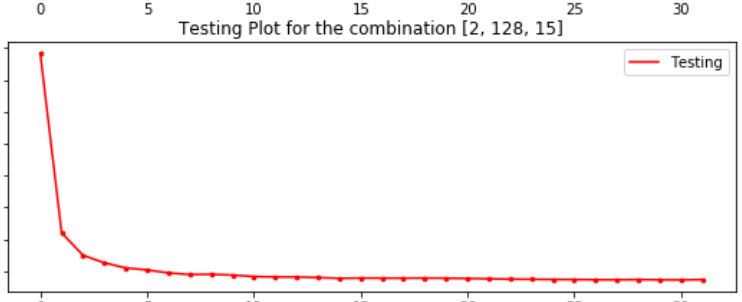

Training Plot for the combination [2, 16, 15]
Training
54000
53000
52000
51000
50000
49000
0
5
10
15
20
25
30


Testing Plot for the combination [2, 16, 15]
Testing
9000
8800
8600
8400
8200
0
5
10
15
20
25
30


Training Plot for the combination [2, 128, 10]
Training
50000
40000
30000
20000
10000
0
5
10
15
20
25
30


Testing Plot for the combination [2, 128, 10]
Testing
8000
7000
6000
5000
4000
3000
2000
0
5
10
15
20
25
30


Training Plot for the combination [2, 128, 15]
Training
50000
40000
30000
20000
10000
0
5
10
15
20
25
30


Testing Plot for the combination [2, 128, 15]
Testing
9000
8000
7000
6000
5000
4000
3000
2000
0
5
10
15
20
25
30

In [420]:
```
# Tanh activation function for all layers except the output layer
def tanh(s):
    return np.tanh(s)

# Derivative of tanh for all layers except the output layer
def tanhPrime(s):
    return (1 - s**2)

# Activation function for all the input data
def af_predict(t):
#     t = np.tanh(t)
    p =[]
    for i in range(len(t)):
        max = np.argmax(t[i])
        y = np.zeros(len(t[i]))
        y[max] = 1
        p.append(y)
    return np.asarray(p)

# Activation function for the output layer of the feedforward graph
def af(t):
#     t = np.tanh(t)

    max = np.argmax(t[0])
    y = np.zeros(numOutputs)
    y[max] = 1
#         temp = np.asarray(y).reshape(1,self.numOutputs)
    return np.asarray(y)

def misclassifications(x,y):
    count = 0
    for i in range(y.shape[0]):
        if np.any(x[i]-y[i]):
            count += 1
    return count

def predict(data, weights):
    prev = data.T

    for i in range(len(weights)-1):
        temp = (np.matmul(weights[i], prev))
        temp2 = tanh(temp)
```

```
        y=[np.ones(temp2.shape[1])]
        prev = np.append(y, temp2, axis = 0)
#             print(prev.shape)
#             print(f)
    temp_f = np.matmul(weights[nHiddenLayers], prev)
    temp4 = af_predict(np.transpose(temp_f))
    return temp4
```

In [425]:
```
nHiddenLayers = 1
nHiddenNodes =128
numOutputs = 10
# eta = 10
# iter =50

y = predict(x_test, weights[3])
y
misclassifications(dt, y)
```

Out[425]: 1206

In [435]:
```
nHiddenLayers = 1
nHiddenNodes =128
numOutputs = 10
eta = 15
iter =50


NN = Neural_Network(x_train, d, x_test, dt, nHiddenLayers, nHiddenNodes, numOutputs, eta, iter, prec)
w, epoch, obj_training, mis_training, obj_testing, mis_testing = NN.train()
```

In [436]:
```
y = predict(x_test, w)
y
misclassifications(dt, y)
```

Out[436]: 1097