two_layer_net

September 24, 2019

1 Implementing a Neural Network

In this exercise we will develop a neural network with fully-connected layers to perform classification, and test it out on the CIFAR-10 dataset.

[2]:
```
# A bit of setup

import numpy as np
import matplotlib.pyplot as plt

%matplotlib inline
plt.rcParams['figure.figsize'] = (10.0, 8.0) # set default size of plots
plt.rcParams['image.interpolation'] = 'nearest'
plt.rcParams['image.cmap'] = 'gray'

# for auto-reloading external modules
# see http://stackoverflow.com/questions/1907993/
 ↪autoreload-of-modules-in-ipython
%load_ext autoreload
%autoreload 2

def rel_error(x, y):
  """ returns relative error """
  return np.max(np.abs(x - y) / (np.maximum(1e-8, np.abs(x) + np.abs(y))))
```

The neural network parameters will be stored in a dictionary (`model` below), where the keys are the parameter names and the values are numpy arrays. Below, we initialize toy data and a toy model that we will use to verify your implementations.

[19]:
```
# Create some toy data to check your implementations
input_size = 4
hidden_size = 10
num_classes = 3
num_inputs = 5

def init_toy_model():
  model = {}
```

```
  model['W1'] = np.linspace(-0.2, 0.6, num=input_size*hidden_size).
 ↪reshape(input_size, hidden_size)
  model['b1'] = np.linspace(-0.3, 0.7, num=hidden_size)
  model['W2'] = np.linspace(-0.4, 0.1, num=hidden_size*num_classes).
 ↪reshape(hidden_size, num_classes)
  model['b2'] = np.linspace(-0.5, 0.9, num=num_classes)
  return model

def init_toy_data():
  X = np.linspace(-0.2, 0.5, num=num_inputs*input_size).reshape(num_inputs,␣
 ↪input_size)
  y = np.array([0, 1, 2, 2, 1])
  return X, y

model = init_toy_model()
X, y = init_toy_data()
```

2 Forward pass: compute scores

Open the file `cs231n/classifiers/neural_net.py` and look at the function `two_layer_net`. This function is very similar to the loss functions you have written for the Softmax exercise in HW0: It takes the data and weights and computes the class scores, the loss, and the gradients on the parameters.

Implement the first part of the forward pass which uses the weights and biases to compute the scores for all inputs.

[18]:
```
from cs231n.classifiers.neural_net import two_layer_net

scores = two_layer_net(X, model)
print(scores)
correct_scores = [[-0.5328368, 0.20031504, 0.93346689],
 [-0.59412164, 0.15498488, 0.9040914 ],
 [-0.67658362, 0.08978957, 0.85616275],
 [-0.77092643, 0.01339997, 0.79772637],
 [-0.89110401, -0.08754544, 0.71601312]]

# the difference should be very small. We get 3e-8
print('Difference between your scores and correct scores:')
print(np.sum(np.abs(scores - correct_scores)))
```

```
[[-0.5328368   0.20031504  0.93346689]
 [-0.59412164  0.15498488  0.9040914 ]
 [-0.67658362  0.08978957  0.85616275]
 [-0.77092643  0.01339997  0.79772637]
 [-0.89110401 -0.08754544  0.71601312]]
Difference between your scores and correct scores:
```

```
3.848682278081994e-08
```

3 Forward pass: compute loss

In the same function, implement the second part that computes the data and regularizaion loss.

[17]:
```
reg = 0.1
loss, _ = two_layer_net(X, model, y, reg)
correct_loss = 1.38191946092

# should be very small, we get 5e-12
print('Difference between your loss and correct loss:')
print(np.sum(np.abs(loss - correct_loss)))
```

```
Difference between your loss and correct loss:
4.6769255135359344e-12
```

4 Backward pass

Implement the rest of the function. This will compute the gradient of the loss with respect to the variables `W1`, `b1`, `W2`, and `b2`. Now that you (hopefully!) have a correctly implemented forward pass, you can debug your backward pass using a numeric gradient check:

[16]:
```
from cs231n.gradient_check import eval_numerical_gradient

# Use numeric gradient checking to check your implementation of the backward␣
 ↪pass.
# If your implementation is correct, the difference between the numeric and
# analytic gradients should be less than 1e-8 for each of W1, W2, b1, and b2.

loss, grads = two_layer_net(X, model, y, reg)

# these should all be less than 1e-8 or so
for param_name in grads:
  param_grad_num = eval_numerical_gradient(lambda W: two_layer_net(X, model, y,␣
 ↪reg)[0], model[param_name], verbose=False)
  print('%s max relative error: %e' % (param_name, rel_error(param_grad_num,␣
 ↪grads[param_name])))
```

```
W1 max relative error: 4.426512e-09
b1 max relative error: 5.435432e-08
W2 max relative error: 8.023739e-10
b2 max relative error: 8.190173e-11
```

5 Train the network

To train the network we will use SGD with Momentum. Last assignment you implemented vanilla SGD. You will now implement the momentum update and the RMSProp update. Open the file `classifier_trainer.py` and familiarize yourself with the `ClassifierTrainer` class. It performs optimization given an arbitrary cost function data, and model. By default it uses vanilla SGD, which we have already implemented for you. First, run the optimization below using Vanilla SGD:

[20]:
```
from cs231n.classifier_trainer import ClassifierTrainer

model = init_toy_model()
trainer = ClassifierTrainer()
# call the trainer to optimize the loss
# Notice that we're using sample_batches=False, so we're performing Gradient␣
 ↪Descent (no sampled batches of data)
best_model, loss_history, _, _ = trainer.train(X, y, X, y,
                                               model, two_layer_net,
                                               reg=0.001,
                                               learning_rate=1e-1, momentum=0.0,␣
 ↪learning_rate_decay=1,
                                               update='sgd', sample_batches=False,
                                               num_epochs=100,
                                               verbose=False)
print('Final loss with vanilla SGD: %f' % (loss_history[-1], ))
```

```
starting iteration  0
starting iteration  10
starting iteration  20
starting iteration  30
starting iteration  40
starting iteration  50
starting iteration  60
starting iteration  70
starting iteration  80
starting iteration  90
Final loss with vanilla SGD: 0.940686
```

Now fill in the **momentum update** in the first missing code block inside the `train` function, and run the same optimization as above but with the momentum update. You should see a much better result in the final obtained loss:

[22]:
```
model = init_toy_model()
trainer = ClassifierTrainer()
# call the trainer to optimize the loss
# Notice that we're using sample_batches=False, so we're performing Gradient␣
 ↪Descent (no sampled batches of data)
best_model, loss_history, _, _ = trainer.train(X, y, X, y,
                                               model, two_layer_net,
```

```
                                            reg=0.001,
                                            learning_rate=1e-1, momentum=0.9,␣
 ↪learning_rate_decay=1,
                                            update='momentum',␣
 ↪sample_batches=False,
                                            num_epochs=100,
                                            verbose=False)
correct_loss = 0.494394
print('Final loss with momentum SGD: %f. We get: %f' % (loss_history[-1],␣
 ↪correct_loss))
```

```
starting iteration  0
starting iteration  10
starting iteration  20
starting iteration  30
starting iteration  40
starting iteration  50
starting iteration  60
starting iteration  70
starting iteration  80
starting iteration  90
Final loss with momentum SGD: 0.494394. We get: 0.494394
```

The **RMSProp** update step is given as follows:

```
cache = decay_rate * cache + (1 - decay_rate) * dx**2
x += - learning_rate * dx / np.sqrt(cache + 1e-8)
```

Here, `decay_rate` is a hyperparameter and typical values are [0.9, 0.99, 0.999].

Implement the **RMSProp** update rule inside the `train` function and rerun the optimization:

[23]:
```
model = init_toy_model()
trainer = ClassifierTrainer()
# call the trainer to optimize the loss
# Notice that we're using sample_batches=False, so we're performing Gradient␣
 ↪Descent (no sampled batches of data)
best_model, loss_history, _, _ = trainer.train(X, y, X, y,
                                            model, two_layer_net,
                                            reg=0.001,
                                            learning_rate=1e-1, momentum=0.9,␣
 ↪learning_rate_decay=1,
                                            update='rmsprop',␣
 ↪sample_batches=False,
                                            num_epochs=100,
                                            verbose=False)
correct_loss = 0.439368
print('Final loss with RMSProp: %f. We get: %f' % (loss_history[-1],␣
 ↪correct_loss))
```

```
starting iteration  0
starting iteration  10
starting iteration  20
starting iteration  30
starting iteration  40
starting iteration  50
starting iteration  60
starting iteration  70
starting iteration  80
starting iteration  90
Final loss with RMSProp: 0.429848. We get: 0.439368
```

6 Load the data

Now that you have implemented a two-layer network that passes gradient checks, it's time to load up our favorite CIFAR-10 data so we can use it to train a classifier.

[24]:
```
from cs231n.data_utils import load_CIFAR10

def get_CIFAR10_data(num_training=49000, num_validation=1000, num_test=1000):
    """
    Load the CIFAR-10 dataset from disk and perform preprocessing to prepare
    it for the two-layer neural net classifier.
    """
    # Load the raw CIFAR-10 data
    cifar10_dir = 'cs231n/datasets/cifar-10-batches-py'
    X_train, y_train, X_test, y_test = load_CIFAR10(cifar10_dir)

    # Subsample the data
    mask = range(num_training, num_training + num_validation)
    X_val = X_train[mask]
    y_val = y_train[mask]
    mask = range(num_training)
    X_train = X_train[mask]
    y_train = y_train[mask]
    mask = range(num_test)
    X_test = X_test[mask]
    y_test = y_test[mask]

    # Normalize the data: subtract the mean image
    mean_image = np.mean(X_train, axis=0)
    X_train -= mean_image
    X_val -= mean_image
    X_test -= mean_image

    # Reshape data to rows
    X_train = X_train.reshape(num_training, -1)
```

```
    X_val = X_val.reshape(num_validation, -1)
    X_test = X_test.reshape(num_test, -1)

    return X_train, y_train, X_val, y_val, X_test, y_test


# Invoke the above function to get our data.
X_train, y_train, X_val, y_val, X_test, y_test = get_CIFAR10_data()
print('Train data shape: ', X_train.shape)
print('Train labels shape: ', y_train.shape)
print('Validation data shape: ', X_val.shape)
print('Validation labels shape: ', y_val.shape)
print('Test data shape: ', X_test.shape)
print('Test labels shape: ', y_test.shape)
```

```
Train data shape:  (49000, 3072)
Train labels shape:  (49000,)
Validation data shape:  (1000, 3072)
Validation labels shape:  (1000,)
Test data shape:  (1000, 3072)
Test labels shape:  (1000,)
```

7 Train a network

To train our network we will use SGD with momentum. In addition, we will adjust the learning rate with an exponential learning rate schedule as optimization proceeds; after each epoch, we will reduce the learning rate by multiplying it by a decay rate.

[48]:
```
from cs231n.classifiers.neural_net import init_two_layer_model

model = init_two_layer_model(32*32*3, 70, 10) # input size, hidden size, number␣
↪of classes
trainer = ClassifierTrainer()
best_model, loss_history, train_acc, val_acc = trainer.train(X_train, y_train,␣
↪X_val, y_val,
                                             model, two_layer_net,
                                             num_epochs=20, reg=1.0,
                                             momentum=0.90, learning_rate_decay␣
↪= 0.95,
                                             learning_rate=5e-5, verbose=True)
```

```
starting iteration  0
Finished epoch 0 / 20: cost 2.302596, train: 0.085000, val 0.092000, lr
5.000000e-05
starting iteration  10
starting iteration  20
starting iteration  30
```

```
starting iteration  40
starting iteration  50
starting iteration  60
starting iteration  70
starting iteration  80
starting iteration  90
starting iteration  100
starting iteration  110
starting iteration  120
starting iteration  130
starting iteration  140
starting iteration  150
starting iteration  160
starting iteration  170
starting iteration  180
starting iteration  190
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starting iteration  210
starting iteration  220
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starting iteration  320
starting iteration  330
starting iteration  340
starting iteration  350
starting iteration  360
starting iteration  370
starting iteration  380
starting iteration  390
starting iteration  400
starting iteration  410
starting iteration  420
starting iteration  430
starting iteration  440
starting iteration  450
starting iteration  460
starting iteration  470
starting iteration  480
Finished epoch 1 / 20: cost 1.703471, train: 0.370000, val 0.359000, lr
4.750000e-05
starting iteration  490
```

```
starting iteration  500
starting iteration  510
starting iteration  520
starting iteration  530
starting iteration  540
starting iteration  550
starting iteration  560
starting iteration  570
starting iteration  580
starting iteration  590
starting iteration  600
starting iteration  610
starting iteration  620
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starting iteration  640
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starting iteration  690
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starting iteration  880
starting iteration  890
starting iteration  900
starting iteration  910
starting iteration  920
starting iteration  930
starting iteration  940
starting iteration  950
starting iteration  960
starting iteration  970
```

```
Finished epoch 2 / 20: cost 1.692839, train: 0.435000, val 0.444000, lr
4.512500e-05
starting iteration  980
starting iteration  990
starting iteration  1000
starting iteration  1010
starting iteration  1020
starting iteration  1030
starting iteration  1040
starting iteration  1050
starting iteration  1060
starting iteration  1070
starting iteration  1080
starting iteration  1090
starting iteration  1100
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starting iteration  1390
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starting iteration  1410
starting iteration  1420
starting iteration  1430
```

```
starting iteration  1440
starting iteration  1450
starting iteration  1460
Finished epoch 3 / 20: cost 1.549167, train: 0.483000, val 0.451000, lr
4.286875e-05
starting iteration  1470
starting iteration  1480
starting iteration  1490
starting iteration  1500
starting iteration  1510
starting iteration  1520
starting iteration  1530
starting iteration  1540
starting iteration  1550
starting iteration  1560
starting iteration  1570
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starting iteration  1590
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starting iteration  1880
starting iteration  1890
```

```
starting iteration  1900
starting iteration  1910
starting iteration  1920
starting iteration  1930
starting iteration  1940
starting iteration  1950
Finished epoch 4 / 20: cost 1.596957, train: 0.476000, val 0.456000, lr
4.072531e-05
starting iteration  1960
starting iteration  1970
starting iteration  1980
starting iteration  1990
starting iteration  2000
starting iteration  2010
starting iteration  2020
starting iteration  2030
starting iteration  2040
starting iteration  2050
starting iteration  2060
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starting iteration  2080
starting iteration  2090
starting iteration  2100
starting iteration  2110
starting iteration  2120
starting iteration  2130
starting iteration  2140
starting iteration  2150
starting iteration  2160
starting iteration  2170
starting iteration  2180
starting iteration  2190
starting iteration  2200
starting iteration  2210
starting iteration  2220
starting iteration  2230
starting iteration  2240
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starting iteration  2360
starting iteration  2370
starting iteration  2380
starting iteration  2390
starting iteration  2400
starting iteration  2410
starting iteration  2420
starting iteration  2430
starting iteration  2440
Finished epoch 5 / 20: cost 1.591155, train: 0.507000, val 0.465000, lr
3.868905e-05
starting iteration  2450
starting iteration  2460
starting iteration  2470
starting iteration  2480
starting iteration  2490
starting iteration  2500
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starting iteration  2790
starting iteration  2800
starting iteration  2810
```

```
starting iteration  2820
starting iteration  2830
starting iteration  2840
starting iteration  2850
starting iteration  2860
starting iteration  2870
starting iteration  2880
starting iteration  2890
starting iteration  2900
starting iteration  2910
starting iteration  2920
starting iteration  2930
Finished epoch 6 / 20: cost 1.506842, train: 0.504000, val 0.461000, lr
3.675459e-05
starting iteration  2940
starting iteration  2950
starting iteration  2960
starting iteration  2970
starting iteration  2980
starting iteration  2990
starting iteration  3000
starting iteration  3010
starting iteration  3020
starting iteration  3030
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starting iteration  3060
starting iteration  3070
starting iteration  3080
starting iteration  3090
starting iteration  3100
starting iteration  3110
starting iteration  3120
starting iteration  3130
starting iteration  3140
starting iteration  3150
starting iteration  3160
starting iteration  3170
starting iteration  3180
starting iteration  3190
starting iteration  3200
starting iteration  3210
starting iteration  3220
starting iteration  3230
starting iteration  3240
starting iteration  3250
starting iteration  3260
starting iteration  3270
```

```
starting iteration  3280
starting iteration  3290
starting iteration  3300
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starting iteration  3340
starting iteration  3350
starting iteration  3360
starting iteration  3370
starting iteration  3380
starting iteration  3390
starting iteration  3400
starting iteration  3410
starting iteration  3420
Finished epoch 7 / 20: cost 1.512307, train: 0.542000, val 0.484000, lr
3.491686e-05
starting iteration  3430
starting iteration  3440
starting iteration  3450
starting iteration  3460
starting iteration  3470
starting iteration  3480
starting iteration  3490
starting iteration  3500
starting iteration  3510
starting iteration  3520
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starting iteration  3660
starting iteration  3670
starting iteration  3680
starting iteration  3690
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starting iteration  3720
starting iteration  3730
```

```
starting iteration  3740
starting iteration  3750
starting iteration  3760
starting iteration  3770
starting iteration  3780
starting iteration  3790
starting iteration  3800
starting iteration  3810
starting iteration  3820
starting iteration  3830
starting iteration  3840
starting iteration  3850
starting iteration  3860
starting iteration  3870
starting iteration  3880
starting iteration  3890
starting iteration  3900
starting iteration  3910
Finished epoch 8 / 20: cost 1.628261, train: 0.514000, val 0.492000, lr
3.317102e-05
starting iteration  3920
starting iteration  3930
starting iteration  3940
starting iteration  3950
starting iteration  3960
starting iteration  3970
starting iteration  3980
starting iteration  3990
starting iteration  4000
starting iteration  4010
starting iteration  4020
starting iteration  4030
starting iteration  4040
starting iteration  4050
starting iteration  4060
starting iteration  4070
starting iteration  4080
starting iteration  4090
starting iteration  4100
starting iteration  4110
starting iteration  4120
starting iteration  4130
starting iteration  4140
starting iteration  4150
starting iteration  4160
starting iteration  4170
starting iteration  4180
starting iteration  4190
```

```
starting iteration  4200
starting iteration  4210
starting iteration  4220
starting iteration  4230
starting iteration  4240
starting iteration  4250
starting iteration  4260
starting iteration  4270
starting iteration  4280
starting iteration  4290
starting iteration  4300
starting iteration  4310
starting iteration  4320
starting iteration  4330
starting iteration  4340
starting iteration  4350
starting iteration  4360
starting iteration  4370
starting iteration  4380
starting iteration  4390
starting iteration  4400
Finished epoch 9 / 20: cost 1.500103, train: 0.534000, val 0.484000, lr
3.151247e-05
starting iteration  4410
starting iteration  4420
starting iteration  4430
starting iteration  4440
starting iteration  4450
starting iteration  4460
starting iteration  4470
starting iteration  4480
starting iteration  4490
starting iteration  4500
starting iteration  4510
starting iteration  4520
starting iteration  4530
starting iteration  4540
starting iteration  4550
starting iteration  4560
starting iteration  4570
starting iteration  4580
starting iteration  4590
starting iteration  4600
starting iteration  4610
starting iteration  4620
starting iteration  4630
starting iteration  4640
starting iteration  4650
```

```
starting iteration  4660
starting iteration  4670
starting iteration  4680
starting iteration  4690
starting iteration  4700
starting iteration  4710
starting iteration  4720
starting iteration  4730
starting iteration  4740
starting iteration  4750
starting iteration  4760
starting iteration  4770
starting iteration  4780
starting iteration  4790
starting iteration  4800
starting iteration  4810
starting iteration  4820
starting iteration  4830
starting iteration  4840
starting iteration  4850
starting iteration  4860
starting iteration  4870
starting iteration  4880
starting iteration  4890
Finished epoch 10 / 20: cost 1.439580, train: 0.553000, val 0.493000, lr
2.993685e-05
starting iteration  4900
starting iteration  4910
starting iteration  4920
starting iteration  4930
starting iteration  4940
starting iteration  4950
starting iteration  4960
starting iteration  4970
starting iteration  4980
starting iteration  4990
starting iteration  5000
starting iteration  5010
starting iteration  5020
starting iteration  5030
starting iteration  5040
starting iteration  5050
starting iteration  5060
starting iteration  5070
starting iteration  5080
starting iteration  5090
starting iteration  5100
starting iteration  5110
```

```
starting iteration  5120
starting iteration  5130
starting iteration  5140
starting iteration  5150
starting iteration  5160
starting iteration  5170
starting iteration  5180
starting iteration  5190
starting iteration  5200
starting iteration  5210
starting iteration  5220
starting iteration  5230
starting iteration  5240
starting iteration  5250
starting iteration  5260
starting iteration  5270
starting iteration  5280
starting iteration  5290
starting iteration  5300
starting iteration  5310
starting iteration  5320
starting iteration  5330
starting iteration  5340
starting iteration  5350
starting iteration  5360
starting iteration  5370
starting iteration  5380
Finished epoch 11 / 20: cost 1.420972, train: 0.551000, val 0.485000, lr
2.844000e-05
starting iteration  5390
starting iteration  5400
starting iteration  5410
starting iteration  5420
starting iteration  5430
starting iteration  5440
starting iteration  5450
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starting iteration  5850
starting iteration  5860
starting iteration  5870
Finished epoch 12 / 20: cost 1.502760, train: 0.545000, val 0.500000, lr
2.701800e-05
starting iteration  5880
starting iteration  5890
starting iteration  5900
starting iteration  5910
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starting iteration  6000
starting iteration  6010
starting iteration  6020
starting iteration  6030
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starting iteration  6130
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starting iteration  6350
starting iteration  6360
Finished epoch 13 / 20: cost 1.506627, train: 0.535000, val 0.511000, lr
2.566710e-05
starting iteration  6370
starting iteration  6380
starting iteration  6390
starting iteration  6400
starting iteration  6410
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Finished epoch 14 / 20: cost 1.482915, train: 0.572000, val 0.489000, lr
2.438375e-05
starting iteration  6860
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starting iteration  7330
starting iteration  7340
Finished epoch 15 / 20: cost 1.639811, train: 0.568000, val 0.502000, lr
2.316456e-05
starting iteration  7350
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Finished epoch 16 / 20: cost 1.512649, train: 0.550000, val 0.506000, lr
2.200633e-05
starting iteration  7840
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starting iteration  8270
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starting iteration  8300
starting iteration  8310
starting iteration  8320
Finished epoch 17 / 20: cost 1.473777, train: 0.555000, val 0.517000, lr
2.090602e-05
starting iteration  8330
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starting iteration  8340
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starting iteration  8790
starting iteration  8800
starting iteration  8810
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Finished epoch 18 / 20: cost 1.556926, train: 0.562000, val 0.509000, lr
1.986072e-05
starting iteration  8820
starting iteration  8830
starting iteration  8840
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starting iteration  8890
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starting iteration  9250
starting iteration  9260
starting iteration  9270
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starting iteration  9280
starting iteration  9290
starting iteration  9300
Finished epoch 19 / 20: cost 1.502153, train: 0.546000, val 0.513000, lr
1.886768e-05
starting iteration  9310
starting iteration  9320
starting iteration  9330
starting iteration  9340
starting iteration  9350
starting iteration  9360
starting iteration  9370
starting iteration  9380
starting iteration  9390
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starting iteration  9740
starting iteration  9750
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starting iteration  9780
starting iteration  9790
Finished epoch 20 / 20: cost 1.272936, train: 0.561000, val 0.521000, lr
1.792430e-05
finished optimization. best validation accuracy: 0.521000
```

8 Debug the training

With the default parameters we provided above, you should get a validation accuracy of about 0.37 on the validation set. This isn't very good.

One strategy for getting insight into what's wrong is to plot the loss function and the accuracies on the training and validation sets during optimization.

Another strategy is to visualize the weights that were learned in the first layer of the network. In most neural networks trained on visual data, the first layer weights typically show some visible structure when visualized.

[49]:
```
# Plot the loss function and train / validation accuracies
plt.subplot(2, 1, 1)
plt.plot(loss_history)
plt.title('Loss history')
plt.xlabel('Iteration')
plt.ylabel('Loss')

plt.subplot(2, 1, 2)
plt.plot(train_acc)
plt.plot(val_acc)
plt.legend(['Training accuracy', 'Validation accuracy'], loc='lower right')
plt.xlabel('Epoch')
plt.ylabel('Clasification accuracy')
```

[49]:
```
Text(0, 0.5, 'Clasification accuracy')
```

[50]:
```
from cs231n.vis_utils import visualize_grid

# Visualize the weights of the network

def show_net_weights(model):
    plt.imshow(visualize_grid(model['W1'].T.reshape(-1, 32, 32, 3), padding=3).
 ↪astype('uint8'))
    plt.gca().axis('off')
    plt.show()

show_net_weights(model)
```

9 Tune your hyperparameters

What's wrong?. Looking at the visualizations above, we see that the loss is decreasing more or less linearly, which seems to suggest that the learning rate may be too low. Moreover, there is no gap between the training and validation accuracy, suggesting that the model we used has low capacity, and that we should increase its size. On the other hand, with a very large model we would expect to see more overfitting, which would manifest itself as a very large gap between the training and validation accuracy.

Tuning. Tuning the hyperparameters and developing intuition for how they affect the final performance is a large part of using Neural Networks, so we want you to get a lot of practice. Below, you should experiment with different values of the various hyperparameters, including hidden layer size, learning rate, numer of training epochs, and regularization strength. You might also consider tuning the momentum and learning rate decay parameters, but you should be able to get good performance using the default values.

Approximate results. You should be aim to achieve a classification accuracy of greater than 50% on the validation set. Our best network gets over 56% on the validation set.

Experiment: You goal in this exercise is to get as good of a result on CIFAR-10 as you can, with a fully-connected Neural Network. For every 1% above 56% on the Test set we will award you with one extra bonus point. Feel free implement your own techniques (e.g. PCA to reduce dimensionality, or adding dropout, or adding features to the solver, etc.).

[52]:
```
best_model = None # store the best model into this

################################################################################
```

```
# TODO: Tune hyperparameters using the validation set. Store your best trained␣
 ↪#
# model in best_model.                                                          ␣
 ↪#
#                                                                              ␣
 ↪#
# To help debug your network, it may help to use visualizations similar to the ␣
 ↪#
# ones we used above; these visualizations will have significant qualitative   ␣
 ↪#
# differences from the ones we saw above for the poorly tuned network.         ␣
 ↪#
#                                                                              ␣
 ↪#
# Tweaking hyperparameters by hand can be fun, but you might find it useful to ␣
 ↪#
# write code to sweep through possible combinations of hyperparameters         ␣
 ↪#
# automatically like we did on the previous assignment.                        ␣
 ↪#
################################################################################
# input size, hidden size, number of classes
model = init_two_layer_model(32*32*3, 1000, 10)
trainer = ClassifierTrainer()
best_model, loss_history, train_acc, val_acc = trainer.train(X_train, y_train,␣
 ↪X_val, y_val,
                                             model, two_layer_net,
                                             num_epochs=20, reg=1.0,
                                             momentum=0.90, learning_rate_decay␣
 ↪= 0.95,
                                             learning_rate=5e-5, verbose=True)
################################################################################
#                               END OF YOUR CODE                               ␣
 ↪#
################################################################################
```

```
starting iteration  0
Finished epoch 0 / 20: cost 2.302740, train: 0.088000, val 0.085000, lr
5.000000e-05
starting iteration  10
starting iteration  20
starting iteration  30
starting iteration  40
starting iteration  50
starting iteration  60
starting iteration  70
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starting iteration  80
starting iteration  90
starting iteration  100
starting iteration  110
starting iteration  120
starting iteration  130
starting iteration  140
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starting iteration  400
starting iteration  410
starting iteration  420
starting iteration  430
starting iteration  440
starting iteration  450
starting iteration  460
starting iteration  470
starting iteration  480
Finished epoch 1 / 20: cost 1.800183, train: 0.359000, val 0.386000, lr
4.750000e-05
starting iteration  490
starting iteration  500
starting iteration  510
starting iteration  520
starting iteration  530
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starting iteration  540
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starting iteration  900
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starting iteration  920
starting iteration  930
starting iteration  940
starting iteration  950
starting iteration  960
starting iteration  970
Finished epoch 2 / 20: cost 1.586629, train: 0.431000, val 0.452000, lr
4.512500e-05
starting iteration  980
starting iteration  990
```

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starting iteration  1000
starting iteration  1010
starting iteration  1020
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starting iteration  1040
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starting iteration  1450
starting iteration  1460
Finished epoch 3 / 20: cost 1.681464, train: 0.477000, val 0.466000, lr
```

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4.286875e-05
starting iteration  1470
starting iteration  1480
starting iteration  1490
starting iteration  1500
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starting iteration  1900
starting iteration  1910
starting iteration  1920
starting iteration  1930
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starting iteration  1940
starting iteration  1950
Finished epoch 4 / 20: cost 1.542658, train: 0.497000, val 0.479000, lr
4.072531e-05
starting iteration  1960
starting iteration  1970
starting iteration  1980
starting iteration  1990
starting iteration  2000
starting iteration  2010
starting iteration  2020
starting iteration  2030
starting iteration  2040
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starting iteration  2110
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starting iteration  2380
starting iteration  2390
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starting iteration  2400
starting iteration  2410
starting iteration  2420
starting iteration  2430
starting iteration  2440
Finished epoch 5 / 20: cost 1.421326, train: 0.503000, val 0.498000, lr
3.868905e-05
starting iteration  2450
starting iteration  2460
starting iteration  2470
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starting iteration  2860
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starting iteration  2890
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starting iteration  2920
starting iteration  2930
Finished epoch 6 / 20: cost 1.476008, train: 0.514000, val 0.500000, lr
3.675459e-05
starting iteration  2940
starting iteration  2950
starting iteration  2960
starting iteration  2970
starting iteration  2980
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starting iteration  3010
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starting iteration  3400
starting iteration  3410
starting iteration  3420
Finished epoch 7 / 20: cost 1.537347, train: 0.551000, val 0.528000, lr
3.491686e-05
starting iteration  3430
starting iteration  3440
starting iteration  3450
starting iteration  3460
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starting iteration  3870
starting iteration  3880
starting iteration  3890
starting iteration  3900
starting iteration  3910
Finished epoch 8 / 20: cost 1.493411, train: 0.535000, val 0.482000, lr
3.317102e-05
starting iteration  3920
starting iteration  3930
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starting iteration  3960
starting iteration  3970
starting iteration  3980
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starting iteration  4240
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starting iteration  4320
starting iteration  4330
starting iteration  4340
starting iteration  4350
starting iteration  4360
starting iteration  4370
starting iteration  4380
starting iteration  4390
starting iteration  4400
Finished epoch 9 / 20: cost 1.323490, train: 0.548000, val 0.510000, lr
3.151247e-05
starting iteration  4410
starting iteration  4420
starting iteration  4430
starting iteration  4440
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starting iteration  4470
starting iteration  4480
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Finished epoch 10 / 20: cost 1.398117, train: 0.565000, val 0.520000, lr
2.993685e-05
starting iteration  4900
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starting iteration  5160
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starting iteration  5360
starting iteration  5370
starting iteration  5380
Finished epoch 11 / 20: cost 1.619243, train: 0.569000, val 0.508000, lr
2.844000e-05
starting iteration  5390
starting iteration  5400
starting iteration  5410
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starting iteration  5860
starting iteration  5870
Finished epoch 12 / 20: cost 1.483477, train: 0.563000, val 0.523000, lr
2.701800e-05
starting iteration  5880
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Finished epoch 13 / 20: cost 1.403796, train: 0.542000, val 0.523000, lr
2.566710e-05
starting iteration  6370
starting iteration  6380
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Finished epoch 14 / 20: cost 1.512430, train: 0.603000, val 0.525000, lr
2.438375e-05
starting iteration  6860
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starting iteration  7270
starting iteration  7280
starting iteration  7290
starting iteration  7300
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starting iteration  7320
starting iteration  7330
starting iteration  7340
Finished epoch 15 / 20: cost 1.381355, train: 0.591000, val 0.541000, lr
2.316456e-05
starting iteration  7350
starting iteration  7360
starting iteration  7370
starting iteration  7380
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Finished epoch 16 / 20: cost 1.410587, train: 0.602000, val 0.540000, lr
2.200633e-05
starting iteration  7840
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Finished epoch 17 / 20: cost 1.482933, train: 0.619000, val 0.549000, lr
2.090602e-05
starting iteration  8330
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starting iteration  8360
starting iteration  8370
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Finished epoch 18 / 20: cost 1.184236, train: 0.616000, val 0.528000, lr
1.986072e-05
starting iteration  8820
starting iteration  8830
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Finished epoch 19 / 20: cost 1.375873, train: 0.629000, val 0.545000, lr
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1.886768e-05
starting iteration  9310
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starting iteration  9780
starting iteration  9790
Finished epoch 20 / 20: cost 1.288014, train: 0.616000, val 0.535000, lr
1.792430e-05
finished optimization. best validation accuracy: 0.549000
```
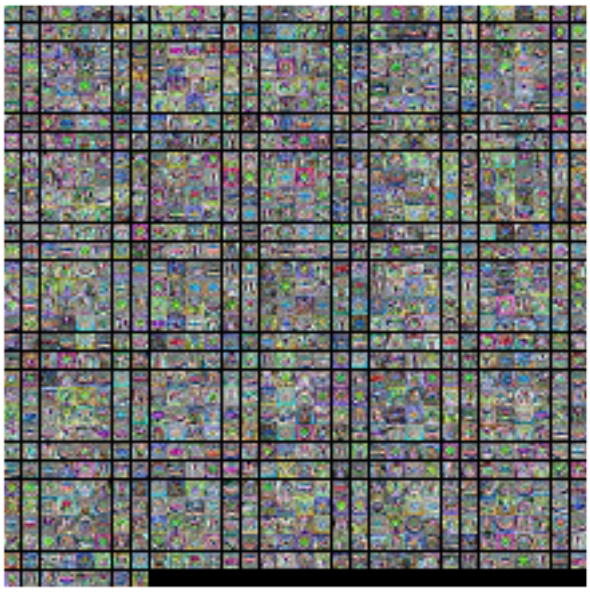

[53]:
```
# visualize the weights
show_net_weights(best_model)
```



10 Run on the test set

When you are done experimenting, you should evaluate your final trained network on the test set.

[54]:
```
scores_test = two_layer_net(X_test, best_model)
print('Test accuracy: ', np.mean(np.argmax(scores_test, axis=1) == y_test))
```

```
Test accuracy:  0.536
```

[ ]:
```

```