Fully-Connected Neural Nets

In the previous homework you implemented a fully-connected two-layer neural network on CIFAR-10. The implementation was simple but not very modular since the loss and gradient were computed in a single monolithic function. This is manageable for a simple two-layer network, but would become impractical as we move to bigger models. Ideally we want to build networks using a more modular design so that we can implement different layer types in isolation and then snap them together into models with different architectures.

In this exercise we will implement fully-connected networks using a more modular approach. For each layer we will implement a `forward` and a `backward` function. The `forward` function will receive inputs, weights, and other parameters and will return both an output and a `cache` object storing data needed for the backward pass, like this:

```
def layer_forward(x, w):
  """ Receive inputs x and weights w """
  # Do some computations ...
  z = # ... some intermediate value
  # Do some more computations ...
  out = # the output

  cache = (x, w, z, out) # Values we need to compute gradients

  return out, cache
```

The backward pass will receive upstream derivatives and the `cache` object, and will return gradients with respect to the inputs and weights, like this:

```
def layer_backward(dout, cache):
  """
  Receive dout (derivative of loss with respect to outputs) and cache,
  and compute derivative with respect to inputs.
  """
  # Unpack cache values
  x, w, z, out = cache

  # Use values in cache to compute derivatives
  dx = # Derivative of loss with respect to x
  dw = # Derivative of loss with respect to w

  return dx, dw
```

After implementing a bunch of layers this way, we will be able to easily combine them to build classifiers with different architectures.

In addition to implementing fully-connected networks of arbitrary depth, we will also explore different update rules for optimization, and introduce Dropout as a regularizer and Batch/Layer Normalization as a tool to more efficiently optimize deep networks.

In [1]:

```
# As usual, a bit of setup
from __future__ import print_function
import time
import numpy as np
import matplotlib.pyplot as plt
from cs231n.classifiers.fc_net import *
from cs231n.data_utils import get_CIFAR10_data
from cs231n.gradient_check import eval_numerical_gradient, eval_numerical_gradie
nt_array
from cs231n.solver import Solver

%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-ipytho
n
%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))))
```

In [2]:

```
# Load the (preprocessed) CIFAR10 data.

data = get_CIFAR10_data()
for k, v in list(data.items()):
  print(('%s: ' % k, v.shape))
```

```
('X_train: ', (49000, 3, 32, 32))
('y_train: ', (49000,))
('X_val: ', (1000, 3, 32, 32))
('y_val: ', (1000,))
('X_test: ', (1000, 3, 32, 32))
('y_test: ', (1000,))
```

Affine layer: foward

Open the file `cs231n/layers.py` and implement the `affine_forward` function.

Once you are done you can test your implementaion by running the following:

In [3]:

```
# Test the affine_forward function

num_inputs = 2
input_shape = (4, 5, 6)
output_dim = 3

input_size = num_inputs * np.prod(input_shape)
weight_size = output_dim * np.prod(input_shape)

x = np.linspace(-0.1, 0.5, num=input_size).reshape(num_inputs, *input_shape)
w = np.linspace(-0.2, 0.3, num=weight_size).reshape(np.prod(input_shape), output
_dim)
b = np.linspace(-0.3, 0.1, num=output_dim)

out, _ = affine_forward(x, w, b)
correct_out = np.array([[ 1.49834967,  1.70660132,  1.91485297],
                        [ 3.25553199,  3.5141327,   3.77273342]])

# Compare your output with ours. The error should be around e-9 or less.
print('Testing affine_forward function:')
print('difference: ', rel_error(out, correct_out))
```

```
Testing affine_forward function:
difference:  9.769847728806635e-10
```

Affine layer: backward

Now implement the `affine_backward` function and test your implementation using numeric gradient checking.

In [4]:

```
# Test the affine_backward function
np.random.seed(231)
x = np.random.randn(10, 2, 3)
w = np.random.randn(6, 5)
b = np.random.randn(5)
dout = np.random.randn(10, 5)

dx_num = eval_numerical_gradient_array(lambda x: affine_forward(x, w, b)[0], x,
dout)
dw_num = eval_numerical_gradient_array(lambda w: affine_forward(x, w, b)[0], w,
dout)
db_num = eval_numerical_gradient_array(lambda b: affine_forward(x, w, b)[0], b,
dout)

_, cache = affine_forward(x, w, b)
dx, dw, db = affine_backward(dout, cache)

# The error should be around e-10 or less
print('Testing affine_backward function:')
print('dx error: ', rel_error(dx_num, dx))
print('dw error: ', rel_error(dw_num, dw))
print('db error: ', rel_error(db_num, db))
```

```
Testing affine_backward function:
dx error:  5.399100368651805e-11
dw error:  9.904023583987626e-11
db error:  2.4122867568119087e-11
```

ReLU activation: forward

Implement the forward pass for the ReLU activation function in the `relu_forward` function and test your implementation using the following:

In [5]:

```
# Test the relu_forward function

x = np.linspace(-0.5, 0.5, num=12).reshape(3, 4)

out, _ = relu_forward(x)
correct_out = np.array([[ 0.,          0.,          0.,          0.,        ],
                        [ 0.,          0.,          0.04545455,  0.13636364,],
                        [ 0.22727273,  0.31818182,  0.40909091,  0.5,       ]])

# Compare your output with ours. The error should be on the order of e-8
print('Testing relu_forward function:')
print('difference: ', rel_error(out, correct_out))
```

```
Testing relu_forward function:
difference:  4.999999798022158e-08
```

ReLU activation: backward

Now implement the backward pass for the ReLU activation function in the `relu_backward` function and test your implementation using numeric gradient checking:

In [6]:

```
np.random.seed(231)
x = np.random.randn(10, 10)
dout = np.random.randn(*x.shape)

dx_num = eval_numerical_gradient_array(lambda x: relu_forward(x)[0], x, dout)

_, cache = relu_forward(x)
dx = relu_backward(dout, cache)

# The error should be on the order of e-12
print('Testing relu_backward function:')
print('dx error: ', rel_error(dx_num, dx))
```

```
Testing relu_backward function:
dx error:  3.2756349136310288e-12
```

Inline Question 1:

We've only asked you to implement ReLU, but there are a number of different activation functions that one could use in neural networks, each with its pros and cons. In particular, an issue commonly seen with activation functions is getting zero (or close to zero) gradient flow during backpropagation. Which of the following activation functions have this problem? If you consider these functions in the one dimensional case, what types of input would lead to this behaviour?

1. Sigmoid
2. ReLU
3. Leaky ReLU

Answer:

[FILL THIS IN]

"Sandwich" layers

There are some common patterns of layers that are frequently used in neural nets. For example, affine layers are frequently followed by a ReLU nonlinearity. To make these common patterns easy, we define several convenience layers in the file `cs231n/layer_utils.py` .

For now take a look at the `affine_relu_forward` and `affine_relu_backward` functions, and run the following to numerically gradient check the backward pass:

In [7]:

```
from cs231n.layer_utils import affine_relu_forward, affine_relu_backward
np.random.seed(231)
x = np.random.randn(2, 3, 4)
w = np.random.randn(12, 10)
b = np.random.randn(10)
dout = np.random.randn(2, 10)

out, cache = affine_relu_forward(x, w, b)
dx, dw, db = affine_relu_backward(dout, cache)

dx_num = eval_numerical_gradient_array(lambda x: affine_relu_forward(x, w, b)[0
], x, dout)
dw_num = eval_numerical_gradient_array(lambda w: affine_relu_forward(x, w, b)[0
], w, dout)
db_num = eval_numerical_gradient_array(lambda b: affine_relu_forward(x, w, b)[0
], b, dout)

# Relative error should be around e-10 or less
print('Testing affine_relu_forward and affine_relu_backward:')
print('dx error: ', rel_error(dx_num, dx))
print('dw error: ', rel_error(dw_num, dw))
print('db error: ', rel_error(db_num, db))
```

```
Testing affine_relu_forward and affine_relu_backward:
dx error:  6.750562121603446e-11
dw error:  8.162015570444288e-11
db error:  7.826724021458994e-12
```

Loss layers: Softmax and SVM

You implemented these loss functions in the last assignment, so we'll give them to you for free here. You should still make sure you understand how they work by looking at the implementations in `cs231n/layers.py` .

You can make sure that the implementations are correct by running the following:

In [8]:

```
np.random.seed(231)
num_classes, num_inputs = 10, 50
x = 0.001 * np.random.randn(num_inputs, num_classes)
y = np.random.randint(num_classes, size=num_inputs)

dx_num = eval_numerical_gradient(lambda x: svm_loss(x, y)[0], x, verbose=False)
loss, dx = svm_loss(x, y)

# Test svm_loss function. Loss should be around 9 and dx error should be around
 the order of e-9
print('Testing svm_loss:')
print('loss: ', loss)
print('dx error: ', rel_error(dx_num, dx))

dx_num = eval_numerical_gradient(lambda x: softmax_loss(x, y)[0], x, verbose=Fal
se)
loss, dx = softmax_loss(x, y)

# Test softmax_loss function. Loss should be close to 2.3 and dx error should be
 around e-8
print('\nTesting softmax_loss:')
print('loss: ', loss)
print('dx error: ', rel_error(dx_num, dx))
```

```
Testing svm_loss:
loss:  8.999602749096233
dx error:  1.4021566006651672e-09

Testing softmax_loss:
loss:  2.302545844500738
dx error:  9.384673161989355e-09
```

Two-layer network

In the previous assignment you implemented a two-layer neural network in a single monolithic class. Now that you have implemented modular versions of the necessary layers, you will reimplement the two layer network using these modular implementations.

Open the file `cs231n/classifiers/fc_net.py` and complete the implementation of the `TwoLayerNet` class. This class will serve as a model for the other networks you will implement in this assignment, so read through it to make sure you understand the API. You can run the cell below to test your implementation.

In [9]:

```
np.random.seed(231)
N, D, H, C = 3, 5, 50, 7
X = np.random.randn(N, D)
y = np.random.randint(C, size=N)

std = 1e-3
model = TwoLayerNet(input_dim=D, hidden_dim=H, num_classes=C, weight_scale=std)

print('Testing initialization ... ')
W1_std = abs(model.params['W1'].std() - std)
b1 = model.params['b1']
W2_std = abs(model.params['W2'].std() - std)
b2 = model.params['b2']
assert W1_std < std / 10, 'First layer weights do not seem right'
assert np.all(b1 == 0), 'First layer biases do not seem right'
assert W2_std < std / 10, 'Second layer weights do not seem right'
assert np.all(b2 == 0), 'Second layer biases do not seem right'

print('Testing test-time forward pass ... ')
model.params['W1'] = np.linspace(-0.7, 0.3, num=D*H).reshape(D, H)
model.params['b1'] = np.linspace(-0.1, 0.9, num=H)
model.params['W2'] = np.linspace(-0.3, 0.4, num=H*C).reshape(H, C)
model.params['b2'] = np.linspace(-0.9, 0.1, num=C)
X = np.linspace(-5.5, 4.5, num=N*D).reshape(D, N).T
scores = model.loss(X)
correct_scores = np.asarray(
  [[11.53165108,  12.2917344,   13.05181771,  13.81190102,  14.57198434, 15.3320
6765,  16.09215096],
   [12.05769098,  12.74614105,  13.43459113,  14.1230412,   14.81149128, 15.4999
4135,  16.18839143],
   [12.58373087,  13.20054771,  13.81736455,  14.43418138,  15.05099822, 15.6678
1506,  16.2846319 ]])
scores_diff = np.abs(scores - correct_scores).sum()
assert scores_diff < 1e-6, 'Problem with test-time forward pass'

print('Testing training loss (no regularization)')
y = np.asarray([0, 5, 1])
loss, grads = model.loss(X, y)
correct_loss = 3.4702243556
assert abs(loss - correct_loss) < 1e-10, 'Problem with training-time loss'

model.reg = 1.0
loss, grads = model.loss(X, y)
correct_loss = 26.5948426952
assert abs(loss - correct_loss) < 1e-10, 'Problem with regularization loss'

# Errors should be around e-7 or less
for reg in [0.0, 0.7]:
  print('Running numeric gradient check with reg = ', reg)
  model.reg = reg
  loss, grads = model.loss(X, y)

  for name in sorted(grads):
    f = lambda _: model.loss(X, y)[0]
    grad_num = eval_numerical_gradient(f, model.params[name], verbose=False)
    print('%s relative error: %.2e' % (name, rel_error(grad_num, grads[name])))
```

```
Testing initialization ...
Testing test-time forward pass ...
Testing training loss (no regularization)
Running numeric gradient check with reg =  0.0
W1 relative error: 1.22e-08
W2 relative error: 3.48e-10
b1 relative error: 6.55e-09
b2 relative error: 4.33e-10
Running numeric gradient check with reg =  0.7
W1 relative error: 8.18e-07
W2 relative error: 2.85e-08
b1 relative error: 1.09e-09
b2 relative error: 7.76e-10
```

Solver

In the previous assignment, the logic for training models was coupled to the models themselves. Following a more modular design, for this assignment we have split the logic for training models into a separate class.

Open the file `cs231n/solver.py` and read through it to familiarize yourself with the API. After doing so, use a `Solver` instance to train a `TwoLayerNet` that achieves at least `50%` accuracy on the validation set.

In [10]:

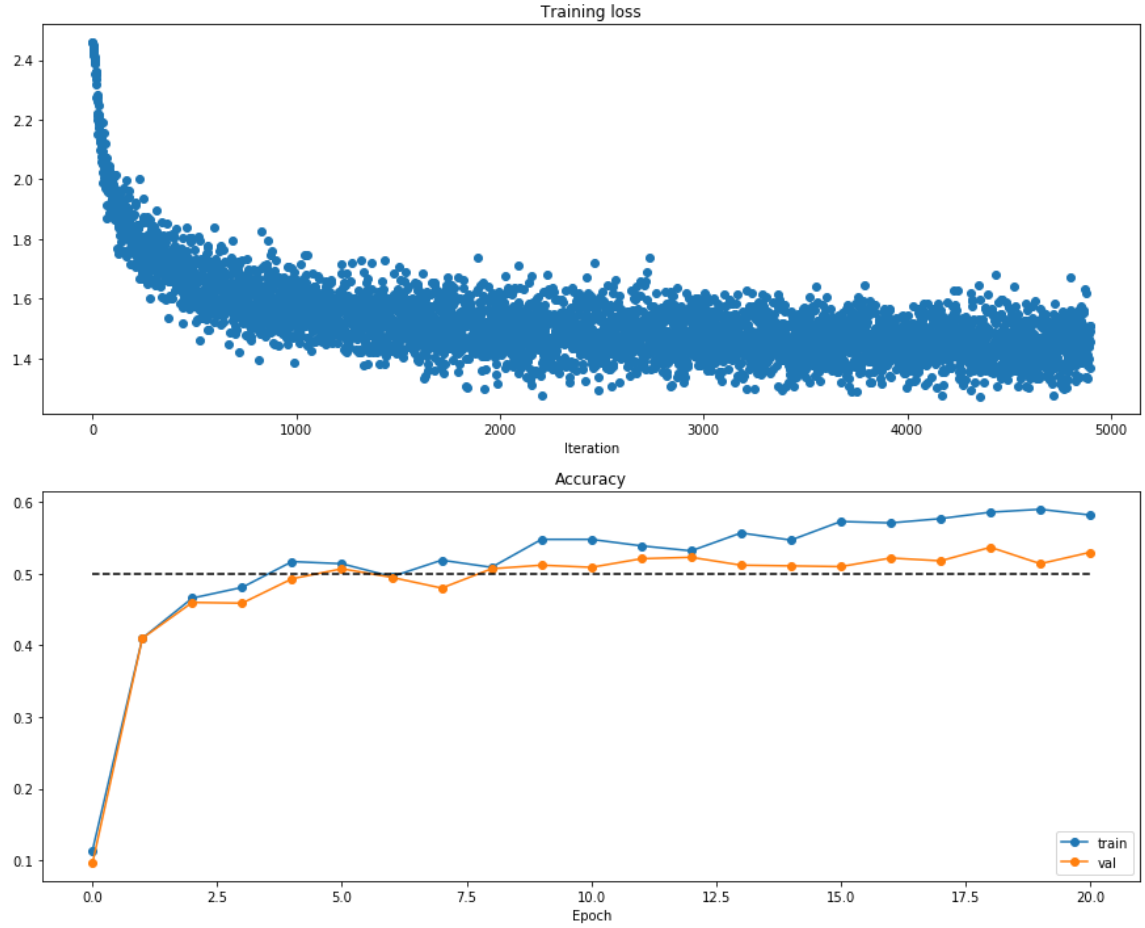
```
model = TwoLayerNet(input_dim=3*32*32, hidden_dim=100, num_classes=10, reg=1.0)
solver = None
################################################################################
# Use a Solver instance to train a TwoLayerNet that achieves at least        #
# 50% accuracy on the validation set.                                          #
################################################################################
solver = Solver(model, data,
                update_rule='sgd',
                optim_config={
                    'learning_rate': 1e-3,
                },
                lr_decay=0.95,
                num_epochs=20, batch_size=200,
                print_every=100)
solver.train()
print('Best Validated Accuracy:', solver.best_val_acc)
################################################################################
#                              END OF YOUR CODE                                #
################################################################################
```

```
(Iteration 1 / 4900) loss: 2.459784
(Epoch 0 / 20) train acc: 0.114000; val_acc: 0.096000
(Iteration 101 / 4900) loss: 2.010333
(Iteration 201 / 4900) loss: 1.755809
(Epoch 1 / 20) train acc: 0.410000; val_acc: 0.410000
(Iteration 301 / 4900) loss: 1.714395
(Iteration 401 / 4900) loss: 1.814213
(Epoch 2 / 20) train acc: 0.466000; val_acc: 0.460000
(Iteration 501 / 4900) loss: 1.620402
(Iteration 601 / 4900) loss: 1.837650
(Iteration 701 / 4900) loss: 1.481639
(Epoch 3 / 20) train acc: 0.481000; val_acc: 0.459000
(Iteration 801 / 4900) loss: 1.571398
(Iteration 901 / 4900) loss: 1.576508
(Epoch 4 / 20) train acc: 0.517000; val_acc: 0.493000
(Iteration 1001 / 4900) loss: 1.647557
(Iteration 1101 / 4900) loss: 1.464961
(Iteration 1201 / 4900) loss: 1.452461
(Epoch 5 / 20) train acc: 0.514000; val_acc: 0.507000
(Iteration 1301 / 4900) loss: 1.588941
(Iteration 1401 / 4900) loss: 1.623165
(Epoch 6 / 20) train acc: 0.496000; val_acc: 0.495000
(Iteration 1501 / 4900) loss: 1.594972
(Iteration 1601 / 4900) loss: 1.403374
(Iteration 1701 / 4900) loss: 1.602380
(Epoch 7 / 20) train acc: 0.519000; val_acc: 0.480000
(Iteration 1801 / 4900) loss: 1.482943
(Iteration 1901 / 4900) loss: 1.548029
(Epoch 8 / 20) train acc: 0.509000; val_acc: 0.507000
(Iteration 2001 / 4900) loss: 1.543690
(Iteration 2101 / 4900) loss: 1.399289
(Iteration 2201 / 4900) loss: 1.534254
(Epoch 9 / 20) train acc: 0.548000; val_acc: 0.512000
(Iteration 2301 / 4900) loss: 1.501427
(Iteration 2401 / 4900) loss: 1.421687
(Epoch 10 / 20) train acc: 0.548000; val_acc: 0.509000
(Iteration 2501 / 4900) loss: 1.547068
(Iteration 2601 / 4900) loss: 1.477136
(Epoch 11 / 20) train acc: 0.539000; val_acc: 0.521000
(Iteration 2701 / 4900) loss: 1.383401
(Iteration 2801 / 4900) loss: 1.381487
(Iteration 2901 / 4900) loss: 1.477882
(Epoch 12 / 20) train acc: 0.532000; val_acc: 0.523000
(Iteration 3001 / 4900) loss: 1.469024
(Iteration 3101 / 4900) loss: 1.524732
(Epoch 13 / 20) train acc: 0.557000; val_acc: 0.512000
(Iteration 3201 / 4900) loss: 1.415082
(Iteration 3301 / 4900) loss: 1.394017
(Iteration 3401 / 4900) loss: 1.415485
(Epoch 14 / 20) train acc: 0.547000; val_acc: 0.511000
(Iteration 3501 / 4900) loss: 1.389711
(Iteration 3601 / 4900) loss: 1.427288
(Epoch 15 / 20) train acc: 0.573000; val_acc: 0.510000
(Iteration 3701 / 4900) loss: 1.364854
(Iteration 3801 / 4900) loss: 1.558920
(Iteration 3901 / 4900) loss: 1.421904
(Epoch 16 / 20) train acc: 0.571000; val_acc: 0.522000
(Iteration 4001 / 4900) loss: 1.366800
(Iteration 4101 / 4900) loss: 1.422116
(Epoch 17 / 20) train acc: 0.577000; val_acc: 0.518000
(Iteration 4201 / 4900) loss: 1.486240
```

```
(Iteration 4301 / 4900) loss: 1.405969
(Iteration 4401 / 4900) loss: 1.484729
(Epoch 18 / 20) train acc: 0.586000; val_acc: 0.537000
(Iteration 4501 / 4900) loss: 1.411897
(Iteration 4601 / 4900) loss: 1.440688
(Epoch 19 / 20) train acc: 0.590000; val_acc: 0.514000
(Iteration 4701 / 4900) loss: 1.327514
(Iteration 4801 / 4900) loss: 1.395546
(Epoch 20 / 20) train acc: 0.582000; val_acc: 0.530000
Best Validated Accuracy: 0.537
```

In [11]:

```
# Run this cell to visualize training loss and train / val accuracy

plt.subplot(2, 1, 1)
plt.title('Training loss')
plt.plot(solver.loss_history, 'o')
plt.xlabel('Iteration')

plt.subplot(2, 1, 2)
plt.title('Accuracy')
plt.plot(solver.train_acc_history, '-o', label='train')
plt.plot(solver.val_acc_history, '-o', label='val')
plt.plot([0.5] * len(solver.val_acc_history), 'k--')
plt.xlabel('Epoch')
plt.legend(loc='lower right')
plt.gcf().set_size_inches(15, 12)
plt.show()
```



Multilayer network

Next you will implement a fully-connected network with an arbitrary number of hidden layers.

Read through the `FullyConnectedNet` class in the file `cs231n/classifiers/fc_net.py`.

Implement the initialization, the forward pass, and the backward pass. For the moment don't worry about implementing dropout or batch/layer normalization; we will add those features soon.

Initial loss and gradient check

As a sanity check, run the following to check the initial loss and to gradient check the network both with and without regularization. Do the initial losses seem reasonable?

For gradient checking, you should expect to see errors around 1e-7 or less.

In [12]:

```
np.random.seed(231)
N, D, H1, H2, C = 2, 15, 20, 30, 10
X = np.random.randn(N, D)
y = np.random.randint(C, size=(N,))

for reg in [0, 3.14]:
  print('Running check with reg = ', reg)
  model = FullyConnectedNet([H1, H2], input_dim=D, num_classes=C,
                            reg=reg, weight_scale=5e-2, dtype=np.float64)

  loss, grads = model.loss(X, y)
  print('Initial loss: ', loss)

  # Most of the errors should be on the order of e-7 or smaller.
  # NOTE: It is fine however to see an error for W2 on the order of e-5
  # for the check when reg = 0.0
  for name in sorted(grads):
    f = lambda _: model.loss(X, y)[0]
    grad_num = eval_numerical_gradient(f, model.params[name], verbose=False, h=1
e-5)
    print('%s relative error: %.2e' % (name, rel_error(grad_num, grads[name])))
```

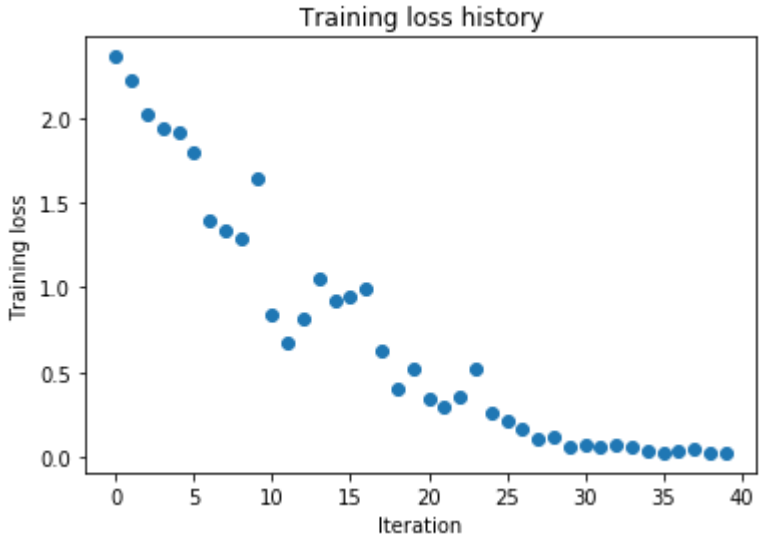
```
Running check with reg =  0
Initial loss:  2.3004790897684924
W1 relative error: 1.48e-07
W2 relative error: 2.21e-05
W3 relative error: 3.53e-07
b1 relative error: 5.38e-09
b2 relative error: 2.09e-09
b3 relative error: 5.80e-11
Running check with reg =  3.14
Initial loss:  7.052114776533016
W1 relative error: 6.86e-09
W2 relative error: 3.52e-08
W3 relative error: 1.32e-08
b1 relative error: 1.48e-08
b2 relative error: 1.72e-09
b3 relative error: 1.80e-10
```

As another sanity check, make sure you can overfit a small dataset of 50 images. First we will try a three-layer network with 100 units in each hidden layer. In the following cell, tweak the learning rate and initialization scale to overfit and achieve 100% training accuracy within 20 epochs.

In [13]:

```
# TODO: Use a three-layer Net to overfit 50 training examples by
# tweaking just the learning rate and initialization scale.

num_train = 50
small_data = {
  'X_train': data['X_train'][:num_train],
  'y_train': data['y_train'][:num_train],
  'X_val': data['X_val'],
  'y_val': data['y_val'],
}

weight_scale = 1e-2
learning_rate = 1e-2
model = FullyConnectedNet([100, 100],
              weight_scale=weight_scale, dtype=np.float64)
solver = Solver(model, small_data,
                print_every=10, num_epochs=20, batch_size=25,
                update_rule='sgd',
                optim_config={
                  'learning_rate': learning_rate,
                }
         )
solver.train()

plt.plot(solver.loss_history, 'o')
plt.title('Training loss history')
plt.xlabel('Iteration')
plt.ylabel('Training loss')
plt.show()
```

```
(Iteration 1 / 40) loss: 2.363364
(Epoch 0 / 20) train acc: 0.180000; val_acc: 0.108000
(Epoch 1 / 20) train acc: 0.320000; val_acc: 0.127000
(Epoch 2 / 20) train acc: 0.440000; val_acc: 0.172000
(Epoch 3 / 20) train acc: 0.500000; val_acc: 0.184000
(Epoch 4 / 20) train acc: 0.540000; val_acc: 0.181000
(Epoch 5 / 20) train acc: 0.740000; val_acc: 0.190000
(Iteration 11 / 40) loss: 0.839976
(Epoch 6 / 20) train acc: 0.740000; val_acc: 0.187000
(Epoch 7 / 20) train acc: 0.740000; val_acc: 0.183000
(Epoch 8 / 20) train acc: 0.820000; val_acc: 0.177000
(Epoch 9 / 20) train acc: 0.860000; val_acc: 0.200000
(Epoch 10 / 20) train acc: 0.920000; val_acc: 0.191000
(Iteration 21 / 40) loss: 0.337174
(Epoch 11 / 20) train acc: 0.960000; val_acc: 0.189000
(Epoch 12 / 20) train acc: 0.940000; val_acc: 0.180000
(Epoch 13 / 20) train acc: 1.000000; val_acc: 0.199000
(Epoch 14 / 20) train acc: 1.000000; val_acc: 0.199000
(Epoch 15 / 20) train acc: 1.000000; val_acc: 0.195000
(Iteration 31 / 40) loss: 0.075911
(Epoch 16 / 20) train acc: 1.000000; val_acc: 0.182000
(Epoch 17 / 20) train acc: 1.000000; val_acc: 0.201000
(Epoch 18 / 20) train acc: 1.000000; val_acc: 0.207000
(Epoch 19 / 20) train acc: 1.000000; val_acc: 0.185000
(Epoch 20 / 20) train acc: 1.000000; val_acc: 0.192000
```



Now try to use a five-layer network with 100 units on each layer to overfit 50 training examples. Again you will have to adjust the learning rate and weight initialization, but you should be able to achieve 100% training accuracy within 20 epochs.

In [14]:

```
# TODO: Use a five-layer Net to overfit 50 training examples by
# tweaking just the learning rate and initialization scale.

num_train = 50
small_data = {
  'X_train': data['X_train'][:num_train],
  'y_train': data['y_train'][:num_train],
  'X_val': data['X_val'],
  'y_val': data['y_val'],
}

learning_rate = 2e-4
weight_scale = 1e-1
model = FullyConnectedNet([100, 100, 100, 100],
                weight_scale=weight_scale, dtype=np.float64)
solver = Solver(model, small_data,
                print_every=10, num_epochs=20, batch_size=25,
                update_rule='sgd',
                optim_config={
                  'learning_rate': learning_rate,
                }
         )
solver.train()

plt.plot(solver.loss_history, 'o')
plt.title('Training loss history')
plt.xlabel('Iteration')
plt.ylabel('Training loss')
plt.show()
```

```
(Iteration 1 / 40) loss: 166.501707
(Epoch 0 / 20) train acc: 0.160000; val_acc: 0.118000
(Epoch 1 / 20) train acc: 0.300000; val_acc: 0.121000
(Epoch 2 / 20) train acc: 0.380000; val_acc: 0.116000
(Epoch 3 / 20) train acc: 0.480000; val_acc: 0.128000
(Epoch 4 / 20) train acc: 0.640000; val_acc: 0.122000
(Epoch 5 / 20) train acc: 0.600000; val_acc: 0.106000
(Iteration 11 / 40) loss: 10.077159
(Epoch 6 / 20) train acc: 0.740000; val_acc: 0.134000
(Epoch 7 / 20) train acc: 0.720000; val_acc: 0.122000
(Epoch 8 / 20) train acc: 0.860000; val_acc: 0.125000
(Epoch 9 / 20) train acc: 0.880000; val_acc: 0.122000
(Epoch 10 / 20) train acc: 0.920000; val_acc: 0.123000
(Iteration 21 / 40) loss: 0.699683
(Epoch 11 / 20) train acc: 0.940000; val_acc: 0.129000
(Epoch 12 / 20) train acc: 0.920000; val_acc: 0.130000
(Epoch 13 / 20) train acc: 0.940000; val_acc: 0.130000
(Epoch 14 / 20) train acc: 0.980000; val_acc: 0.126000
(Epoch 15 / 20) train acc: 0.960000; val_acc: 0.128000
(Iteration 31 / 40) loss: 0.254041
(Epoch 16 / 20) train acc: 0.980000; val_acc: 0.126000
(Epoch 17 / 20) train acc: 0.980000; val_acc: 0.127000
(Epoch 18 / 20) train acc: 0.960000; val_acc: 0.131000
(Epoch 19 / 20) train acc: 1.000000; val_acc: 0.129000
(Epoch 20 / 20) train acc: 1.000000; val_acc: 0.129000
```

Inline Question 2:

Did you notice anything about the comparative difficulty of training the three-layer net vs training the five layer net? In particular, based on your experience, which network seemed more sensitive to the initialization scale? Why do you think that is the case?

Answer:

[FILL THIS IN]

Update rules

So far we have used vanilla stochastic gradient descent (SGD) as our update rule. More sophisticated update rules can make it easier to train deep networks. We will implement a few of the most commonly used update rules and compare them to vanilla SGD.

SGD+Momentum

Stochastic gradient descent with momentum is a widely used update rule that tends to make deep networks converge faster than vanilla stochastic gradient descent. See the Momentum Update section at http://cs231n.github.io/neural-networks-3/#sgd (http://cs231n.github.io/neural-networks-3/#sgd) for more information.

Open the file `cs231n/optim.py` and read the documentation at the top of the file to make sure you understand the API. Implement the SGD+momentum update rule in the function `sgd_momentum` and run the following to check your implementation. You should see errors less than e-8.

In [15]:

```
from cs231n.optim import sgd_momentum

N, D = 4, 5
w = np.linspace(-0.4, 0.6, num=N*D).reshape(N, D)
dw = np.linspace(-0.6, 0.4, num=N*D).reshape(N, D)
v = np.linspace(0.6, 0.9, num=N*D).reshape(N, D)

config = {'learning_rate': 1e-3, 'velocity': v}
next_w, _ = sgd_momentum(w, dw, config=config)

expected_next_w = np.asarray([
  [ 0.1406,      0.20738947,  0.27417895,  0.34096842,  0.40775789],
  [ 0.47454737,  0.54133684,  0.60812632,  0.67491579,  0.74170526],
  [ 0.80849474,  0.87528421,  0.94207368,  1.00886316,  1.07565263],
  [ 1.14244211,  1.20923158,  1.27602105,  1.34281053,  1.4096    ]])
expected_velocity = np.asarray([
  [ 0.5406,      0.55475789,  0.56891579, 0.58307368,  0.59723158],
  [ 0.61138947,  0.62554737,  0.63970526,  0.65386316,  0.66802105],
  [ 0.68217895,  0.69633684,  0.71049474,  0.72465263,  0.73881053],
  [ 0.75296842,  0.76712632,  0.78128421,  0.79544211,  0.8096    ]])

# Should see relative errors around e-8 or less
print('next_w error: ', rel_error(next_w, expected_next_w))
print('velocity error: ', rel_error(expected_velocity, config['velocity']))
```

```
next_w error:  8.882347033505819e-09
velocity error:  4.269287743278663e-09
```

Once you have done so, run the following to train a six-layer network with both SGD and SGD+momentum. You should see the SGD+momentum update rule converge faster.

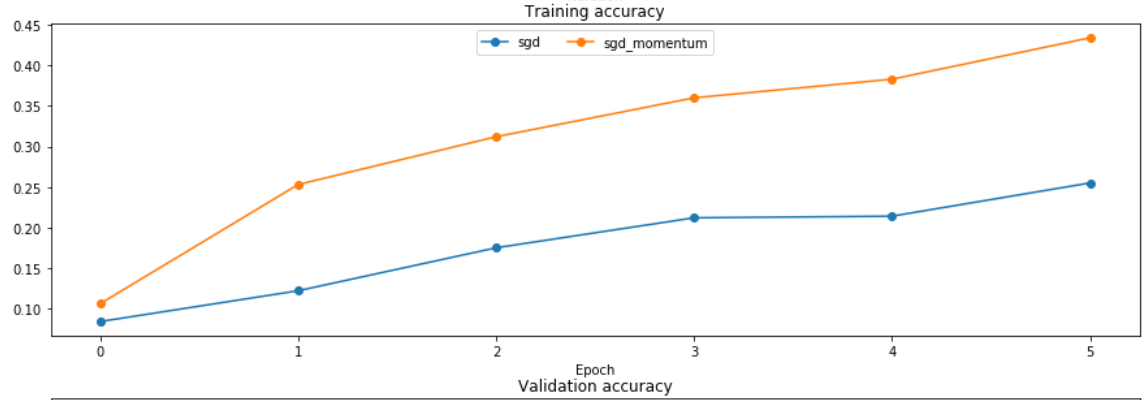
In [16]:

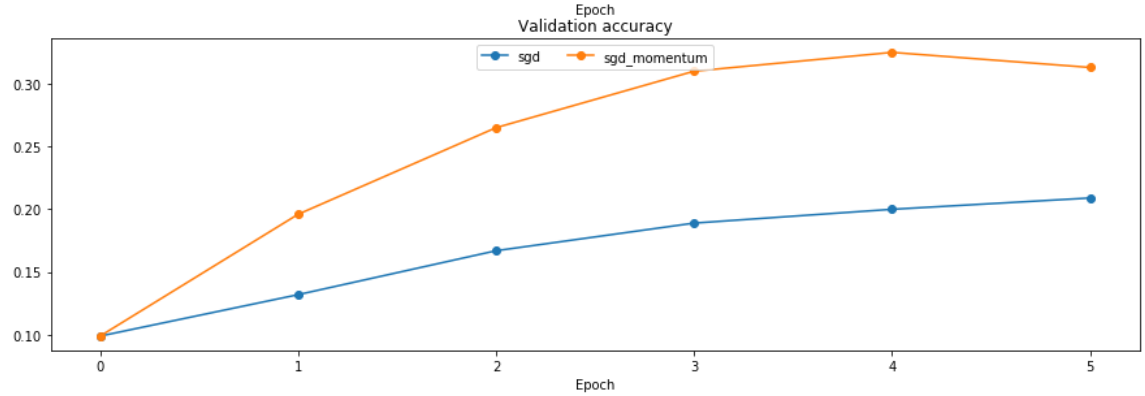
```
num_train = 4000
small_data = {
  'X_train': data['X_train'][:num_train],
  'y_train': data['y_train'][:num_train],
  'X_val': data['X_val'],
  'y_val': data['y_val'],
}

solvers = {}

for update_rule in ['sgd', 'sgd_momentum']:
  print('running with ', update_rule)
  model = FullyConnectedNet([100, 100, 100, 100, 100], weight_scale=5e-2)

  solver = Solver(model, small_data,
                  num_epochs=5, batch_size=100,
                  update_rule=update_rule,
                  optim_config={
                    'learning_rate': 1e-3,
                  },
                  verbose=True)
  solvers[update_rule] = solver
  solver.train()
  print()

plt.subplot(3, 1, 1)
plt.title('Training loss')
plt.xlabel('Iteration')

plt.subplot(3, 1, 2)
plt.title('Training accuracy')
plt.xlabel('Epoch')

plt.subplot(3, 1, 3)
plt.title('Validation accuracy')
plt.xlabel('Epoch')

for update_rule, solver in list(solvers.items()):
  plt.subplot(3, 1, 1)
  plt.plot(solver.loss_history, 'o', label=update_rule)

  plt.subplot(3, 1, 2)
  plt.plot(solver.train_acc_history, '-o', label=update_rule)

  plt.subplot(3, 1, 3)
  plt.plot(solver.val_acc_history, '-o', label=update_rule)

for i in [1, 2, 3]:
  plt.subplot(3, 1, i)
  plt.legend(loc='upper center', ncol=4)
plt.gcf().set_size_inches(15, 15)
plt.show()
```

```
running with  sgd
(Iteration 1 / 200) loss: 2.559978
(Epoch 0 / 5) train acc: 0.084000; val_acc: 0.099000
(Iteration 11 / 200) loss: 2.542560
(Iteration 21 / 200) loss: 2.331715
(Iteration 31 / 200) loss: 2.331713
(Epoch 1 / 5) train acc: 0.122000; val_acc: 0.132000
(Iteration 41 / 200) loss: 2.286616
(Iteration 51 / 200) loss: 2.285883
(Iteration 61 / 200) loss: 2.251813
(Iteration 71 / 200) loss: 2.314993
(Epoch 2 / 5) train acc: 0.175000; val_acc: 0.167000
(Iteration 81 / 200) loss: 2.260731
(Iteration 91 / 200) loss: 2.190671
(Iteration 101 / 200) loss: 2.219679
(Iteration 111 / 200) loss: 2.182050
(Epoch 3 / 5) train acc: 0.212000; val_acc: 0.189000
(Iteration 121 / 200) loss: 2.153370
(Iteration 131 / 200) loss: 2.171419
(Iteration 141 / 200) loss: 2.262907
(Iteration 151 / 200) loss: 2.183984
(Epoch 4 / 5) train acc: 0.214000; val_acc: 0.200000
(Iteration 161 / 200) loss: 2.174004
(Iteration 171 / 200) loss: 2.220756
(Iteration 181 / 200) loss: 2.092740
(Iteration 191 / 200) loss: 2.142216
(Epoch 5 / 5) train acc: 0.255000; val_acc: 0.209000

running with  sgd_momentum
(Iteration 1 / 200) loss: 3.153778
(Epoch 0 / 5) train acc: 0.106000; val_acc: 0.099000
(Iteration 11 / 200) loss: 2.363123
(Iteration 21 / 200) loss: 2.264722
(Iteration 31 / 200) loss: 2.064652
(Epoch 1 / 5) train acc: 0.253000; val_acc: 0.196000
(Iteration 41 / 200) loss: 2.047322
(Iteration 51 / 200) loss: 1.911808
(Iteration 61 / 200) loss: 1.895158
(Iteration 71 / 200) loss: 2.047965
(Epoch 2 / 5) train acc: 0.312000; val_acc: 0.265000
(Iteration 81 / 200) loss: 2.047845
(Iteration 91 / 200) loss: 1.886363
(Iteration 101 / 200) loss: 1.712218
(Iteration 111 / 200) loss: 1.648467
(Epoch 3 / 5) train acc: 0.360000; val_acc: 0.310000
(Iteration 121 / 200) loss: 1.900023
(Iteration 131 / 200) loss: 1.766267
(Iteration 141 / 200) loss: 1.732521
(Iteration 151 / 200) loss: 1.968742
(Epoch 4 / 5) train acc: 0.383000; val_acc: 0.325000
(Iteration 161 / 200) loss: 1.634582
(Iteration 171 / 200) loss: 1.688223
(Iteration 181 / 200) loss: 1.596789
(Iteration 191 / 200) loss: 1.627381
(Epoch 5 / 5) train acc: 0.434000; val_acc: 0.313000
```

```
/home/tanishq/anaconda3/lib/python3.7/site-packages/matplotlib/figur
e.py:98: MatplotlibDeprecationWarning:
Adding an axes using the same arguments as a previous axes currently
reuses the earlier instance.  In a future version, a new instance wi
ll always be created and returned.  Meanwhile, this warning can be s
uppressed, and the future behavior ensured, by passing a unique labe
l to each axes instance.
  "Adding an axes using the same arguments as a previous axes "
```


Training loss
sgd
sgd_momentum
3.00
2.75
2.50
2.25
2.00
1.75
1.50
0
25
50
75
100
125
150
175
200
Iteration


Training accuracy
sgd
sgd_momentum
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0
1
2
3
4
5
Epoch


Validation accuracy
sgd
sgd_momentum
0.30
0.25
0.20
0.15
0.10
0
1
2
3
4
5
Epoch

RMSProp and Adam

RMSProp [1] and Adam [2] are update rules that set per-parameter learning rates by using a running average of the second moments of gradients.

In the file `cs231n/optim.py`, implement the RMSProp update rule in the `rmsprop` function and implement the Adam update rule in the `adam` function, and check your implementations using the tests below.

NOTE: Please implement the *complete* Adam update rule (with the bias correction mechanism), not the first simplified version mentioned in the course notes.

[1] Tijmen Tieleman and Geoffrey Hinton. "Lecture 6.5-rmsprop: Divide the gradient by a running average of its recent magnitude." COURSERA: Neural Networks for Machine Learning 4 (2012).

[2] Diederik Kingma and Jimmy Ba, "Adam: A Method for Stochastic Optimization", ICLR 2015.

In [17]:

```
# Test RMSProp implementation
from cs231n.optim import rmsprop

N, D = 4, 5
w = np.linspace(-0.4, 0.6, num=N*D).reshape(N, D)
dw = np.linspace(-0.6, 0.4, num=N*D).reshape(N, D)
cache = np.linspace(0.6, 0.9, num=N*D).reshape(N, D)

config = {'learning_rate': 1e-2, 'cache': cache}
next_w, _ = rmsprop(w, dw, config=config)

expected_next_w = np.asarray([
  [-0.39223849, -0.34037513, -0.28849239, -0.23659121, -0.18467247],
  [-0.132737,   -0.08078555, -0.02881884,  0.02316247,  0.07515774],
  [ 0.12716641,  0.17918792,  0.23122175,  0.28326742,  0.33532447],
  [ 0.38739248,  0.43947102,  0.49155973,  0.54365823,  0.59576619]])
expected_cache = np.asarray([
  [ 0.5976,      0.6126277,   0.6277108,   0.64284931,  0.65804321],
  [ 0.67329252,  0.68859723,  0.70395734,  0.71937285,  0.73484377],
  [ 0.75037008,  0.7659518,   0.78158892,  0.79728144,  0.81302936],
  [ 0.82883269,  0.84469141,  0.86060554,  0.87657507,  0.8926    ]])

# You should see relative errors around e-7 or less
print('next_w error: ', rel_error(expected_next_w, next_w))
print('cache error: ', rel_error(expected_cache, config['cache']))
```

```
next_w error:  9.524687511038133e-08
cache error:  2.6477955807156126e-09
```

In [18]:

```
# Test Adam implementation
from cs231n.optim import adam

N, D = 4, 5
w = np.linspace(-0.4, 0.6, num=N*D).reshape(N, D)
dw = np.linspace(-0.6, 0.4, num=N*D).reshape(N, D)
m = np.linspace(0.6, 0.9, num=N*D).reshape(N, D)
v = np.linspace(0.7, 0.5, num=N*D).reshape(N, D)

config = {'learning_rate': 1e-2, 'm': m, 'v': v, 't': 5}
next_w, _ = adam(w, dw, config=config)

expected_next_w = np.asarray([
  [-0.40094747, -0.34836187, -0.29577703, -0.24319299, -0.19060977],
  [-0.1380274,  -0.08544591, -0.03286534,  0.01971428,  0.0722929],
  [ 0.1248705,   0.17744702,  0.23002243,  0.28259667,  0.33516969],
  [ 0.38774145,  0.44031188,  0.49288093,  0.54544852,  0.59801459]])
expected_v = np.asarray([
  [ 0.69966,     0.68908382,  0.67851319,  0.66794809,  0.65738853,],
  [ 0.64683452,  0.63628604,  0.6257431,   0.61520571,  0.60467385,],
  [ 0.59414753,  0.58362676,  0.57311152,  0.56260183,  0.55209767,],
  [ 0.54159906,  0.53110598,  0.52061845,  0.51013645,  0.49966,   ]])
expected_m = np.asarray([
  [ 0.48,        0.49947368,  0.51894737,  0.53842105,  0.55789474],
  [ 0.57736842,  0.59684211,  0.61631579,  0.63578947,  0.65526316],
  [ 0.67473684,  0.69421053,  0.71368421,  0.73315789,  0.75263158],
  [ 0.77210526,  0.79157895,  0.81105263,  0.83052632,  0.85      ]])

# You should see relative errors around e-7 or less
print('next_w error: ', rel_error(expected_next_w, next_w))
print('v error: ', rel_error(expected_v, config['v']))
print('m error: ', rel_error(expected_m, config['m']))
```

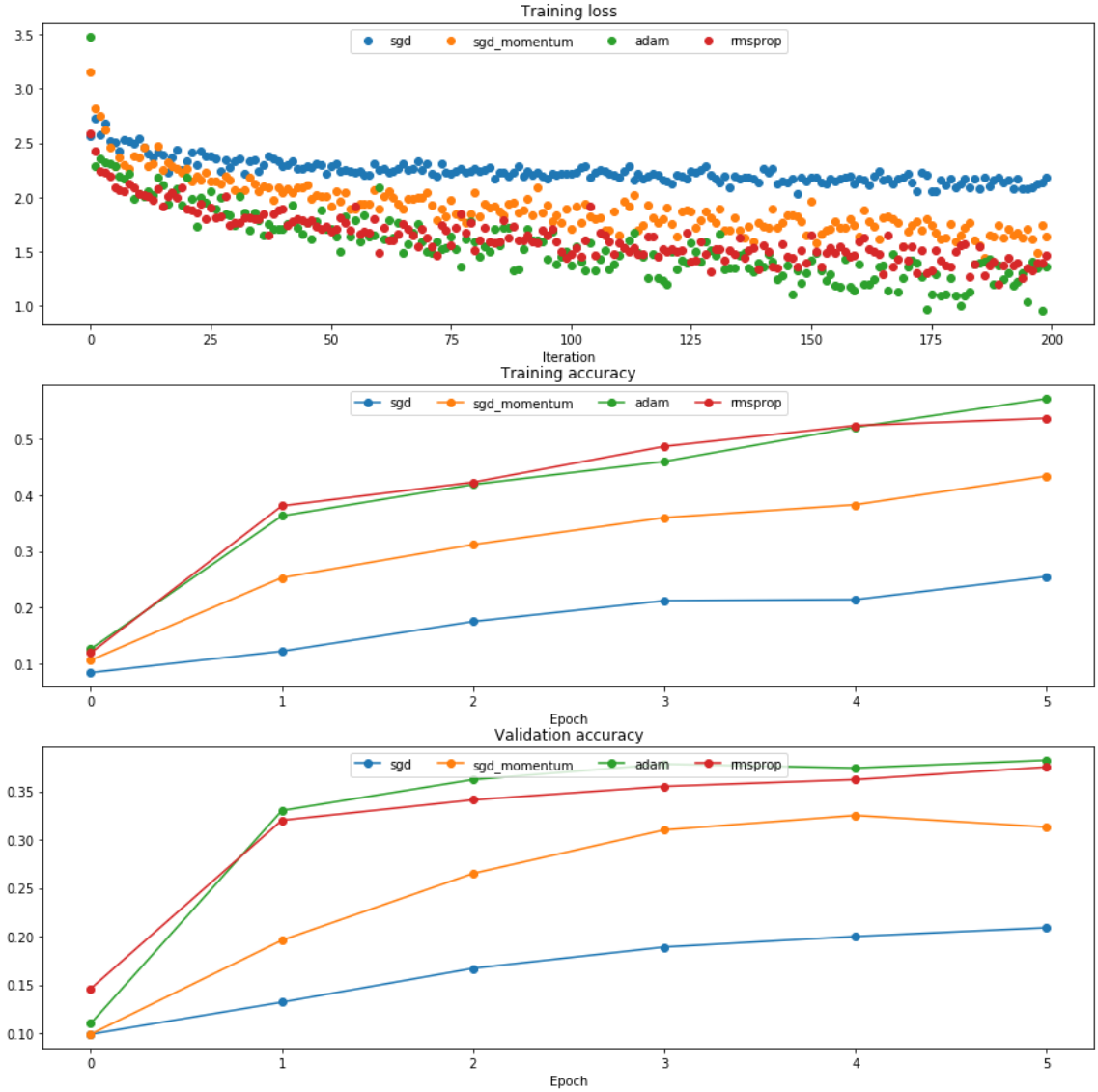
```
next_w error:  1.1395691798535431e-07
v error:  4.208314038113071e-09
m error:  4.214963193114416e-09
```

Once you have debugged your RMSProp and Adam implementations, run the following to train a pair of deep networks using these new update rules:

In [19]:

```
learning_rates = {'rmsprop': 1e-4, 'adam': 1e-3}
for update_rule in ['adam', 'rmsprop']:
  print('running with ', update_rule)
  model = FullyConnectedNet([100, 100, 100, 100, 100], weight_scale=5e-2)

  solver = Solver(model, small_data,
                  num_epochs=5, batch_size=100,
                  update_rule=update_rule,
                  optim_config={
                    'learning_rate': learning_rates[update_rule]
                  },
                  verbose=True)
  solvers[update_rule] = solver
  solver.train()
  print()

plt.subplot(3, 1, 1)
plt.title('Training loss')
plt.xlabel('Iteration')

plt.subplot(3, 1, 2)
plt.title('Training accuracy')
plt.xlabel('Epoch')

plt.subplot(3, 1, 3)
plt.title('Validation accuracy')
plt.xlabel('Epoch')

for update_rule, solver in list(solvers.items()):
  plt.subplot(3, 1, 1)
  plt.plot(solver.loss_history, 'o', label=update_rule)

  plt.subplot(3, 1, 2)
  plt.plot(solver.train_acc_history, '-o', label=update_rule)

  plt.subplot(3, 1, 3)
  plt.plot(solver.val_acc_history, '-o', label=update_rule)

for i in [1, 2, 3]:
  plt.subplot(3, 1, i)
  plt.legend(loc='upper center', ncol=4)
plt.gcf().set_size_inches(15, 15)
plt.show()
```

```
running with  adam
(Iteration 1 / 200) loss: 3.476928
(Epoch 0 / 5) train acc: 0.126000; val_acc: 0.110000
(Iteration 11 / 200) loss: 2.027712
(Iteration 21 / 200) loss: 2.183358
(Iteration 31 / 200) loss: 1.744257
(Epoch 1 / 5) train acc: 0.363000; val_acc: 0.330000
(Iteration 41 / 200) loss: 1.707951
(Iteration 51 / 200) loss: 1.703835
(Iteration 61 / 200) loss: 2.094758
(Iteration 71 / 200) loss: 1.505558
(Epoch 2 / 5) train acc: 0.419000; val_acc: 0.362000
(Iteration 81 / 200) loss: 1.594429
(Iteration 91 / 200) loss: 1.519017
(Iteration 101 / 200) loss: 1.368523
(Iteration 111 / 200) loss: 1.470400
(Epoch 3 / 5) train acc: 0.460000; val_acc: 0.378000
(Iteration 121 / 200) loss: 1.199064
(Iteration 131 / 200) loss: 1.464705
(Iteration 141 / 200) loss: 1.359863
(Iteration 151 / 200) loss: 1.415069
(Epoch 4 / 5) train acc: 0.521000; val_acc: 0.374000
(Iteration 161 / 200) loss: 1.382818
(Iteration 171 / 200) loss: 1.359900
(Iteration 181 / 200) loss: 1.095948
(Iteration 191 / 200) loss: 1.243087
(Epoch 5 / 5) train acc: 0.572000; val_acc: 0.382000

running with  rmsprop
(Iteration 1 / 200) loss: 2.589166
(Epoch 0 / 5) train acc: 0.119000; val_acc: 0.146000
(Iteration 11 / 200) loss: 2.032921
(Iteration 21 / 200) loss: 1.897277
(Iteration 31 / 200) loss: 1.770793
(Epoch 1 / 5) train acc: 0.381000; val_acc: 0.320000
(Iteration 41 / 200) loss: 1.895731
(Iteration 51 / 200) loss: 1.681091
(Iteration 61 / 200) loss: 1.486923
(Iteration 71 / 200) loss: 1.628511
(Epoch 2 / 5) train acc: 0.423000; val_acc: 0.341000
(Iteration 81 / 200) loss: 1.506182
(Iteration 91 / 200) loss: 1.600674
(Iteration 101 / 200) loss: 1.478501
(Iteration 111 / 200) loss: 1.577709
(Epoch 3 / 5) train acc: 0.487000; val_acc: 0.355000
(Iteration 121 / 200) loss: 1.495931
(Iteration 131 / 200) loss: 1.525799
(Iteration 141 / 200) loss: 1.552580
(Iteration 151 / 200) loss: 1.654283
(Epoch 4 / 5) train acc: 0.524000; val_acc: 0.362000
(Iteration 161 / 200) loss: 1.589372
(Iteration 171 / 200) loss: 1.413529
(Iteration 181 / 200) loss: 1.500597
(Iteration 191 / 200) loss: 1.367965
(Epoch 5 / 5) train acc: 0.537000; val_acc: 0.375000
```



Inline Question 3:

AdaGrad, like Adam, is a per-parameter optimization method that uses the following update rule:

```
cache += dw**2
w += - learning_rate * dw / (np.sqrt(cache) + eps)
```

John notices that when he was training a network with AdaGrad that the updates became very small, and that his network was learning slowly. Using your knowledge of the AdaGrad update rule, why do you think the updates would become very small? Would Adam have the same issue?

Answer:

Train a good model!

Train the best fully-connected model that you can on CIFAR-10, storing your best model in the `best_model` variable. We require you to get at least 50% accuracy on the validation set using a fully-connected net.

If you are careful it should be possible to get accuracies above 55%, but we don't require it for this part and won't assign extra credit for doing so. Later in the assignment we will ask you to train the best convolutional network that you can on CIFAR-10, and we would prefer that you spend your effort working on convolutional nets rather than fully-connected nets.

You might find it useful to complete the `BatchNormalization.ipynb` and `Dropout.ipynb` notebooks before completing this part, since those techniques can help you train powerful models.

In [22]:

```
best_model = None
################################################################################
# Train the best FullyConnectedNet that you can on CIFAR-10. You might         #
# find batch/layer normalization and dropout useful. Store your best model in  #
# the best_model variable.                                                     #
################################################################################
best_model = FullyConnectedNet([100, 100, 100, 100, 100],
                               weight_scale=5e-2,
                               normalization='batchnorm',
                               reg=0.0)
solver = Solver(best_model, data,
                  num_epochs=10, batch_size=200,
                  update_rule='adam',
                  print_every=1000,
                  optim_config={
                    'learning_rate': 1e-3
                  },
                  verbose=True)
solver.train()
################################################################################
#                              END OF YOUR CODE                                #
################################################################################
```

```
(Iteration 1 / 2450) loss: 2.346419
(Epoch 0 / 10) train acc: 0.117000; val_acc: 0.126000
(Epoch 1 / 10) train acc: 0.463000; val_acc: 0.447000
(Epoch 2 / 10) train acc: 0.529000; val_acc: 0.496000
(Epoch 3 / 10) train acc: 0.556000; val_acc: 0.506000
(Epoch 4 / 10) train acc: 0.568000; val_acc: 0.524000
(Iteration 1001 / 2450) loss: 1.206724
(Epoch 5 / 10) train acc: 0.585000; val_acc: 0.515000
(Epoch 6 / 10) train acc: 0.641000; val_acc: 0.526000
(Epoch 7 / 10) train acc: 0.633000; val_acc: 0.526000
(Epoch 8 / 10) train acc: 0.670000; val_acc: 0.534000
(Iteration 2001 / 2450) loss: 1.194888
(Epoch 9 / 10) train acc: 0.665000; val_acc: 0.544000
(Epoch 10 / 10) train acc: 0.693000; val_acc: 0.535000
```

Test your model!

Run your best model on the validation and test sets. You should achieve above 50% accuracy on the validation set.

In [23]:

```
y_test_pred = np.argmax(best_model.loss(data['X_test']), axis=1)
y_val_pred = np.argmax(best_model.loss(data['X_val']), axis=1)
print('Validation set accuracy: ', (y_val_pred == data['y_val']).mean())
print('Test set accuracy: ', (y_test_pred == data['y_test']).mean())
```

```
Validation set accuracy:  0.521
Test set accuracy:  0.514
```

In [ ]:

```

```

Batch Normalization

One way to make deep networks easier to train is to use more sophisticated optimization procedures such as SGD+momentum, RMSProp, or Adam. Another strategy is to change the architecture of the network to make it easier to train. One idea along these lines is batch normalization which was proposed by [3] in 2015.

The idea is relatively straightforward. Machine learning methods tend to work better when their input data consists of uncorrelated features with zero mean and unit variance. When training a neural network, we can preprocess the data before feeding it to the network to explicitly decorrelate its features; this will ensure that the first layer of the network sees data that follows a nice distribution. However, even if we preprocess the input data, the activations at deeper layers of the network will likely no longer be decorrelated and will no longer have zero mean or unit variance since they are output from earlier layers in the network. Even worse, during the training process the distribution of features at each layer of the network will shift as the weights of each layer are updated.

The authors of [3] hypothesize that the shifting distribution of features inside deep neural networks may make training deep networks more difficult. To overcome this problem, [3] proposes to insert batch normalization layers into the network. At training time, a batch normalization layer uses a minibatch of data to estimate the mean and standard deviation of each feature. These estimated means and standard deviations are then used to center and normalize the features of the minibatch. A running average of these means and standard deviations is kept during training, and at test time these running averages are used to center and normalize features.

It is possible that this normalization strategy could reduce the representational power of the network, since it may sometimes be optimal for certain layers to have features that are not zero-mean or unit variance. To this end, the batch normalization layer includes learnable shift and scale parameters for each feature dimension.

[3] Sergey Ioffe and Christian Szegedy, "Batch Normalization: Accelerating Deep Network Training by Reducing Internal Covariate Shift", ICML 2015. (https://arxiv.org/abs/1502.03167)

In [1]:

```
# As usual, a bit of setup
import time
import numpy as np
import matplotlib.pyplot as plt
from cs231n.classifiers.fc_net import *
from cs231n.data_utils import get_CIFAR10_data
from cs231n.gradient_check import eval_numerical_gradient, eval_numerical_gradie
nt_array
from cs231n.solver import Solver

%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-ipytho
n
%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))))

def print_mean_std(x,axis=0):
    print('  means: ', x.mean(axis=axis))
    print('  stds:  ', x.std(axis=axis))
    print()
```

In [2]:

```
# Load the (preprocessed) CIFAR10 data.
data = get_CIFAR10_data()
for k, v in data.items():
  print('%s: ' % k, v.shape)
```

```
X_train:  (49000, 3, 32, 32)
y_train:  (49000,)
X_val:  (1000, 3, 32, 32)
y_val:  (1000,)
X_test:  (1000, 3, 32, 32)
y_test:  (1000,)
```

Batch normalization: forward

In the file `cs231n/layers.py`, implement the batch normalization forward pass in the function `batchnorm_forward`. Once you have done so, run the following to test your implementation.

Referencing the paper linked to above would be helpful!

In [3]:

```
# Check the training-time forward pass by checking means and variances
# of features both before and after batch normalization

# Simulate the forward pass for a two-layer network
np.random.seed(231)
N, D1, D2, D3 = 200, 50, 60, 3
X = np.random.randn(N, D1)
W1 = np.random.randn(D1, D2)
W2 = np.random.randn(D2, D3)
a = np.maximum(0, X.dot(W1)).dot(W2)

print('Before batch normalization:')
print_mean_std(a,axis=0)

gamma = np.ones((D3,))
beta = np.zeros((D3,))
# Means should be close to zero and stds close to one
print('After batch normalization (gamma=1, beta=0)')
a_norm, _ = batchnorm_forward(a, gamma, beta, {'mode': 'train'})
print_mean_std(a_norm,axis=0)

gamma = np.asarray([1.0, 2.0, 3.0])
beta = np.asarray([11.0, 12.0, 13.0])
# Now means should be close to beta and stds close to gamma
print('After batch normalization (gamma=', gamma, ', beta=', beta, ')')
a_norm, _ = batchnorm_forward(a, gamma, beta, {'mode': 'train'})
print_mean_std(a_norm,axis=0)
```

```
Before batch normalization:
  means:  [ -2.3814598  -13.18038246   1.91780462]
  stds:   [27.18502186 34.21455511 37.68611762]

After batch normalization (gamma=1, beta=0)
  means:  [2.22044605e-17 8.16013923e-17 4.46864767e-17]
  stds:   [0.99999999 1.         1.        ]

After batch normalization (gamma= [1. 2. 3.] , beta= [11. 12. 13.] )
  means:  [11. 12. 13.]
  stds:   [0.99999999 1.99999999 2.99999999]
```

In [4]:

```
# Check the test-time forward pass by running the training-time
# forward pass many times to warm up the running averages, and then
# checking the means and variances of activations after a test-time
# forward pass.

np.random.seed(231)
N, D1, D2, D3 = 200, 50, 60, 3
W1 = np.random.randn(D1, D2)
W2 = np.random.randn(D2, D3)

bn_param = {'mode': 'train'}
gamma = np.ones(D3)
beta = np.zeros(D3)

for t in range(50):
  X = np.random.randn(N, D1)
  a = np.maximum(0, X.dot(W1)).dot(W2)
  batchnorm_forward(a, gamma, beta, bn_param)

bn_param['mode'] = 'test'
X = np.random.randn(N, D1)
a = np.maximum(0, X.dot(W1)).dot(W2)
a_norm, _ = batchnorm_forward(a, gamma, beta, bn_param)

# Means should be close to zero and stds close to one, but will be
# noisier than training-time forward passes.
print('After batch normalization (test-time):')
print_mean_std(a_norm,axis=0)
```

```
After batch normalization (test-time):
  means:  [-0.03927354 -0.04349152 -0.10452688]
  stds:   [1.01531428 1.01238373 0.97819988]
```

Batch normalization: backward

Now implement the backward pass for batch normalization in the function `batchnorm_backward`.

To derive the backward pass you should write out the computation graph for batch normalization and backprop through each of the intermediate nodes. Some intermediates may have multiple outgoing branches; make sure to sum gradients across these branches in the backward pass.

Once you have finished, run the following to numerically check your backward pass.

In [5]:

```
# Gradient check batchnorm backward pass
np.random.seed(231)
N, D = 4, 5
x = 5 * np.random.randn(N, D) + 12
gamma = np.random.randn(D)
beta = np.random.randn(D)
dout = np.random.randn(N, D)

bn_param = {'mode': 'train'}
fx = lambda x: batchnorm_forward(x, gamma, beta, bn_param)[0]
fg = lambda a: batchnorm_forward(x, a, beta, bn_param)[0]
fb = lambda b: batchnorm_forward(x, gamma, b, bn_param)[0]

dx_num = eval_numerical_gradient_array(fx, x, dout)
da_num = eval_numerical_gradient_array(fg, gamma.copy(), dout)
db_num = eval_numerical_gradient_array(fb, beta.copy(), dout)

_, cache = batchnorm_forward(x, gamma, beta, bn_param)
dx, dgamma, dbeta = batchnorm_backward(dout, cache)
#You should expect to see relative errors between 1e-13 and 1e-8
print('dx error: ', rel_error(dx_num, dx))
print('dgamma error: ', rel_error(da_num, dgamma))
print('dbeta error: ', rel_error(db_num, dbeta))
```

```
dx error:  1.7029235612572515e-09
dgamma error:  7.420414216247087e-13
dbeta error:  2.8795057655839487e-12
```

Batch normalization: alternative backward

In class we talked about two different implementations for the sigmoid backward pass. One strategy is to write out a computation graph composed of simple operations and backprop through all intermediate values. Another strategy is to work out the derivatives on paper. For example, you can derive a very simple formula for the sigmoid function's backward pass by simplifying gradients on paper.

Surprisingly, it turns out that you can do a similar simplification for the batch normalization backward pass too.

Given a set of inputs $X = \begin{bmatrix} x_1 \\ x_2 \\ \dots \\ x_N \end{bmatrix}$, we first calculate the mean $\mu = \frac{1}{N}\sum_{k=1}^{N} x_k$ and variance $v = \frac{1}{N}\sum_{k=1}^{N}(x_k - \mu)^2$.
With μ and v calculated, we can calculate the standard deviation $\sigma = \sqrt{v + \epsilon}$ and normalized data Y with $y_i = \frac{x_i - \mu}{\sigma}$.

The meat of our problem is to get $\frac{\partial L}{\partial X}$ from the upstream gradient $\frac{\partial L}{\partial Y}$. It might be challenging to directly reason about the gradients over X and Y - try reasoning about it in terms of x_i and y_i first.

You will need to come up with the derivations for $\frac{\partial L}{\partial x_i}$, by relying on the Chain Rule to first calculate the intermediate $\frac{\partial \mu}{\partial x_i}$, $\frac{\partial v}{\partial x_i}$, $\frac{\partial \sigma}{\partial x_i}$, then assemble these pieces to calculate $\frac{\partial y_i}{\partial x_i}$. You should make sure each of the intermediary steps are all as simple as possible.

After doing so, implement the simplified batch normalization backward pass in the function `batchnorm_backward_alt` and compare the two implementations by running the following. Your two implementations should compute nearly identical results, but the alternative implementation should be a bit faster.

In [6]:

```
np.random.seed(231)
N, D = 100, 500
x = 5 * np.random.randn(N, D) + 12
gamma = np.random.randn(D)
beta = np.random.randn(D)
dout = np.random.randn(N, D)

bn_param = {'mode': 'train'}
out, cache = batchnorm_forward(x, gamma, beta, bn_param)

t1 = time.time()
dx1, dgamma1, dbeta1 = batchnorm_backward(dout, cache)
t2 = time.time()
dx2, dgamma2, dbeta2 = batchnorm_backward_alt(dout, cache)
t3 = time.time()

print('dx difference: ', rel_error(dx1, dx2))
print('dgamma difference: ', rel_error(dgamma1, dgamma2))
print('dbeta difference: ', rel_error(dbeta1, dbeta2))
print('speedup: %.2fx' % ((t2 - t1) / (t3 - t2)))
```

```
dx difference:  1.3630859035235324e-12
dgamma difference:  0.0
dbeta difference:  0.0
speedup: 1.70x
```

Fully Connected Nets with Batch Normalization

Now that you have a working implementation for batch normalization, go back to your `FullyConnectedNet` in the file `cs231n/classifiers/fc_net.py`. Modify your implementation to add batch normalization.

Concretely, when the `normalization` flag is set to `"batchnorm"` in the constructor, you should insert a batch normalization layer before each ReLU nonlinearity. The outputs from the last layer of the network should not be normalized. Once you are done, run the following to gradient-check your implementation.

HINT: You might find it useful to define an additional helper layer similar to those in the file `cs231n/layer_utils.py`. If you decide to do so, do it in the file `cs231n/classifiers/fc_net.py`.

In [7]:

```
np.random.seed(231)
N, D, H1, H2, C = 2, 15, 20, 30, 10
X = np.random.randn(N, D)
y = np.random.randint(C, size=(N,))

# You should expect losses between 1e-4~1e-10 for W,
# losses between 1e-08~1e-10 for b,
# and losses between 1e-08~1e-09 for beta and gammas.
for reg in [0, 3.14]:
  print('Running check with reg = ', reg)
  model = FullyConnectedNet([H1, H2], input_dim=D, num_classes=C,
                            reg=reg, weight_scale=5e-2, dtype=np.float64,
                            normalization='batchnorm')

  loss, grads = model.loss(X, y)
  print('Initial loss: ', loss)

  for name in sorted(grads):
    f = lambda _: model.loss(X, y)[0]
    grad_num = eval_numerical_gradient(f, model.params[name], verbose=False, h=1
e-5)
    print('%s relative error: %.2e' % (name, rel_error(grad_num, grads[name])))
  if reg == 0: print()
```

```
Running check with reg =  0
Initial loss:  2.2611955101340957
W1 relative error: 1.10e-04
W2 relative error: 2.85e-06
W3 relative error: 3.92e-10
b1 relative error: 1.05e-08
b2 relative error: 2.19e-07
b3 relative error: 4.78e-11
beta1 relative error: 7.33e-09
beta2 relative error: 1.89e-09
gamma1 relative error: 7.57e-09
gamma2 relative error: 1.96e-09

Running check with reg =  3.14
Initial loss:  6.996533220108303
W1 relative error: 1.98e-06
W2 relative error: 2.29e-06
W3 relative error: 1.11e-08
b1 relative error: 1.12e-08
b2 relative error: 2.27e-08
b3 relative error: 2.23e-10
beta1 relative error: 6.65e-09
beta2 relative error: 3.48e-09
gamma1 relative error: 5.94e-09
gamma2 relative error: 4.14e-09
```

Batchnorm for deep networks

Run the following to train a six-layer network on a subset of 1000 training examples both with and without batch normalization.

In [8]:

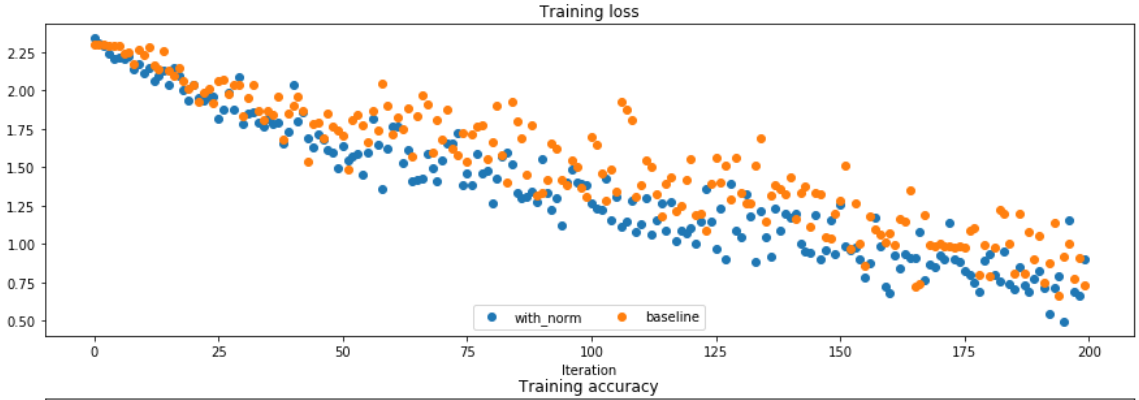
```
np.random.seed(231)
# Try training a very deep net with batchnorm
hidden_dims = [100, 100, 100, 100, 100]

num_train = 1000
small_data = {
  'X_train': data['X_train'][:num_train],
  'y_train': data['y_train'][:num_train],
  'X_val': data['X_val'],
  'y_val': data['y_val'],
}

weight_scale = 2e-2
bn_model = FullyConnectedNet(hidden_dims, weight_scale=weight_scale, normalizati
on='batchnorm')
model = FullyConnectedNet(hidden_dims, weight_scale=weight_scale, normalization=
None)

bn_solver = Solver(bn_model, small_data,
                num_epochs=10, batch_size=50,
                update_rule='adam',
                optim_config={
                  'learning_rate': 1e-3,
                },
                verbose=True,print_every=20)
bn_solver.train()

solver = Solver(model, small_data,
                num_epochs=10, batch_size=50,
                update_rule='adam',
                optim_config={
                  'learning_rate': 1e-3,
                },
                verbose=True, print_every=20)
solver.train()
```

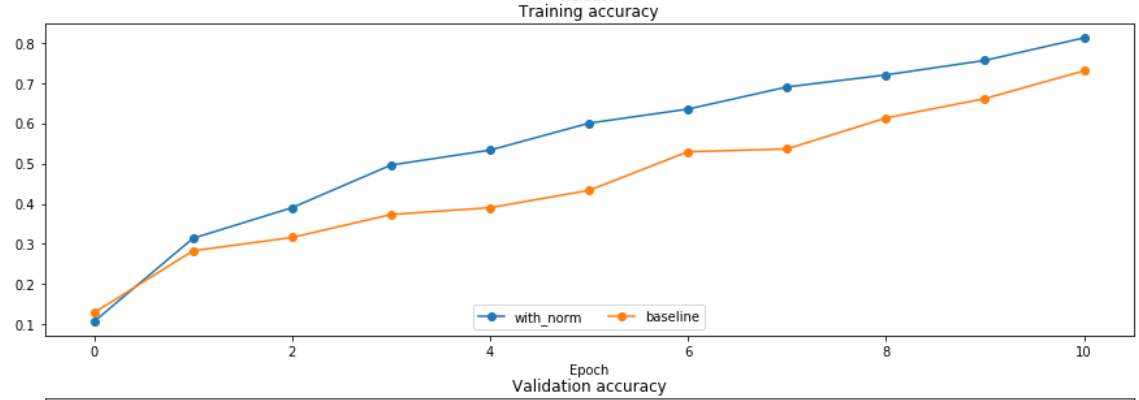
```
(Iteration 1 / 200) loss: 2.340974
(Epoch 0 / 10) train acc: 0.107000; val_acc: 0.115000
(Epoch 1 / 10) train acc: 0.314000; val_acc: 0.266000
(Iteration 21 / 200) loss: 2.039365
(Epoch 2 / 10) train acc: 0.390000; val_acc: 0.279000
(Iteration 41 / 200) loss: 2.036710
(Epoch 3 / 10) train acc: 0.496000; val_acc: 0.316000
(Iteration 61 / 200) loss: 1.769764
(Epoch 4 / 10) train acc: 0.533000; val_acc: 0.309000
(Iteration 81 / 200) loss: 1.268883
(Epoch 5 / 10) train acc: 0.600000; val_acc: 0.325000
(Iteration 101 / 200) loss: 1.263426
(Epoch 6 / 10) train acc: 0.635000; val_acc: 0.317000
(Iteration 121 / 200) loss: 1.108585
(Epoch 7 / 10) train acc: 0.690000; val_acc: 0.341000
(Iteration 141 / 200) loss: 1.176694
(Epoch 8 / 10) train acc: 0.720000; val_acc: 0.317000
(Iteration 161 / 200) loss: 0.684738
(Epoch 9 / 10) train acc: 0.756000; val_acc: 0.319000
(Iteration 181 / 200) loss: 0.933365
(Epoch 10 / 10) train acc: 0.812000; val_acc: 0.328000
(Iteration 1 / 200) loss: 2.302332
(Epoch 0 / 10) train acc: 0.129000; val_acc: 0.131000
(Epoch 1 / 10) train acc: 0.283000; val_acc: 0.250000
(Iteration 21 / 200) loss: 2.041970
(Epoch 2 / 10) train acc: 0.316000; val_acc: 0.277000
(Iteration 41 / 200) loss: 1.900473
(Epoch 3 / 10) train acc: 0.373000; val_acc: 0.282000
(Iteration 61 / 200) loss: 1.713156
(Epoch 4 / 10) train acc: 0.390000; val_acc: 0.310000
(Iteration 81 / 200) loss: 1.662208
(Epoch 5 / 10) train acc: 0.433000; val_acc: 0.300000
(Iteration 101 / 200) loss: 1.696236
(Epoch 6 / 10) train acc: 0.529000; val_acc: 0.345000
(Iteration 121 / 200) loss: 1.555476
(Epoch 7 / 10) train acc: 0.536000; val_acc: 0.301000
(Iteration 141 / 200) loss: 1.434626
(Epoch 8 / 10) train acc: 0.613000; val_acc: 0.324000
(Iteration 161 / 200) loss: 1.068730
(Epoch 9 / 10) train acc: 0.661000; val_acc: 0.335000
(Iteration 181 / 200) loss: 0.790277
(Epoch 10 / 10) train acc: 0.730000; val_acc: 0.319000
```

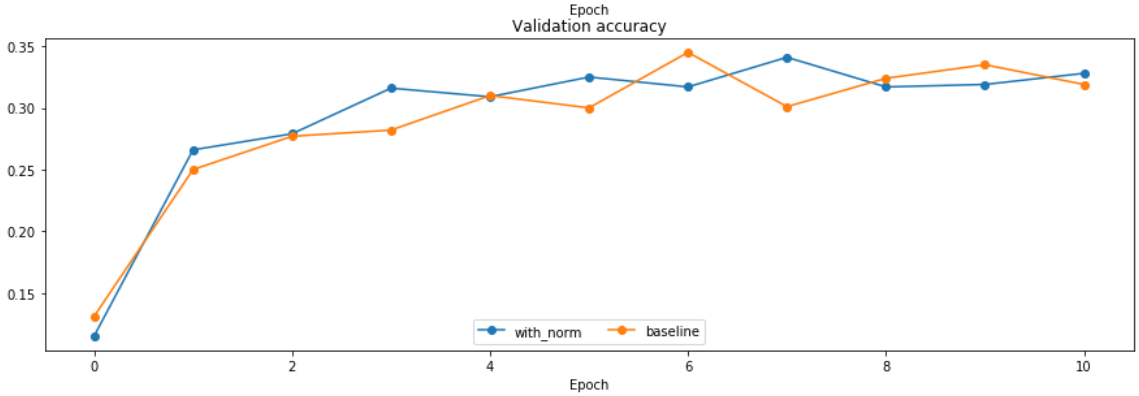
Run the following to visualize the results from two networks trained above. You should find that using batch normalization helps the network to converge much faster.

In [9]:

```
def plot_training_history(title, label, baseline, bn_solvers, plot_fn, bl_marker
='.', bn_marker='.', labels=None):
    """utility function for plotting training history"""
    plt.title(title)
    plt.xlabel(label)
    bn_plots = [plot_fn(bn_solver) for bn_solver in bn_solvers]
    bl_plot = plot_fn(baseline)
    num_bn = len(bn_plots)
    for i in range(num_bn):
        label='with_norm'
        if labels is not None:
            label += str(labels[i])
        plt.plot(bn_plots[i], bn_marker, label=label)
    label='baseline'
    if labels is not None:
        label += str(labels[0])
    plt.plot(bl_plot, bl_marker, label=label)
    plt.legend(loc='lower center', ncol=num_bn+1)


plt.subplot(3, 1, 1)
plot_training_history('Training loss','Iteration', solver, [bn_solver], \
                      lambda x: x.loss_history, bl_marker='o', bn_marker='o')
plt.subplot(3, 1, 2)
plot_training_history('Training accuracy','Epoch', solver, [bn_solver], \
                      lambda x: x.train_acc_history, bl_marker='-o', bn_marker=
'-o')
plt.subplot(3, 1, 3)
plot_training_history('Validation accuracy','Epoch', solver, [bn_solver], \
                      lambda x: x.val_acc_history, bl_marker='-o', bn_marker='-
o')

plt.gcf().set_size_inches(15, 15)
plt.show()
```







Batch normalization and initialization

We will now run a small experiment to study the interaction of batch normalization and weight initialization.

The first cell will train 8-layer networks both with and without batch normalization using different scales for weight initialization. The second layer will plot training accuracy, validation set accuracy, and training loss as a function of the weight initialization scale.

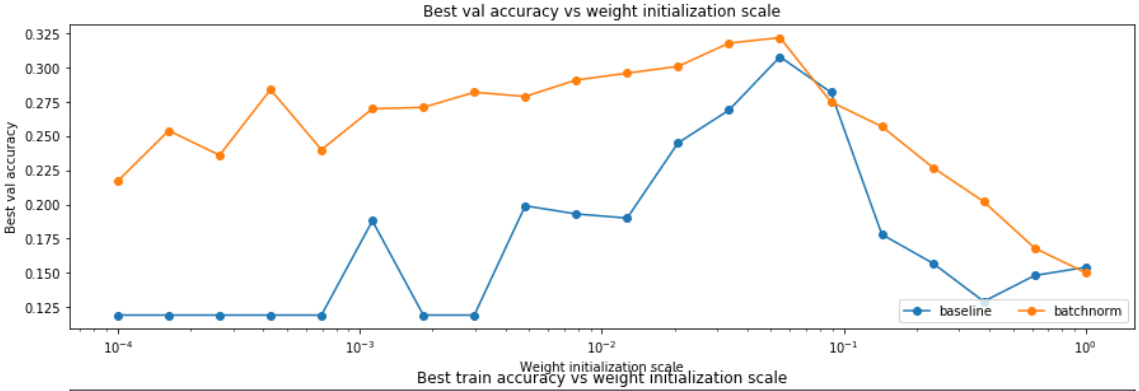
In [10]:

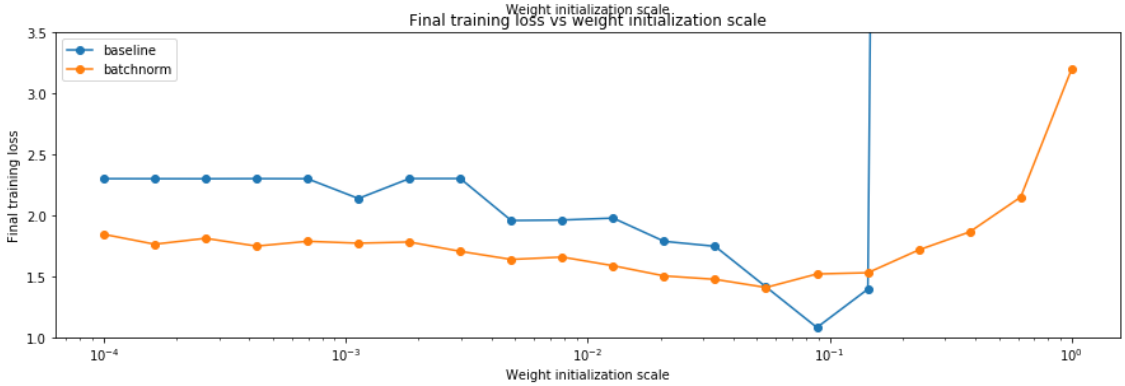
```
np.random.seed(231)
# Try training a very deep net with batchnorm
hidden_dims = [50, 50, 50, 50, 50, 50, 50]
num_train = 1000
small_data = {
  'X_train': data['X_train'][:num_train],
  'y_train': data['y_train'][:num_train],
  'X_val': data['X_val'],
  'y_val': data['y_val'],
}

bn_solvers_ws = {}
solvers_ws = {}
weight_scales = np.logspace(-4, 0, num=20)
for i, weight_scale in enumerate(weight_scales):
  print('Running weight scale %d / %d' % (i + 1, len(weight_scales)))
  bn_model = FullyConnectedNet(hidden_dims, weight_scale=weight_scale, normaliza
tion='batchnorm')
  model = FullyConnectedNet(hidden_dims, weight_scale=weight_scale, normalizatio
n=None)

  bn_solver = Solver(bn_model, small_data,
                 num_epochs=10, batch_size=50,
                 update_rule='adam',
                 optim_config={
                   'learning_rate': 1e-3,
                 },
                 verbose=False, print_every=200)
  bn_solver.train()
  bn_solvers_ws[weight_scale] = bn_solver

  solver = Solver(model, small_data,
                 num_epochs=10, batch_size=50,
                 update_rule='adam',
                 optim_config={
                   'learning_rate': 1e-3,
                 },
                 verbose=False, print_every=200)
  solver.train()
  solvers_ws[weight_scale] = solver
```

```
Running weight scale 1 / 20
Running weight scale 2 / 20
Running weight scale 3 / 20
Running weight scale 4 / 20
Running weight scale 5 / 20
Running weight scale 6 / 20
Running weight scale 7 / 20
Running weight scale 8 / 20
Running weight scale 9 / 20
Running weight scale 10 / 20
Running weight scale 11 / 20
Running weight scale 12 / 20
Running weight scale 13 / 20
Running weight scale 14 / 20
Running weight scale 15 / 20
Running weight scale 16 / 20
Running weight scale 17 / 20
Running weight scale 18 / 20
Running weight scale 19 / 20
Running weight scale 20 / 20
```

In [11]:

```
# Plot results of weight scale experiment
best_train_accs, bn_best_train_accs = [], []
best_val_accs, bn_best_val_accs = [], []
final_train_loss, bn_final_train_loss = [], []

for ws in weight_scales:
  best_train_accs.append(max(solvers_ws[ws].train_acc_history))
  bn_best_train_accs.append(max(bn_solvers_ws[ws].train_acc_history))

  best_val_accs.append(max(solvers_ws[ws].val_acc_history))
  bn_best_val_accs.append(max(bn_solvers_ws[ws].val_acc_history))

  final_train_loss.append(np.mean(solvers_ws[ws].loss_history[-100:]))
  bn_final_train_loss.append(np.mean(bn_solvers_ws[ws].loss_history[-100:]))

plt.subplot(3, 1, 1)
plt.title('Best val accuracy vs weight initialization scale')
plt.xlabel('Weight initialization scale')
plt.ylabel('Best val accuracy')
plt.semilogx(weight_scales, best_val_accs, '-o', label='baseline')
plt.semilogx(weight_scales, bn_best_val_accs, '-o', label='batchnorm')
plt.legend(ncol=2, loc='lower right')

plt.subplot(3, 1, 2)
plt.title('Best train accuracy vs weight initialization scale')
plt.xlabel('Weight initialization scale')
plt.ylabel('Best training accuracy')
plt.semilogx(weight_scales, best_train_accs, '-o', label='baseline')
plt.semilogx(weight_scales, bn_best_train_accs, '-o', label='batchnorm')
plt.legend()

plt.subplot(3, 1, 3)
plt.title('Final training loss vs weight initialization scale')
plt.xlabel('Weight initialization scale')
plt.ylabel('Final training loss')
plt.semilogx(weight_scales, final_train_loss, '-o', label='baseline')
plt.semilogx(weight_scales, bn_final_train_loss, '-o', label='batchnorm')
plt.legend()
plt.gca().set_ylim(1.0, 3.5)

plt.gcf().set_size_inches(15, 15)
plt.show()
```





Inline Question 1:

Describe the results of this experiment. How does the scale of weight initialization affect models with/without batch normalization differently, and why?

Answer:

Batch normalization and batch size

We will now run a small experiment to study the interaction of batch normalization and batch size.

The first cell will train 6-layer networks both with and without batch normalization using different batch sizes. The second layer will plot training accuracy and validation set accuracy over time.

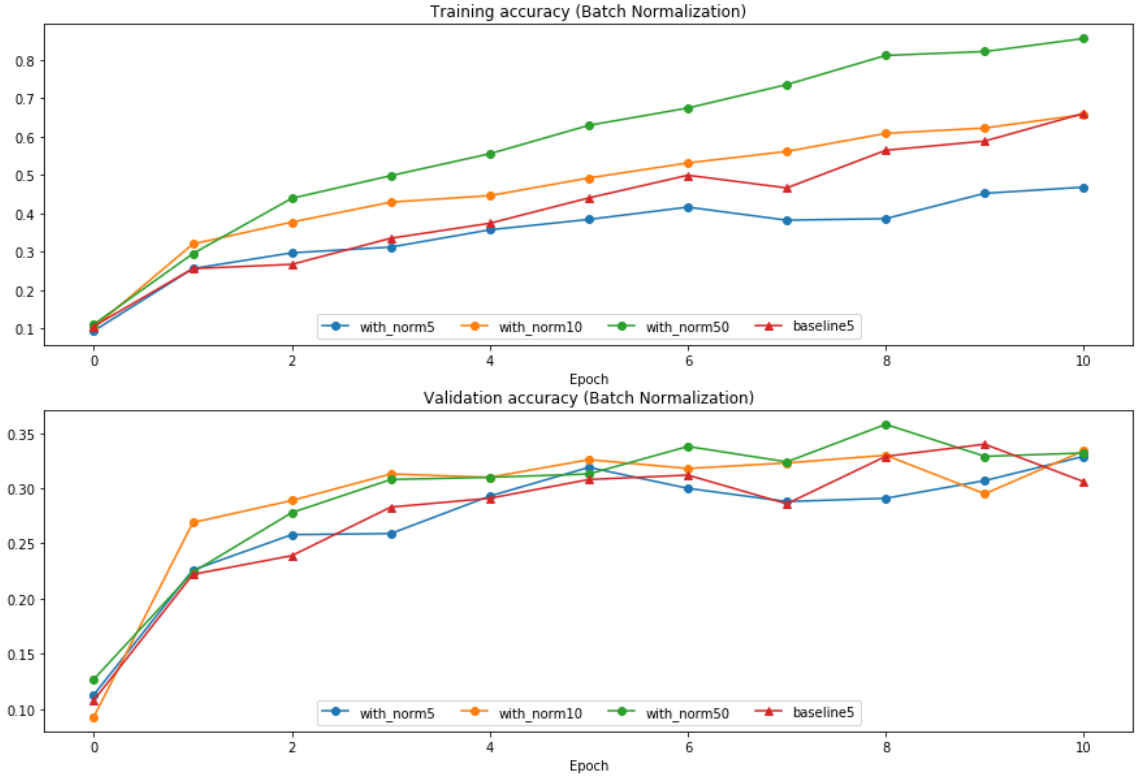
In [12]:

```
def run_batchsize_experiments(normalization_mode):
    np.random.seed(231)
    # Try training a very deep net with batchnorm
    hidden_dims = [100, 100, 100, 100, 100]
    num_train = 1000
    small_data = {
      'X_train': data['X_train'][:num_train],
      'y_train': data['y_train'][:num_train],
      'X_val': data['X_val'],
      'y_val': data['y_val'],
    }
    n_epochs=10
    weight_scale = 2e-2
    batch_sizes = [5,10,50]
    lr = 10**(-3.5)
    solver_bsize = batch_sizes[0]

    print('No normalization: batch size = ',solver_bsize)
    model = FullyConnectedNet(hidden_dims, weight_scale=weight_scale, normalizat
ion=None)
    solver = Solver(model, small_data,
                    num_epochs=n_epochs, batch_size=solver_bsize,
                    update_rule='adam',
                    optim_config={
                      'learning_rate': lr,
                    },
                    verbose=False)
    solver.train()

    bn_solvers = []
    for i in range(len(batch_sizes)):
        b_size=batch_sizes[i]
        print('Normalization: batch size = ',b_size)
        bn_model = FullyConnectedNet(hidden_dims, weight_scale=weight_scale, nor
malization=normalization_mode)
        bn_solver = Solver(bn_model, small_data,
                        num_epochs=n_epochs, batch_size=b_size,
                        update_rule='adam',
                        optim_config={
                          'learning_rate': lr,
                        },
                        verbose=False)
        bn_solver.train()
        bn_solvers.append(bn_solver)

    return bn_solvers, solver, batch_sizes

batch_sizes = [5,10,50]
bn_solvers_bsize, solver_bsize, batch_sizes = run_batchsize_experiments('batchno
rm')
```

```
No normalization: batch size =  5
Normalization: batch size =  5
Normalization: batch size =  10
Normalization: batch size =  50
```

In [13]:

```
plt.subplot(2, 1, 1)
plot_training_history('Training accuracy (Batch Normalization)','Epoch', solver_
bsize, bn_solvers_bsize, \
                      lambda x: x.train_acc_history, bl_marker='-^', bn_marker=
'-o', labels=batch_sizes)
plt.subplot(2, 1, 2)
plot_training_history('Validation accuracy (Batch Normalization)','Epoch', solve
r_bsize, bn_solvers_bsize, \
                      lambda x: x.val_acc_history, bl_marker='-^', bn_marker='-
o', labels=batch_sizes)

plt.gcf().set_size_inches(15, 10)
plt.show()
```



Inline Question 2:

Describe the results of this experiment. What does this imply about the relationship between batch normalization and batch size? Why is this relationship observed?

Answer:

Layer Normalization

Batch normalization has proved to be effective in making networks easier to train, but the dependency on batch size makes it less useful in complex networks which have a cap on the input batch size due to hardware limitations.

Several alternatives to batch normalization have been proposed to mitigate this problem; one such technique is Layer Normalization [4]. Instead of normalizing over the batch, we normalize over the features. In other words, when using Layer Normalization, each feature vector corresponding to a single datapoint is normalized based on the sum of all terms within that feature vector.

[4] Ba, Jimmy Lei, Jamie Ryan Kiros, and Geoffrey E. Hinton. "Layer Normalization." stat 1050 (2016): 21. (https://arxiv.org/pdf/1607.06450.pdf)

Inline Question 3:

Which of these data preprocessing steps is analogous to batch normalization, and which is analogous to layer normalization?

1. Scaling each image in the dataset, so that the RGB channels for each row of pixels within an image sums up to 1.
2. Scaling each image in the dataset, so that the RGB channels for all pixels within an image sums up to 1.
3. Subtracting the mean image of the dataset from each image in the dataset.
4. Setting all RGB values to either 0 or 1 depending on a given threshold.

Answer:

Layer Normalization: Implementation

Now you'll implement layer normalization. This step should be relatively straightforward, as conceptually the implementation is almost identical to that of batch normalization. One significant difference though is that for layer normalization, we do not keep track of the moving moments, and the testing phase is identical to the training phase, where the mean and variance are directly calculated per datapoint.

Here's what you need to do:

- In `cs231n/layers.py`, implement the forward pass for layer normalization in the function `layernorm_backward`.

Run the cell below to check your results.

- In `cs231n/layers.py`, implement the backward pass for layer normalization in the function `layernorm_backward`.

Run the second cell below to check your results.

- Modify `cs231n/classifiers/fc_net.py` to add layer normalization to the `FullyConnectedNet`. When the `normalization` flag is set to `"layernorm"` in the constructor, you should insert a layer normalization layer before each ReLU nonlinearity.

Run the third cell below to run the batch size experiment on layer normalization.

In [14]:

```
# Check the training-time forward pass by checking means and variances
# of features both before and after layer normalization

# Simulate the forward pass for a two-layer network
np.random.seed(231)
N, D1, D2, D3 =4, 50, 60, 3
X = np.random.randn(N, D1)
W1 = np.random.randn(D1, D2)
W2 = np.random.randn(D2, D3)
a = np.maximum(0, X.dot(W1)).dot(W2)

print('Before layer normalization:')
print_mean_std(a,axis=1)

gamma = np.ones(D3)
beta = np.zeros(D3)
# Means should be close to zero and stds close to one
print('After layer normalization (gamma=1, beta=0)')
a_norm, _ = layernorm_forward(a, gamma, beta, {'mode': 'train'})
print_mean_std(a_norm,axis=1)

gamma = np.asarray([3.0,3.0,3.0])
beta = np.asarray([5.0,5.0,5.0])
# Now means should be close to beta and stds close to gamma
print('After layer normalization (gamma=', gamma, ', beta=', beta, ')')
a_norm, _ = layernorm_forward(a, gamma, beta, {'mode': 'train'})
print_mean_std(a_norm,axis=1)
```

```
Before layer normalization:
  means:  [-59.06673243 -47.60782686 -43.31137368 -26.40991744]
  stds:   [10.07429373 28.39478981 35.28360729  4.01831507]

After layer normalization (gamma=1, beta=0)
  means:  [-4.81096644e-16  0.00000000e+00  7.40148683e-17 -5.551115
12e-16]
  stds:   [0.99999995 0.99999999 1.         0.99999969]

After layer normalization (gamma= [3. 3. 3.] , beta= [5. 5. 5.] )
  means:  [5. 5. 5. 5.]
  stds:   [2.99999985 2.99999998 2.99999999 2.99999907]
```

In [15]:

```
# Gradient check batchnorm backward pass
np.random.seed(231)
N, D = 4, 5
x = 5 * np.random.randn(N, D) + 12
gamma = np.random.randn(D)
beta = np.random.randn(D)
dout = np.random.randn(N, D)

ln_param = {}
fx = lambda x: layernorm_forward(x, gamma, beta, ln_param)[0]
fg = lambda a: layernorm_forward(x, a, beta, ln_param)[0]
fb = lambda b: layernorm_forward(x, gamma, b, ln_param)[0]

dx_num = eval_numerical_gradient_array(fx, x, dout)
da_num = eval_numerical_gradient_array(fg, gamma.copy(), dout)
db_num = eval_numerical_gradient_array(fb, beta.copy(), dout)

_, cache = layernorm_forward(x, gamma, beta, ln_param)
dx, dgamma, dbeta = layernorm_backward(dout, cache)

#You should expect to see relative errors between 1e-12 and 1e-8
print('dx error: ', rel_error(dx_num, dx))
print('dgamma error: ', rel_error(da_num, dgamma))
print('dbeta error: ', rel_error(db_num, dbeta))
```

```
dx error:  1.4336161049967258e-09
dgamma error:  4.519489546032799e-12
dbeta error:  2.276445013433725e-12
```

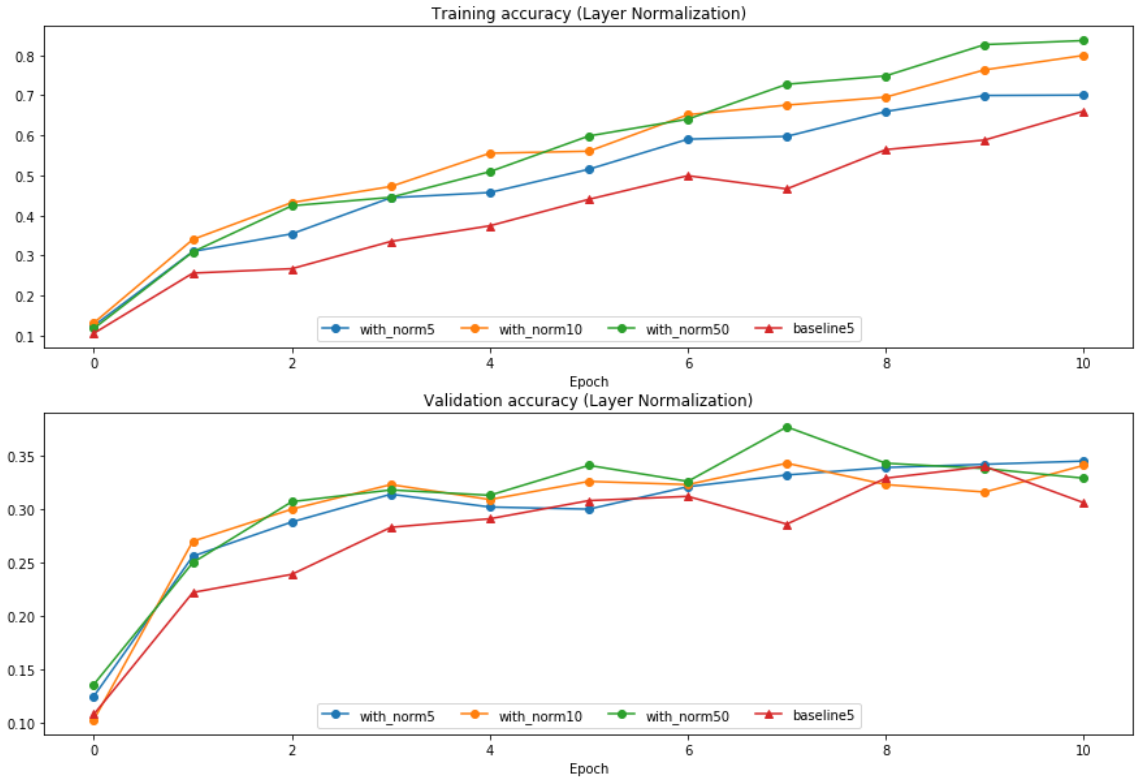
Layer Normalization and batch size

We will now run the previous batch size experiment with layer normalization instead of batch normalization. Compared to the previous experiment, you should see a markedly smaller influence of batch size on the training history!

In [16]:

```
ln_solvers_bsize, solver_bsize, batch_sizes = run_batchsize_experiments('layerno
rm')

plt.subplot(2, 1, 1)
plot_training_history('Training accuracy (Layer Normalization)','Epoch', solver_
bsize, ln_solvers_bsize, \
                      lambda x: x.train_acc_history, bl_marker='-^', bn_marker=
'-o', labels=batch_sizes)
plt.subplot(2, 1, 2)
plot_training_history('Validation accuracy (Layer Normalization)','Epoch', solve
r_bsize, ln_solvers_bsize, \
                      lambda x: x.val_acc_history, bl_marker='-^', bn_marker='-
o', labels=batch_sizes)

plt.gcf().set_size_inches(15, 10)
plt.show()
```

```
No normalization: batch size =  5
Normalization: batch size =  5
Normalization: batch size =  10
Normalization: batch size =  50
```



Inline Question 4:

When is layer normalization likely to not work well, and why?

1. Using it in a very deep network
2. Having a very small dimension of features
3. Having a high regularization term

Answer:

Dropout

Dropout [1] is a technique for regularizing neural networks by randomly setting some features to zero during the forward pass. In this exercise you will implement a dropout layer and modify your fully-connected network to optionally use dropout.

[1] Geoffrey E. Hinton et al, "Improving neural networks by preventing co-adaptation of feature detectors", arXiv 2012 (https://arxiv.org/abs/1207.0580)

In [1]:

```
# As usual, a bit of setup
from __future__ import print_function
import time
import numpy as np
import matplotlib.pyplot as plt
from cs231n.classifiers.fc_net import *
from cs231n.data_utils import get_CIFAR10_data
from cs231n.gradient_check import eval_numerical_gradient, eval_numerical_gradie
nt_array
from cs231n.solver import Solver

%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-ipytho
n
%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))))
```

In [2]:

```
# Load the (preprocessed) CIFAR10 data.

data = get_CIFAR10_data()
for k, v in data.items():
  print('%s: ' % k, v.shape)
```

```
X_train:  (49000, 3, 32, 32)
y_train:  (49000,)
X_val:  (1000, 3, 32, 32)
y_val:  (1000,)
X_test:  (1000, 3, 32, 32)
y_test:  (1000,)
```

Dropout forward pass

In the file `cs231n/layers.py`, implement the forward pass for dropout. Since dropout behaves differently during training and testing, make sure to implement the operation for both modes.

Once you have done so, run the cell below to test your implementation.

In [3]:

```
np.random.seed(231)
x = np.random.randn(500, 500) + 10

for p in [0.25, 0.4, 0.7]:
  out, _ = dropout_forward(x, {'mode': 'train', 'p': p})
  out_test, _ = dropout_forward(x, {'mode': 'test', 'p': p})

  print('Running tests with p = ', p)
  print('Mean of input: ', x.mean())
  print('Mean of train-time output: ', out.mean())
  print('Mean of test-time output: ', out_test.mean())
  print('Fraction of train-time output set to zero: ', (out == 0).mean())
  print('Fraction of test-time output set to zero: ', (out_test == 0).mean())
  print()
```

```
Running tests with p =  0.25
Mean of input:  10.000207878477502
Mean of train-time output:  10.014059116977283
Mean of test-time output:  10.000207878477502
Fraction of train-time output set to zero:  0.749784
Fraction of test-time output set to zero:  0.0

Running tests with p =  0.4
Mean of input:  10.000207878477502
Mean of train-time output:  9.977917658761159
Mean of test-time output:  10.000207878477502
Fraction of train-time output set to zero:  0.600796
Fraction of test-time output set to zero:  0.0

Running tests with p =  0.7
Mean of input:  10.000207878477502
Mean of train-time output:  9.987811912159426
Mean of test-time output:  10.000207878477502
Fraction of train-time output set to zero:  0.30074
Fraction of test-time output set to zero:  0.0
```

Dropout backward pass

In the file `cs231n/layers.py`, implement the backward pass for dropout. After doing so, run the following cell to numerically gradient-check your implementation.

In [4]:

```
np.random.seed(231)
x = np.random.randn(10, 10) + 10
dout = np.random.randn(*x.shape)

dropout_param = {'mode': 'train', 'p': 0.2, 'seed': 123}
out, cache = dropout_forward(x, dropout_param)
dx = dropout_backward(dout, cache)
dx_num = eval_numerical_gradient_array(lambda xx: dropout_forward(xx, dropout_pa
ram)[0], x, dout)

# Error should be around e-10 or less
print('dx relative error: ', rel_error(dx, dx_num))
```

```
dx relative error:  5.44560814873387e-11
```

Inline Question 1:

What happens if we do not divide the values being passed through inverse dropout by `p` in the dropout layer? Why does that happen?

Answer:

Fully-connected nets with Dropout

In the file `cs231n/classifiers/fc_net.py`, modify your implementation to use dropout. Specifically, if the constructor of the net receives a value that is not 1 for the `dropout` parameter, then the net should add dropout immediately after every ReLU nonlinearity. After doing so, run the following to numerically gradient-check your implementation.

In [5]:

```
np.random.seed(231)
N, D, H1, H2, C = 2, 15, 20, 30, 10
X = np.random.randn(N, D)
y = np.random.randint(C, size=(N,))

for dropout in [1, 0.75, 0.5]:
  print('Running check with dropout = ', dropout)
  model = FullyConnectedNet([H1, H2], input_dim=D, num_classes=C,
                            weight_scale=5e-2, dtype=np.float64,
                            dropout=dropout, seed=123)

  loss, grads = model.loss(X, y)
  print('Initial loss: ', loss)

  # Relative errors should be around e-6 or less; Note that it's fine
  # if for dropout=1 you have W2 error be on the order of e-5.
  for name in sorted(grads):
    f = lambda _: model.loss(X, y)[0]
    grad_num = eval_numerical_gradient(f, model.params[name], verbose=False, h=1
e-5)
    print('%s relative error: %.2e' % (name, rel_error(grad_num, grads[name])))
  print()
```

```
Running check with dropout =  1
Initial loss:  2.3004790897684924
W1 relative error: 1.48e-07
W2 relative error: 2.21e-05
W3 relative error: 3.53e-07
b1 relative error: 5.38e-09
b2 relative error: 2.09e-09
b3 relative error: 5.80e-11

Running check with dropout =  0.75
Initial loss:  2.302371489704412
W1 relative error: 1.90e-07
W2 relative error: 4.76e-06
W3 relative error: 2.60e-08
b1 relative error: 4.73e-09
b2 relative error: 1.82e-09
b3 relative error: 1.70e-10

Running check with dropout =  0.5
Initial loss:  2.3042759220785896
W1 relative error: 3.11e-07
W2 relative error: 1.84e-08
W3 relative error: 5.35e-08
b1 relative error: 2.58e-08
b2 relative error: 2.99e-09
b3 relative error: 1.13e-10
```

Regularization experiment

As an experiment, we will train a pair of two-layer networks on 500 training examples: one will use no dropout, and one will use a keep probability of 0.25. We will then visualize the training and validation accuracies of the two networks over time.

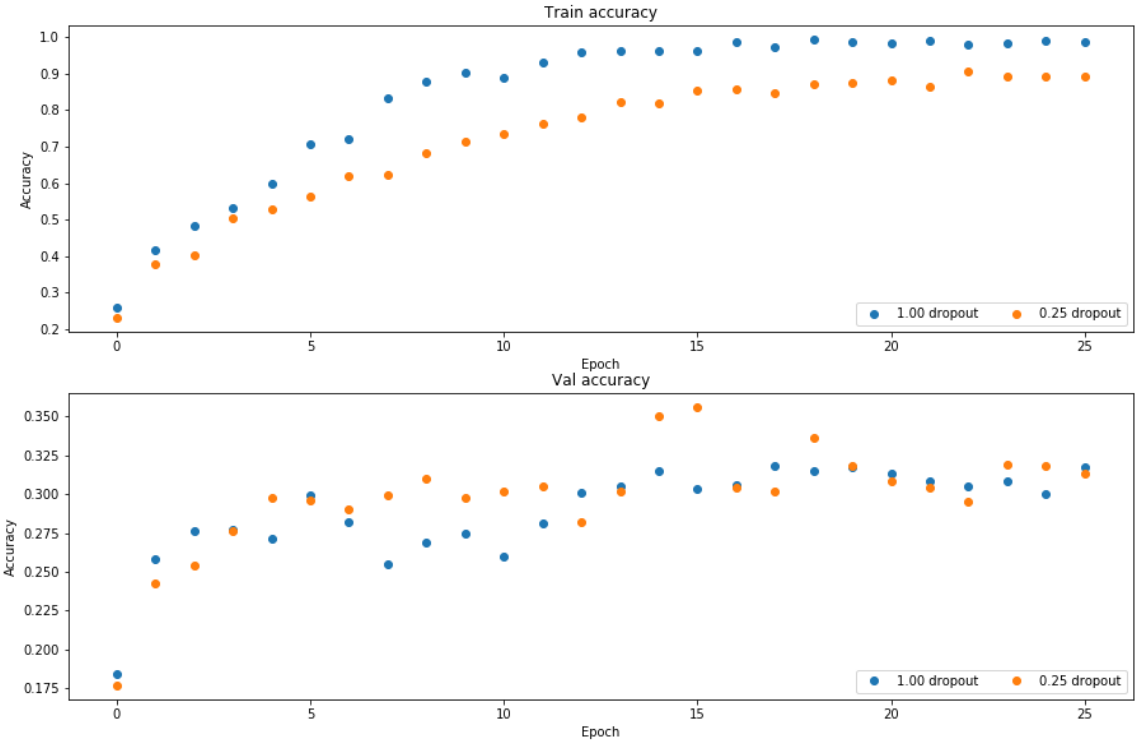
In [6]:

```
# Train two identical nets, one with dropout and one without
np.random.seed(231)
num_train = 500
small_data = {
  'X_train': data['X_train'][:num_train],
  'y_train': data['y_train'][:num_train],
  'X_val': data['X_val'],
  'y_val': data['y_val'],
}

solvers = {}
dropout_choices = [1, 0.25]
for dropout in dropout_choices:
  model = FullyConnectedNet([500], dropout=dropout)
  print(dropout)

  solver = Solver(model, small_data,
                  num_epochs=25, batch_size=100,
                  update_rule='adam',
                  optim_config={
                    'learning_rate': 5e-4,
                  },
                  verbose=True, print_every=100)
  solver.train()
  solvers[dropout] = solver
```

```
1
(Iteration 1 / 125) loss: 7.856644
(Epoch 0 / 25) train acc: 0.260000; val_acc: 0.184000
(Epoch 1 / 25) train acc: 0.416000; val_acc: 0.258000
(Epoch 2 / 25) train acc: 0.482000; val_acc: 0.276000
(Epoch 3 / 25) train acc: 0.532000; val_acc: 0.277000
(Epoch 4 / 25) train acc: 0.600000; val_acc: 0.271000
(Epoch 5 / 25) train acc: 0.708000; val_acc: 0.299000
(Epoch 6 / 25) train acc: 0.722000; val_acc: 0.282000
(Epoch 7 / 25) train acc: 0.832000; val_acc: 0.255000
(Epoch 8 / 25) train acc: 0.878000; val_acc: 0.269000
(Epoch 9 / 25) train acc: 0.902000; val_acc: 0.275000
(Epoch 10 / 25) train acc: 0.890000; val_acc: 0.260000
(Epoch 11 / 25) train acc: 0.930000; val_acc: 0.281000
(Epoch 12 / 25) train acc: 0.958000; val_acc: 0.301000
(Epoch 13 / 25) train acc: 0.964000; val_acc: 0.305000
(Epoch 14 / 25) train acc: 0.962000; val_acc: 0.315000
(Epoch 15 / 25) train acc: 0.962000; val_acc: 0.303000
(Epoch 16 / 25) train acc: 0.986000; val_acc: 0.306000
(Epoch 17 / 25) train acc: 0.974000; val_acc: 0.318000
(Epoch 18 / 25) train acc: 0.994000; val_acc: 0.315000
(Epoch 19 / 25) train acc: 0.986000; val_acc: 0.317000
(Epoch 20 / 25) train acc: 0.984000; val_acc: 0.313000
(Iteration 101 / 125) loss: 0.000194
(Epoch 21 / 25) train acc: 0.992000; val_acc: 0.308000
(Epoch 22 / 25) train acc: 0.982000; val_acc: 0.305000
(Epoch 23 / 25) train acc: 0.984000; val_acc: 0.308000
(Epoch 24 / 25) train acc: 0.990000; val_acc: 0.300000
(Epoch 25 / 25) train acc: 0.986000; val_acc: 0.317000
0.25
(Iteration 1 / 125) loss: 17.318480
(Epoch 0 / 25) train acc: 0.230000; val_acc: 0.177000
(Epoch 1 / 25) train acc: 0.378000; val_acc: 0.243000
(Epoch 2 / 25) train acc: 0.402000; val_acc: 0.254000
(Epoch 3 / 25) train acc: 0.502000; val_acc: 0.276000
(Epoch 4 / 25) train acc: 0.528000; val_acc: 0.298000
(Epoch 5 / 25) train acc: 0.562000; val_acc: 0.296000
(Epoch 6 / 25) train acc: 0.620000; val_acc: 0.290000
(Epoch 7 / 25) train acc: 0.624000; val_acc: 0.299000
(Epoch 8 / 25) train acc: 0.682000; val_acc: 0.310000
(Epoch 9 / 25) train acc: 0.714000; val_acc: 0.298000
(Epoch 10 / 25) train acc: 0.736000; val_acc: 0.302000
(Epoch 11 / 25) train acc: 0.762000; val_acc: 0.305000
(Epoch 12 / 25) train acc: 0.782000; val_acc: 0.282000
(Epoch 13 / 25) train acc: 0.822000; val_acc: 0.302000
(Epoch 14 / 25) train acc: 0.818000; val_acc: 0.350000
(Epoch 15 / 25) train acc: 0.854000; val_acc: 0.356000
(Epoch 16 / 25) train acc: 0.856000; val_acc: 0.304000
(Epoch 17 / 25) train acc: 0.846000; val_acc: 0.302000
(Epoch 18 / 25) train acc: 0.870000; val_acc: 0.336000
(Epoch 19 / 25) train acc: 0.876000; val_acc: 0.318000
(Epoch 20 / 25) train acc: 0.882000; val_acc: 0.308000
(Iteration 101 / 125) loss: 4.692026
(Epoch 21 / 25) train acc: 0.866000; val_acc: 0.304000
(Epoch 22 / 25) train acc: 0.908000; val_acc: 0.295000
(Epoch 23 / 25) train acc: 0.894000; val_acc: 0.319000
(Epoch 24 / 25) train acc: 0.894000; val_acc: 0.318000
(Epoch 25 / 25) train acc: 0.894000; val_acc: 0.313000
```

In [7]:

```
# Plot train and validation accuracies of the two models

train_accs = []
val_accs = []
for dropout in dropout_choices:
  solver = solvers[dropout]
  train_accs.append(solver.train_acc_history[-1])
  val_accs.append(solver.val_acc_history[-1])

plt.subplot(3, 1, 1)
for dropout in dropout_choices:
  plt.plot(solvers[dropout].train_acc_history, 'o', label='%.2f dropout' % dropo
ut)
plt.title('Train accuracy')
plt.xlabel('Epoch')
plt.ylabel('Accuracy')
plt.legend(ncol=2, loc='lower right')

plt.subplot(3, 1, 2)
for dropout in dropout_choices:
  plt.plot(solvers[dropout].val_acc_history, 'o', label='%.2f dropout' % dropout
)
plt.title('Val accuracy')
plt.xlabel('Epoch')
plt.ylabel('Accuracy')
plt.legend(ncol=2, loc='lower right')

plt.gcf().set_size_inches(15, 15)
plt.show()
```



Inline Question 2:

Compare the validation and training accuracies with and without dropout -- what do your results suggest about dropout as a regularizer?

Answer:

Inline Question 3:

Suppose we are training a deep fully-connected network for image classification, with dropout after hidden layers (parameterized by keep probability p). How should we modify p, if at all, if we decide to decrease the size of the hidden layers (that is, the number of nodes in each layer)?

Answer:

In [ ]:

Convolutional Networks ¶

So far we have worked with deep fully-connected networks, using them to explore different optimization strategies and network architectures. Fully-connected networks are a good testbed for experimentation because they are very computationally efficient, but in practice all state-of-the-art results use convolutional networks instead.

First you will implement several layer types that are used in convolutional networks. You will then use these layers to train a convolutional network on the CIFAR-10 dataset.

In [1]:

```
# As usual, a bit of setup
import numpy as np
import matplotlib.pyplot as plt
from cs231n.classifiers.cnn import *
from cs231n.data_utils import get_CIFAR10_data
from cs231n.gradient_check import eval_numerical_gradient_array, eval_numerical_
gradient
from cs231n.layers import *
from cs231n.fast_layers import *
from cs231n.solver import Solver

%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-ipytho
n
%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))))
```

In [2]:

```
# Load the (preprocessed) CIFAR10 data.

data = get_CIFAR10_data()
for k, v in data.items():
  print('%s: ' % k, v.shape)
```

```
X_train:  (49000, 3, 32, 32)
y_train:  (49000,)
X_val:  (1000, 3, 32, 32)
y_val:  (1000,)
X_test:  (1000, 3, 32, 32)
y_test:  (1000,)
```

Convolution: Naive forward pass

The core of a convolutional network is the convolution operation. In the file `cs231n/layers.py`, implement the forward pass for the convolution layer in the function `conv_forward_naive`.

You don't have to worry too much about efficiency at this point; just write the code in whatever way you find most clear.

You can test your implementation by running the following:

In [3]:

```
x_shape = (2, 3, 4, 4)
w_shape = (3, 3, 4, 4)
x = np.linspace(-0.1, 0.5, num=np.prod(x_shape)).reshape(x_shape)
w = np.linspace(-0.2, 0.3, num=np.prod(w_shape)).reshape(w_shape)
b = np.linspace(-0.1, 0.2, num=3)

conv_param = {'stride': 2, 'pad': 1}
out, _ = conv_forward_naive(x, w, b, conv_param)
correct_out = np.array([[[[-0.08759809, -0.10987781],
                          [-0.18387192, -0.2109216 ]],
                         [[ 0.21027089,  0.21661097],
                          [ 0.22847626,  0.23004637]],
                         [[ 0.50813986,  0.54309974],
                          [ 0.64082444,  0.67101435]]],
                        [[[-0.98053589, -1.03143541],
                          [-1.19128892, -1.24695841]],
                         [[ 0.69108355,  0.66880383],
                          [ 0.59480972,  0.56776003]],
                         [[ 2.36270298,  2.36904306],
                          [ 2.38090835,  2.38247847]]]])

# Compare your output to ours; difference should be around e-8
print('Testing conv_forward_naive')
print('difference: ', rel_error(out, correct_out))
```

```
Testing conv_forward_naive
difference:  2.2121476417505994e-08
```

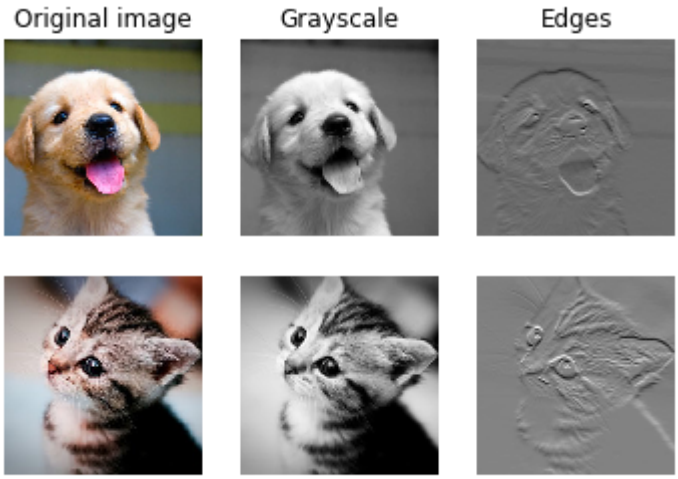
Aside: Image processing via convolutions

As fun way to both check your implementation and gain a better understanding of the type of operation that convolutional layers can perform, we will set up an input containing two images and manually set up filters that perform common image processing operations (grayscale conversion and edge detection). The convolution forward pass will apply these operations to each of the input images. We can then visualize the results as a sanity check.

In [4]:

```
from scipy.misc import imread, imresize

kitten, puppy = imread('kitten.jpg'), imread('puppy.jpg')
# kitten is wide, and puppy is already square
d = kitten.shape[1] - kitten.shape[0]
kitten_cropped = kitten[:, d//2:-d//2, :]

img_size = 200   # Make this smaller if it runs too slow
x = np.zeros((2, 3, img_size, img_size))
x[0, :, :, :] = imresize(puppy, (img_size, img_size)).transpose((2, 0, 1))
x[1, :, :, :] = imresize(kitten_cropped, (img_size, img_size)).transpose((2, 0,
1))

# Set up a convolutional weights holding 2 filters, each 3x3
w = np.zeros((2, 3, 3, 3))

# The first filter converts the image to grayscale.
# Set up the red, green, and blue channels of the filter.
w[0, 0, :, :] = [[0, 0, 0], [0, 0.3, 0], [0, 0, 0]]
w[0, 1, :, :] = [[0, 0, 0], [0, 0.6, 0], [0, 0, 0]]
w[0, 2, :, :] = [[0, 0, 0], [0, 0.1, 0], [0, 0, 0]]

# Second filter detects horizontal edges in the blue channel.
w[1, 2, :, :] = [[1, 2, 1], [0, 0, 0], [-1, -2, -1]]

# Vector of biases. We don't need any bias for the grayscale
# filter, but for the edge detection filter we want to add 128
# to each output so that nothing is negative.
b = np.array([0, 128])

# Compute the result of convolving each input in x with each filter in w,
# offsetting by b, and storing the results in out.
out, _ = conv_forward_naive(x, w, b, {'stride': 1, 'pad': 1})

def imshow_noax(img, normalize=True):
    """ Tiny helper to show images as uint8 and remove axis labels """
    if normalize:
        img_max, img_min = np.max(img), np.min(img)
        img = 255.0 * (img - img_min) / (img_max - img_min)
    plt.imshow(img.astype('uint8'))
    plt.gca().axis('off')

# Show the original images and the results of the conv operation
plt.subplot(2, 3, 1)
imshow_noax(puppy, normalize=False)
plt.title('Original image')
plt.subplot(2, 3, 2)
imshow_noax(out[0, 0])
plt.title('Grayscale')
plt.subplot(2, 3, 3)
imshow_noax(out[0, 1])
plt.title('Edges')
plt.subplot(2, 3, 4)
imshow_noax(kitten_cropped, normalize=False)
plt.subplot(2, 3, 5)
imshow_noax(out[1, 0])
plt.subplot(2, 3, 6)
imshow_noax(out[1, 1])
plt.show()
```

```
/home/tanishq/anaconda3/lib/python3.7/site-packages/ipykernel_launch
er.py:3: DeprecationWarning: `imread` is deprecated!
`imread` is deprecated in SciPy 1.0.0, and will be removed in 1.2.0.
Use ``imageio.imread`` instead.
  This is separate from the ipykernel package so we can avoid doing
imports until
/home/tanishq/anaconda3/lib/python3.7/site-packages/ipykernel_launch
er.py:10: DeprecationWarning: `imresize` is deprecated!
`imresize` is deprecated in SciPy 1.0.0, and will be removed in 1.3.
0.
Use Pillow instead: ``numpy.array(Image.fromarray(arr).resize())``.
  # Remove the CWD from sys.path while we load stuff.
/home/tanishq/anaconda3/lib/python3.7/site-packages/ipykernel_launch
er.py:11: DeprecationWarning: `imresize` is deprecated!
`imresize` is deprecated in SciPy 1.0.0, and will be removed in 1.3.
0.
Use Pillow instead: ``numpy.array(Image.fromarray(arr).resize())``.
  # This is added back by InteractiveShellApp.init_path()
```



Convolution: Naive backward pass

Implement the backward pass for the convolution operation in the function `conv_backward_naive` in the file `cs231n/layers.py`. Again, you don't need to worry too much about computational efficiency.

When you are done, run the following to check your backward pass with a numeric gradient check.

In [5]:

```
np.random.seed(231)
x = np.random.randn(4, 3, 5, 5)
w = np.random.randn(2, 3, 3, 3)
b = np.random.randn(2,)
dout = np.random.randn(4, 2, 5, 5)
conv_param = {'stride': 1, 'pad': 1}

dx_num = eval_numerical_gradient_array(lambda x: conv_forward_naive(x, w, b, con
v_param)[0], x, dout)
dw_num = eval_numerical_gradient_array(lambda w: conv_forward_naive(x, w, b, con
v_param)[0], w, dout)
db_num = eval_numerical_gradient_array(lambda b: conv_forward_naive(x, w, b, con
v_param)[0], b, dout)

out, cache = conv_forward_naive(x, w, b, conv_param)
dx, dw, db = conv_backward_naive(dout, cache)

# Your errors should be around e-8 or less.
print('Testing conv_backward_naive function')
print('dx error: ', rel_error(dx, dx_num))
print('dw error: ', rel_error(dw, dw_num))
print('db error: ', rel_error(db, db_num))
```

```
Testing conv_backward_naive function
dx error:  1.159803161159293e-08
dw error:  2.2471264748452487e-10
db error:  3.37264006649648e-11
```

Max-Pooling: Naive forward

Implement the forward pass for the max-pooling operation in the function `max_pool_forward_naive` in the file `cs231n/layers.py`. Again, don't worry too much about computational efficiency.

Check your implementation by running the following:

In [6]:

```
x_shape = (2, 3, 4, 4)
x = np.linspace(-0.3, 0.4, num=np.prod(x_shape)).reshape(x_shape)
pool_param = {'pool_width': 2, 'pool_height': 2, 'stride': 2}

out, _ = max_pool_forward_naive(x, pool_param)

correct_out = np.array([[[[-0.26315789, -0.24842105],
                          [-0.20421053, -0.18947368]],
                         [[-0.14526316, -0.13052632],
                          [-0.08631579, -0.07157895]],
                         [[-0.02736842, -0.01263158],
                          [ 0.03157895,  0.04631579]]],
                        [[[ 0.09052632,  0.10526316],
                          [ 0.14947368,  0.16421053]],
                         [[ 0.20842105,  0.22315789],
                          [ 0.26736842,  0.28210526]],
                         [[ 0.32631579,  0.34105263],
                          [ 0.38526316,  0.4       ]]]])

# Compare your output with ours. Difference should be on the order of e-8.
print('Testing max_pool_forward_naive function:')
print('difference: ', rel_error(out, correct_out))
```

```
Testing max_pool_forward_naive function:
difference:  4.1666665157267834e-08
```

Max-Pooling: Naive backward

Implement the backward pass for the max-pooling operation in the function `max_pool_backward_naive` in the file `cs231n/layers.py`. You don't need to worry about computational efficiency.

Check your implementation with numeric gradient checking by running the following:

In [7]:

```
np.random.seed(231)
x = np.random.randn(3, 2, 8, 8)
dout = np.random.randn(3, 2, 4, 4)
pool_param = {'pool_height': 2, 'pool_width': 2, 'stride': 2}

dx_num = eval_numerical_gradient_array(lambda x: max_pool_forward_naive(x, pool_
param)[0], x, dout)

out, cache = max_pool_forward_naive(x, pool_param)
dx = max_pool_backward_naive(dout, cache)

# Your error should be on the order of e-12
print('Testing max_pool_backward_naive function:')
print('dx error: ', rel_error(dx, dx_num))
```

```
Testing max_pool_backward_naive function:
dx error:  3.27562514223145e-12
```

Fast layers

Making convolution and pooling layers fast can be challenging. To spare you the pain, we've provided fast implementations of the forward and backward passes for convolution and pooling layers in the file `cs231n/fast_layers.py`.

The fast convolution implementation depends on a Cython extension; to compile it you need to run the following from the `cs231n` directory:

```
python setup.py build_ext --inplace
```

The API for the fast versions of the convolution and pooling layers is exactly the same as the naive versions that you implemented above: the forward pass receives data, weights, and parameters and produces outputs and a cache object; the backward pass recieves upstream derivatives and the cache object and produces gradients with respect to the data and weights.

NOTE: The fast implementation for pooling will only perform optimally if the pooling regions are non-overlapping and tile the input. If these conditions are not met then the fast pooling implementation will not be much faster than the naive implementation.

You can compare the performance of the naive and fast versions of these layers by running the following:

In [8]:

```
# Rel errors should be around e-9 or less
from cs231n.fast_layers import conv_forward_fast, conv_backward_fast
from time import time
np.random.seed(231)
x = np.random.randn(100, 3, 31, 31)
w = np.random.randn(25, 3, 3, 3)
b = np.random.randn(25,)
dout = np.random.randn(100, 25, 16, 16)
conv_param = {'stride': 2, 'pad': 1}

t0 = time()
out_naive, cache_naive = conv_forward_naive(x, w, b, conv_param)
t1 = time()
out_fast, cache_fast = conv_forward_fast(x, w, b, conv_param)
t2 = time()

print('Testing conv_forward_fast:')
print('Naive: %fs' % (t1 - t0))
print('Fast: %fs' % (t2 - t1))
print('Speedup: %fx' % ((t1 - t0) / (t2 - t1)))
print('Difference: ', rel_error(out_naive, out_fast))

t0 = time()
dx_naive, dw_naive, db_naive = conv_backward_naive(dout, cache_naive)
t1 = time()
dx_fast, dw_fast, db_fast = conv_backward_fast(dout, cache_fast)
t2 = time()

print('\nTesting conv_backward_fast:')
print('Naive: %fs' % (t1 - t0))
print('Fast: %fs' % (t2 - t1))
print('Speedup: %fx' % ((t1 - t0) / (t2 - t1)))
print('dx difference: ', rel_error(dx_naive, dx_fast))
print('dw difference: ', rel_error(dw_naive, dw_fast))
print('db difference: ', rel_error(db_naive, db_fast))
```

```
Testing conv_forward_fast:
Naive: 4.063907s
Fast: 0.018489s
Speedup: 219.799881x
Difference:  4.926407851494105e-11

Testing conv_backward_fast:
Naive: 6.879874s
Fast: 0.010016s
Speedup: 686.874509x
dx difference:  1.949764775345631e-11
dw difference:  5.684079808685177e-13
db difference:  0.0
```

In [9]:

```
# Relative errors should be close to 0.0
from cs231n.fast_layers import max_pool_forward_fast, max_pool_backward_fast
np.random.seed(231)
x = np.random.randn(100, 3, 32, 32)
dout = np.random.randn(100, 3, 16, 16)
pool_param = {'pool_height': 2, 'pool_width': 2, 'stride': 2}

t0 = time()
out_naive, cache_naive = max_pool_forward_naive(x, pool_param)
t1 = time()
out_fast, cache_fast = max_pool_forward_fast(x, pool_param)
t2 = time()

print('Testing pool_forward_fast:')
print('Naive: %fs' % (t1 - t0))
print('fast: %fs' % (t2 - t1))
print('speedup: %fx' % ((t1 - t0) / (t2 - t1)))
print('difference: ', rel_error(out_naive, out_fast))

t0 = time()
dx_naive = max_pool_backward_naive(dout, cache_naive)
t1 = time()
dx_fast = max_pool_backward_fast(dout, cache_fast)
t2 = time()

print('\nTesting pool_backward_fast:')
print('Naive: %fs' % (t1 - t0))
print('fast: %fs' % (t2 - t1))
print('speedup: %fx' % ((t1 - t0) / (t2 - t1)))
print('dx difference: ', rel_error(dx_naive, dx_fast))
```

```
Testing pool_forward_fast:
Naive: 0.359970s
fast: 0.002004s
speedup: 179.612777x
difference:  0.0

Testing pool_backward_fast:
Naive: 0.394819s
fast: 0.011325s
speedup: 34.863011x
dx difference:  0.0
```

Convolutional "sandwich" layers

Previously we introduced the concept of "sandwich" layers that combine multiple operations into commonly used patterns. In the file `cs231n/layer_utils.py` you will find sandwich layers that implement a few commonly used patterns for convolutional networks.

In [10]:

```
from cs231n.layer_utils import conv_relu_pool_forward, conv_relu_pool_backward
np.random.seed(231)
x = np.random.randn(2, 3, 16, 16)
w = np.random.randn(3, 3, 3, 3)
b = np.random.randn(3,)
dout = np.random.randn(2, 3, 8, 8)
conv_param = {'stride': 1, 'pad': 1}
pool_param = {'pool_height': 2, 'pool_width': 2, 'stride': 2}

out, cache = conv_relu_pool_forward(x, w, b, conv_param, pool_param)
dx, dw, db = conv_relu_pool_backward(dout, cache)

dx_num = eval_numerical_gradient_array(lambda x: conv_relu_pool_forward(x, w, b,
 conv_param, pool_param)[0], x, dout)
dw_num = eval_numerical_gradient_array(lambda w: conv_relu_pool_forward(x, w, b,
 conv_param, pool_param)[0], w, dout)
db_num = eval_numerical_gradient_array(lambda b: conv_relu_pool_forward(x, w, b,
 conv_param, pool_param)[0], b, dout)

# Relative errors should be around e-8 or less
print('Testing conv_relu_pool')
print('dx error: ', rel_error(dx_num, dx))
print('dw error: ', rel_error(dw_num, dw))
print('db error: ', rel_error(db_num, db))
```

```
Testing conv_relu_pool
dx error:  6.514336569263308e-09
dw error:  1.490843753539445e-08
db error:  2.037390356217257e-09
```

In [11]:

```
from cs231n.layer_utils import conv_relu_forward, conv_relu_backward
np.random.seed(231)
x = np.random.randn(2, 3, 8, 8)
w = np.random.randn(3, 3, 3, 3)
b = np.random.randn(3,)
dout = np.random.randn(2, 3, 8, 8)
conv_param = {'stride': 1, 'pad': 1}

out, cache = conv_relu_forward(x, w, b, conv_param)
dx, dw, db = conv_relu_backward(dout, cache)

dx_num = eval_numerical_gradient_array(lambda x: conv_relu_forward(x, w, b, conv
_param)[0], x, dout)
dw_num = eval_numerical_gradient_array(lambda w: conv_relu_forward(x, w, b, conv
_param)[0], w, dout)
db_num = eval_numerical_gradient_array(lambda b: conv_relu_forward(x, w, b, conv
_param)[0], b, dout)

# Relative errors should be around e-8 or less
print('Testing conv_relu:')
print('dx error: ', rel_error(dx_num, dx))
print('dw error: ', rel_error(dw_num, dw))
print('db error: ', rel_error(db_num, db))
```

```
Testing conv_relu:
dx error:  3.5600610115232832e-09
dw error:  2.2497700915729298e-10
db error:  1.3087619975802167e-10
```

Three-layer ConvNet

Now that you have implemented all the necessary layers, we can put them together into a simple convolutional network.

Open the file `cs231n/classifiers/cnn.py` and complete the implementation of the `ThreeLayerConvNet` class. Remember you can use the fast/sandwich layers (already imported for you) in your implementation. Run the following cells to help you debug:

Sanity check loss

After you build a new network, one of the first things you should do is sanity check the loss. When we use the softmax loss, we expect the loss for random weights (and no regularization) to be about `log(C)` for `C` classes. When we add regularization this should go up.

In [12]:

```
model = ThreeLayerConvNet()

N = 50
X = np.random.randn(N, 3, 32, 32)
y = np.random.randint(10, size=N)

loss, grads = model.loss(X, y)
print('Initial loss (no regularization): ', loss)

model.reg = 0.5
loss, grads = model.loss(X, y)
print('Initial loss (with regularization): ', loss)
```

```
Initial loss (no regularization):  2.302586071243987
Initial loss (with regularization):  2.508255638232932
```

Gradient check

After the loss looks reasonable, use numeric gradient checking to make sure that your backward pass is correct. When you use numeric gradient checking you should use a small amount of artifical data and a small number of neurons at each layer. Note: correct implementations may still have relative errors up to the order of e-2.

In [13]:

```
num_inputs = 2
input_dim = (3, 16, 16)
reg = 0.0
num_classes = 10
np.random.seed(231)
X = np.random.randn(num_inputs, *input_dim)
y = np.random.randint(num_classes, size=num_inputs)

model = ThreeLayerConvNet(num_filters=3, filter_size=3,
                          input_dim=input_dim, hidden_dim=7,
                          dtype=np.float64)
loss, grads = model.loss(X, y)
# Errors should be small, but correct implementations may have
# relative errors up to the order of e-2
for param_name in sorted(grads):
    f = lambda _: model.loss(X, y)[0]
    param_grad_num = eval_numerical_gradient(f, model.params[param_name], verbos
e=False, h=1e-6)
    e = rel_error(param_grad_num, grads[param_name])
    print('%s max relative error: %e' % (param_name, rel_error(param_grad_num, g
rads[param_name])))
```

```
W1 max relative error: 1.380104e-04
W2 max relative error: 1.822723e-02
W3 max relative error: 3.064049e-04
b1 max relative error: 3.477652e-05
b2 max relative error: 2.516375e-03
b3 max relative error: 7.945660e-10
```

Overfit small data

A nice trick is to train your model with just a few training samples. You should be able to overfit small datasets, which will result in very high training accuracy and comparatively low validation accuracy.

In [14]:

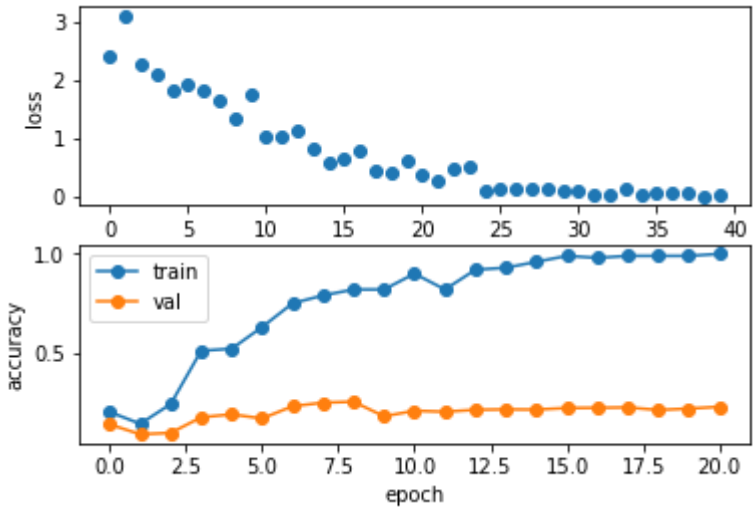
```
np.random.seed(231)

num_train = 100
small_data = {
  'X_train': data['X_train'][:num_train],
  'y_train': data['y_train'][:num_train],
  'X_val': data['X_val'],
  'y_val': data['y_val'],
}

model = ThreeLayerConvNet(weight_scale=1e-2)

solver = Solver(model, small_data,
                num_epochs=20, batch_size=50,
                update_rule='adam',
                optim_config={
                  'learning_rate': 1e-3,
                },
                verbose=True, print_every=1)
solver.train()
```

```
(Iteration 1 / 40) loss: 2.414060
(Epoch 0 / 20) train acc: 0.200000; val_acc: 0.137000
(Iteration 2 / 40) loss: 3.102925
(Epoch 1 / 20) train acc: 0.140000; val_acc: 0.087000
(Iteration 3 / 40) loss: 2.270330
(Iteration 4 / 40) loss: 2.096705
(Epoch 2 / 20) train acc: 0.240000; val_acc: 0.094000
(Iteration 5 / 40) loss: 1.838880
(Iteration 6 / 40) loss: 1.934188
(Epoch 3 / 20) train acc: 0.510000; val_acc: 0.173000
(Iteration 7 / 40) loss: 1.827912
(Iteration 8 / 40) loss: 1.639574
(Epoch 4 / 20) train acc: 0.520000; val_acc: 0.188000
(Iteration 9 / 40) loss: 1.330082
(Iteration 10 / 40) loss: 1.756115
(Epoch 5 / 20) train acc: 0.630000; val_acc: 0.167000
(Iteration 11 / 40) loss: 1.024162
(Iteration 12 / 40) loss: 1.041826
(Epoch 6 / 20) train acc: 0.750000; val_acc: 0.229000
(Iteration 13 / 40) loss: 1.142777
(Iteration 14 / 40) loss: 0.835706
(Epoch 7 / 20) train acc: 0.790000; val_acc: 0.247000
(Iteration 15 / 40) loss: 0.587786
(Iteration 16 / 40) loss: 0.645509
(Epoch 8 / 20) train acc: 0.820000; val_acc: 0.252000
(Iteration 17 / 40) loss: 0.786844
(Iteration 18 / 40) loss: 0.467054
(Epoch 9 / 20) train acc: 0.820000; val_acc: 0.178000
(Iteration 19 / 40) loss: 0.429880
(Iteration 20 / 40) loss: 0.635498
(Epoch 10 / 20) train acc: 0.900000; val_acc: 0.206000
(Iteration 21 / 40) loss: 0.365807
(Iteration 22 / 40) loss: 0.284220
(Epoch 11 / 20) train acc: 0.820000; val_acc: 0.201000
(Iteration 23 / 40) loss: 0.469343
(Iteration 24 / 40) loss: 0.509369
(Epoch 12 / 20) train acc: 0.920000; val_acc: 0.211000
(Iteration 25 / 40) loss: 0.111638
(Iteration 26 / 40) loss: 0.145388
(Epoch 13 / 20) train acc: 0.930000; val_acc: 0.213000
(Iteration 27 / 40) loss: 0.155575
(Iteration 28 / 40) loss: 0.143398
(Epoch 14 / 20) train acc: 0.960000; val_acc: 0.212000
(Iteration 29 / 40) loss: 0.158160
(Iteration 30 / 40) loss: 0.118934
(Epoch 15 / 20) train acc: 0.990000; val_acc: 0.220000
(Iteration 31 / 40) loss: 0.118063
(Iteration 32 / 40) loss: 0.047589
(Epoch 16 / 20) train acc: 0.980000; val_acc: 0.221000
(Iteration 33 / 40) loss: 0.024229
(Iteration 34 / 40) loss: 0.125143
(Epoch 17 / 20) train acc: 0.990000; val_acc: 0.223000
(Iteration 35 / 40) loss: 0.036110
(Iteration 36 / 40) loss: 0.064548
(Epoch 18 / 20) train acc: 0.990000; val_acc: 0.210000
(Iteration 37 / 40) loss: 0.062753
(Iteration 38 / 40) loss: 0.071469
(Epoch 19 / 20) train acc: 0.990000; val_acc: 0.217000
(Iteration 39 / 40) loss: 0.014180
(Iteration 40 / 40) loss: 0.022113
(Epoch 20 / 20) train acc: 1.000000; val_acc: 0.226000
```

Plotting the loss, training accuracy, and validation accuracy should show clear overfitting:

In [15]:

```
plt.subplot(2, 1, 1)
plt.plot(solver.loss_history, 'o')
plt.xlabel('iteration')
plt.ylabel('loss')

plt.subplot(2, 1, 2)
plt.plot(solver.train_acc_history, '-o')
plt.plot(solver.val_acc_history, '-o')
plt.legend(['train', 'val'], loc='upper left')
plt.xlabel('epoch')
plt.ylabel('accuracy')
plt.show()
```



Train the net

By training the three-layer convolutional network for one epoch, you should achieve greater than 40% accuracy on the training set:

In [16]:

```
model = ThreeLayerConvNet(weight_scale=0.001, hidden_dim=500, reg=0.001)

solver = Solver(model, data,
                num_epochs=1, batch_size=50,
                update_rule='adam',
                optim_config={
                  'learning_rate': 1e-3,
                },
                verbose=True, print_every=20)
solver.train()
```

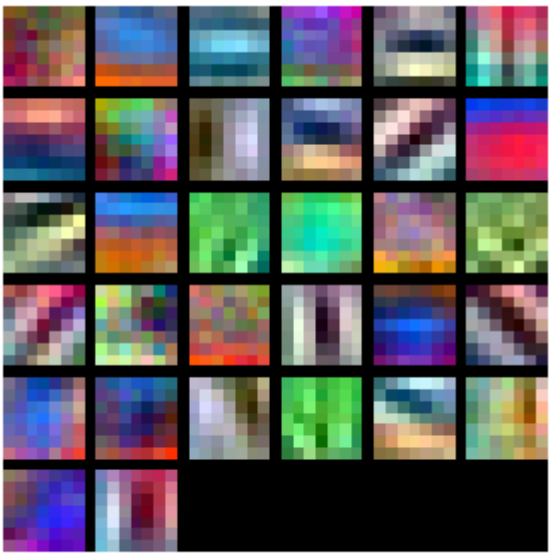
```
(Iteration 1 / 980) loss: 2.304805
(Epoch 0 / 1) train acc: 0.095000; val_acc: 0.102000
(Iteration 21 / 980) loss: 1.959234
(Iteration 41 / 980) loss: 2.139060
(Iteration 61 / 980) loss: 1.812499
(Iteration 81 / 980) loss: 1.711817
(Iteration 101 / 980) loss: 1.798821
(Iteration 121 / 980) loss: 1.683965
(Iteration 141 / 980) loss: 2.059861
(Iteration 161 / 980) loss: 1.876229
(Iteration 181 / 980) loss: 2.267676
(Iteration 201 / 980) loss: 1.559150
(Iteration 221 / 980) loss: 1.895182
(Iteration 241 / 980) loss: 1.702636
(Iteration 261 / 980) loss: 1.931362
(Iteration 281 / 980) loss: 1.969332
(Iteration 301 / 980) loss: 1.553312
(Iteration 321 / 980) loss: 1.538446
(Iteration 341 / 980) loss: 1.393354
(Iteration 361 / 980) loss: 1.396233
(Iteration 381 / 980) loss: 1.842156
(Iteration 401 / 980) loss: 1.320716
(Iteration 421 / 980) loss: 1.537977
(Iteration 441 / 980) loss: 1.661445
(Iteration 461 / 980) loss: 1.713941
(Iteration 481 / 980) loss: 1.749063
(Iteration 501 / 980) loss: 1.722433
(Iteration 521 / 980) loss: 1.577446
(Iteration 541 / 980) loss: 1.697214
(Iteration 561 / 980) loss: 1.923230
(Iteration 581 / 980) loss: 1.735889
(Iteration 601 / 980) loss: 1.477472
(Iteration 621 / 980) loss: 1.719875
(Iteration 641 / 980) loss: 1.398098
(Iteration 661 / 980) loss: 1.580384
(Iteration 681 / 980) loss: 2.046775
(Iteration 701 / 980) loss: 1.478755
(Iteration 721 / 980) loss: 1.602231
(Iteration 741 / 980) loss: 1.450978
(Iteration 761 / 980) loss: 1.706257
(Iteration 781 / 980) loss: 1.391427
(Iteration 801 / 980) loss: 1.375520
(Iteration 821 / 980) loss: 2.114591
(Iteration 841 / 980) loss: 1.631207
(Iteration 861 / 980) loss: 1.189867
(Iteration 881 / 980) loss: 1.389741
(Iteration 901 / 980) loss: 1.478208
(Iteration 921 / 980) loss: 1.386922
(Iteration 941 / 980) loss: 1.591233
(Iteration 961 / 980) loss: 1.514534
(Epoch 1 / 1) train acc: 0.478000; val_acc: 0.519000
```

Visualize Filters

You can visualize the first-layer convolutional filters from the trained network by running the following:

In [17]:

```
from cs231n.vis_utils import visualize_grid

grid = visualize_grid(model.params['W1'].transpose(0, 2, 3, 1))
plt.imshow(grid.astype('uint8'))
plt.axis('off')
plt.gcf().set_size_inches(5, 5)
plt.show()
```



Spatial Batch Normalization

We already saw that batch normalization is a very useful technique for training deep fully-connected networks. As proposed in the original paper [3], batch normalization can also be used for convolutional networks, but we need to tweak it a bit; the modification will be called "spatial batch normalization."

Normally batch-normalization accepts inputs of shape `(N, D)` and produces outputs of shape `(N, D)`, where we normalize across the minibatch dimension `N`. For data coming from convolutional layers, batch normalization needs to accept inputs of shape `(N, C, H, W)` and produce outputs of shape `(N, C, H, W)` where the `N` dimension gives the minibatch size and the `(H, W)` dimensions give the spatial size of the feature map.

If the feature map was produced using convolutions, then we expect the statistics of each feature channel to be relatively consistent both between different imagesand different locations within the same image. Therefore spatial batch normalization computes a mean and variance for each of the `C` feature channels by computing statistics over both the minibatch dimension `N` and the spatial dimensions `H` and `W`.

[3] Sergey Ioffe and Christian Szegedy, "Batch Normalization: Accelerating Deep Network Training by Reducing Internal Covariate Shift", ICML 2015. (https://arxiv.org/abs/1502.03167)

Spatial batch normalization: forward

In the file `cs231n/layers.py`, implement the forward pass for spatial batch normalization in the function `spatial_batchnorm_forward`. Check your implementation by running the following:

In [18]:

```
np.random.seed(231)
# Check the training-time forward pass by checking means and variances
# of features both before and after spatial batch normalization

N, C, H, W = 2, 3, 4, 5
x = 4 * np.random.randn(N, C, H, W) + 10

print('Before spatial batch normalization:')
print('  Shape: ', x.shape)
print('  Means: ', x.mean(axis=(0, 2, 3)))
print('  Stds: ', x.std(axis=(0, 2, 3)))

# Means should be close to zero and stds close to one
gamma, beta = np.ones(C), np.zeros(C)
bn_param = {'mode': 'train'}
out, _ = spatial_batchnorm_forward(x, gamma, beta, bn_param)
print('After spatial batch normalization:')
print('  Shape: ', out.shape)
print('  Means: ', out.mean(axis=(0, 2, 3)))
print('  Stds: ', out.std(axis=(0, 2, 3)))

# Means should be close to beta and stds close to gamma
gamma, beta = np.asarray([3, 4, 5]), np.asarray([6, 7, 8])
out, _ = spatial_batchnorm_forward(x, gamma, beta, bn_param)
print('After spatial batch normalization (nontrivial gamma, beta):')
print('  Shape: ', out.shape)
print('  Means: ', out.mean(axis=(0, 2, 3)))
print('  Stds: ', out.std(axis=(0, 2, 3)))
```

```
Before spatial batch normalization:
  Shape:  (2, 3, 4, 5)
  Means:  [9.33463814 8.90909116 9.11056338]
  Stds:  [3.61447857 3.19347686 3.5168142 ]
After spatial batch normalization:
  Shape:  (2, 3, 4, 5)
  Means:  [ 6.18949336e-16  5.99520433e-16 -1.22124533e-16]
  Stds:  [0.99999962 0.99999951 0.9999996 ]
After spatial batch normalization (nontrivial gamma, beta):
  Shape:  (2, 3, 4, 5)
  Means:  [6. 7. 8.]
  Stds:  [2.99999885 3.99999804 4.99999798]
```

In [19]:

```
np.random.seed(231)
# Check the test-time forward pass by running the training-time
# forward pass many times to warm up the running averages, and then
# checking the means and variances of activations after a test-time
# forward pass.
N, C, H, W = 10, 4, 11, 12

bn_param = {'mode': 'train'}
gamma = np.ones(C)
beta = np.zeros(C)
for t in range(50):
  x = 2.3 * np.random.randn(N, C, H, W) + 13
  spatial_batchnorm_forward(x, gamma, beta, bn_param)
bn_param['mode'] = 'test'
x = 2.3 * np.random.randn(N, C, H, W) + 13
a_norm, _ = spatial_batchnorm_forward(x, gamma, beta, bn_param)

# Means should be close to zero and stds close to one, but will be
# noisier than training-time forward passes.
print('After spatial batch normalization (test-time):')
print('  means: ', a_norm.mean(axis=(0, 2, 3)))
print('  stds: ', a_norm.std(axis=(0, 2, 3)))
```

```
After spatial batch normalization (test-time):
  means:  [-0.08034406  0.07562881  0.05716371  0.04378383]
  stds:  [0.96718744 1.0299714  1.02887624 1.00585577]
```

Spatial batch normalization: backward

In the file `cs231n/layers.py`, implement the backward pass for spatial batch normalization in the function `spatial_batchnorm_backward`. Run the following to check your implementation using a numeric gradient check:

In [20]:

```
np.random.seed(231)
N, C, H, W = 2, 3, 4, 5
x = 5 * np.random.randn(N, C, H, W) + 12
gamma = np.random.randn(C)
beta = np.random.randn(C)
dout = np.random.randn(N, C, H, W)

bn_param = {'mode': 'train'}
fx = lambda x: spatial_batchnorm_forward(x, gamma, beta, bn_param)[0]
fg = lambda a: spatial_batchnorm_forward(x, gamma, beta, bn_param)[0]
fb = lambda b: spatial_batchnorm_forward(x, gamma, beta, bn_param)[0]

dx_num = eval_numerical_gradient_array(fx, x, dout)
da_num = eval_numerical_gradient_array(fg, gamma, dout)
db_num = eval_numerical_gradient_array(fb, beta, dout)

#You should expect errors of magnitudes between 1e-12~1e-06
_, cache = spatial_batchnorm_forward(x, gamma, beta, bn_param)
dx, dgamma, dbeta = spatial_batchnorm_backward(dout, cache)
print('dx error: ', rel_error(dx_num, dx))
print('dgamma error: ', rel_error(da_num, dgamma))
print('dbeta error: ', rel_error(db_num, dbeta))
```

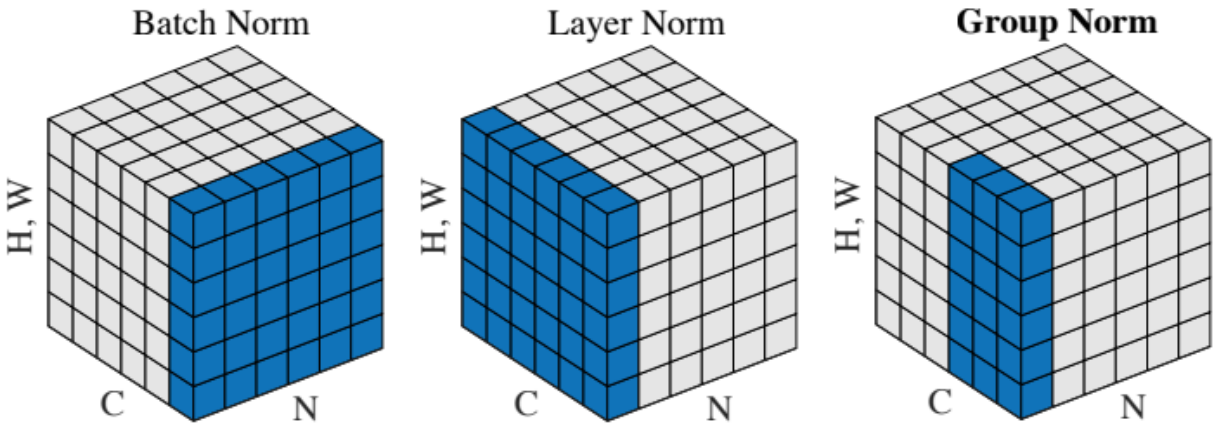
```
dx error:  2.786648193872555e-07
dgamma error:  7.0974817113608705e-12
dbeta error:  3.275608725278405e-12
```

Group Normalization

In the previous notebook, we mentioned that Layer Normalization is an alternative normalization technique that mitigates the batch size limitations of Batch Normalization. However, as the authors of [4] observed, Layer Normalization does not perform as well as Batch Normalization when used with Convolutional Layers:

> With fully connected layers, all the hidden units in a layer tend to make similar contributions to the final prediction, and re-centering and rescaling the summed inputs to a layer works well. However, the assumption of similar contributions is no longer true for convolutional neural networks. The large number of the hidden units whose receptive fields lie near the boundary of the image are rarely turned on and thus have very different statistics from the rest of the hidden units within the same layer.

The authors of [5] propose an intermediary technique. In contrast to Layer Normalization, where you normalize over the entire feature per-datapoint, they suggest a consistent splitting of each per-datapoint feature into G groups, and a per-group per-datapoint normalization instead.



Visual comparison of the normalization techniques discussed so far (image edited from [5])

Even though an assumption of equal contribution is still being made within each group, the authors hypothesize that this is not as problematic, as innate grouping arises within features for visual recognition. One example they use to illustrate this is that many high-performance handcrafted features in traditional Computer Vision have terms that are explicitly grouped together. Take for example Histogram of Oriented Gradients [6]-- after computing histograms per spatially local block, each per-block histogram is normalized before being concatenated together to form the final feature vector.

You will now implement Group Normalization. Note that this normalization technique that you are to implement in the following cells was introduced and published to arXiv *less than a month ago* -- this truly is still an ongoing and excitingly active field of research!

[4] Ba, Jimmy Lei, Jamie Ryan Kiros, and Geoffrey E. Hinton. "Layer Normalization." stat 1050 (2016): 21. (https://arxiv.org/pdf/1607.06450.pdf)

[5] Wu, Yuxin, and Kaiming He. "Group Normalization." arXiv preprint arXiv:1803.08494 (2018). (https://arxiv.org/abs/1803.08494)

[6] N. Dalal and B. Triggs. Histograms of oriented gradients for human detection. In Computer Vision and Pattern Recognition (CVPR), 2005. (https://ieeexplore.ieee.org/abstract/document/1467360/)

Group normalization: forward

In the file `cs231n/layers.py`, implement the forward pass for group normalization in the function `spatial_groupnorm_forward`. Check your implementation by running the following:

In [21]:

```
np.random.seed(231)
# Check the training-time forward pass by checking means and variances
# of features both before and after spatial batch normalization

N, C, H, W = 2, 6, 4, 5
G = 2
x = 4 * np.random.randn(N, C, H, W) + 10
x_g = x.reshape((N*G,-1))
print('Before spatial group normalization:')
print('  Shape: ', x.shape)
print('  Means: ', x_g.mean(axis=1))
print('  Stds: ', x_g.std(axis=1))

# Means should be close to zero and stds close to one
gamma, beta = np.ones((1,C,1,1)), np.zeros((1,C,1,1))
bn_param = {'mode': 'train'}

out, _ = spatial_groupnorm_forward(x, gamma, beta, G, bn_param)
out_g = out.reshape((N*G,-1))
print('After spatial group normalization:')
print('  Shape: ', out.shape)
print('  Means: ', out_g.mean(axis=1))
print('  Stds: ', out_g.std(axis=1))
```

```
Before spatial group normalization:
  Shape:  (2, 6, 4, 5)
  Means:  [9.72505327 8.51114185 8.9147544  9.43448077]
  Stds:  [3.67070958 3.09892597 4.27043622 3.97521327]
After spatial group normalization:
  Shape:  (2, 6, 4, 5)
  Means:  [-2.14643118e-16  5.25505565e-16  2.65528340e-16 -3.386180
23e-16]
  Stds:  [0.99999963 0.99999948 0.99999973 0.99999968]
```

Spatial group normalization: backward

In the file `cs231n/layers.py`, implement the backward pass for spatial batch normalization in the function `spatial_groupnorm_backward`. Run the following to check your implementation using a numeric gradient check:

In [22]:

```
np.random.seed(231)
N, C, H, W = 2, 6, 4, 5
G = 2
x = 5 * np.random.randn(N, C, H, W) + 12
gamma = np.random.randn(1,C,1,1)
beta = np.random.randn(1,C,1,1)
dout = np.random.randn(N, C, H, W)

gn_param = {}
fx = lambda x: spatial_groupnorm_forward(x, gamma, beta, G, gn_param)[0]
fg = lambda a: spatial_groupnorm_forward(x, gamma, beta, G, gn_param)[0]
fb = lambda b: spatial_groupnorm_forward(x, gamma, beta, G, gn_param)[0]

dx_num = eval_numerical_gradient_array(fx, x, dout)
da_num = eval_numerical_gradient_array(fg, gamma, dout)
db_num = eval_numerical_gradient_array(fb, beta, dout)

_, cache = spatial_groupnorm_forward(x, gamma, beta, G, gn_param)
dx, dgamma, dbeta = spatial_groupnorm_backward(dout, cache)
#You should expect errors of magnitudes between 1e-12~1e-07
print('dx error: ', rel_error(dx_num, dx))
print('dgamma error: ', rel_error(da_num, dgamma))
print('dbeta error: ', rel_error(db_num, dbeta))
```

```
dx error:  7.413109404620405e-08
dgamma error:  9.468195772749234e-12
dbeta error:  3.354494437653335e-12
```

What's this PyTorch business?

You've written a lot of code in this assignment to provide a whole host of neural network functionality. Dropout, Batch Norm, and 2D convolutions are some of the workhorses of deep learning in computer vision. You've also worked hard to make your code efficient and vectorized.

For the last part of this assignment, though, we're going to leave behind your beautiful codebase and instead migrate to one of two popular deep learning frameworks: in this instance, PyTorch (or TensorFlow, if you switch over to that notebook).

What is PyTorch?

PyTorch is a system for executing dynamic computational graphs over Tensor objects that behave similarly as numpy ndarray. It comes with a powerful automatic differentiation engine that removes the need for manual back-propagation.

Why?

- Our code will now run on GPUs! Much faster training. When using a framework like PyTorch or TensorFlow you can harness the power of the GPU for your own custom neural network architectures without having to write CUDA code directly (which is beyond the scope of this class).
- We want you to be ready to use one of these frameworks for your project so you can experiment more efficiently than if you were writing every feature you want to use by hand.
- We want you to stand on the shoulders of giants! TensorFlow and PyTorch are both excellent frameworks that will make your lives a lot easier, and now that you understand their guts, you are free to use them :)
- We want you to be exposed to the sort of deep learning code you might run into in academia or industry.

PyTorch versions

This notebook assumes that you are using **PyTorch version 0.4**. Prior to this version, Tensors had to be wrapped in Variable objects to be used in autograd; however Variables have now been deprecated. In addition 0.4 also separates a Tensor's datatype from its device, and uses numpy-style factories for constructing Tensors rather than directly invoking Tensor constructors.

How will I learn PyTorch?

Justin Johnson has made an excellent tutorial (https://github.com/jcjohnson/pytorch-examples) for PyTorch.

You can also find the detailed API doc (http://pytorch.org/docs/stable/index.html) here. If you have other questions that are not addressed by the API docs, the PyTorch forum (https://discuss.pytorch.org/) is a much better place to ask than StackOverflow.

Table of Contents

This assignment has 5 parts. You will learn PyTorch on different levels of abstractions, which will help you understand it better and prepare you for the final project.

1. Preparation: we will use CIFAR-10 dataset.
2. Barebones PyTorch: we will work directly with the lowest-level PyTorch Tensors.
3. PyTorch Module API: we will use `nn.Module` to define arbitrary neural network architecture.
4. PyTorch Sequential API: we will use `nn.Sequential` to define a linear feed-forward network very conveniently.
5. CIFAR-10 open-ended challenge: please implement your own network to get as high accuracy as possible on CIFAR-10. You can experiment with any layer, optimizer, hyperparameters or other advanced features.

Here is a table of comparison:

API	Flexibility	Convenience
Barebone	High	Low
`nn.Module`	High	Medium
`nn.Sequential`	Low	High

Part I. Preparation

First, we load the CIFAR-10 dataset. This might take a couple minutes the first time you do it, but the files should stay cached after that.

In previous parts of the assignment we had to write our own code to download the CIFAR-10 dataset, preprocess it, and iterate through it in minibatches; PyTorch provides convenient tools to automate this process for us.

In [1]:

```
import torch
import torch.nn as nn
import torch.optim as optim
from torch.utils.data import DataLoader
from torch.utils.data import sampler

import torchvision.datasets as dset
import torchvision.transforms as T

import numpy as np
```

In [2]:

```
NUM_TRAIN = 49000

# The torchvision.transforms package provides tools for preprocessing data
# and for performing data augmentation; here we set up a transform to
# preprocess the data by subtracting the mean RGB value and dividing by the
# standard deviation of each RGB value; we've hardcoded the mean and std.
transform = T.Compose([
                T.ToTensor(),
                T.Normalize((0.4914, 0.4822, 0.4465), (0.2023, 0.1994, 0.2010))
            ])

# We set up a Dataset object for each split (train / val / test); Datasets load
# training examples one at a time, so we wrap each Dataset in a DataLoader which
# iterates through the Dataset and forms minibatches. We divide the CIFAR-10
# training set into train and val sets by passing a Sampler object to the
# DataLoader telling how it should sample from the underlying Dataset.
cifar10_train = dset.CIFAR10('./cs231n/datasets', train=True, download=True,
                             transform=transform)
loader_train = DataLoader(cifar10_train, batch_size=64,
                          sampler=sampler.SubsetRandomSampler(range(NUM_TRAIN)))

cifar10_val = dset.CIFAR10('./cs231n/datasets', train=True, download=True,
                           transform=transform)
loader_val = DataLoader(cifar10_val, batch_size=64,
                        sampler=sampler.SubsetRandomSampler(range(NUM_TRAIN, 500
00)))

cifar10_test = dset.CIFAR10('./cs231n/datasets', train=False, download=True,
                            transform=transform)
loader_test = DataLoader(cifar10_test, batch_size=64)
```

```
Files already downloaded and verified
Files already downloaded and verified
Files already downloaded and verified
```

You have an option to **use GPU by setting the flag to True below**. It is not necessary to use GPU for this assignment. Note that if your computer does not have CUDA enabled, `torch.cuda.is_available()` will return False and this notebook will fallback to CPU mode.

The global variables `dtype` and `device` will control the data types throughout this assignment.

In [3]:

```
USE_GPU = True

dtype = torch.float32 # we will be using float throughout this tutorial

if USE_GPU and torch.cuda.is_available():
    device = torch.device('cuda')
else:
    device = torch.device('cpu')

# Constant to control how frequently we print train loss
print_every = 100

print('using device:', device)
```

```
using device: cpu
```

Part II. Barebones PyTorch

PyTorch ships with high-level APIs to help us define model architectures conveniently, which we will cover in Part II of this tutorial. In this section, we will start with the barebone PyTorch elements to understand the autograd engine better. After this exercise, you will come to appreciate the high-level model API more.

We will start with a simple fully-connected ReLU network with two hidden layers and no biases for CIFAR classification. This implementation computes the forward pass using operations on PyTorch Tensors, and uses PyTorch autograd to compute gradients. It is important that you understand every line, because you will write a harder version after the example.

When we create a PyTorch Tensor with `requires_grad=True`, then operations involving that Tensor will not just compute values; they will also build up a computational graph in the background, allowing us to easily backpropagate through the graph to compute gradients of some Tensors with respect to a downstream loss. Concretely if x is a Tensor with `x.requires_grad == True` then after backpropagation `x.grad` will be another Tensor holding the gradient of x with respect to the scalar loss at the end.

PyTorch Tensors: Flatten Function

A PyTorch Tensor is conceptionally similar to a numpy array: it is an n-dimensional grid of numbers, and like numpy PyTorch provides many functions to efficiently operate on Tensors. As a simple example, we provide a `flatten` function below which reshapes image data for use in a fully-connected neural network.

Recall that image data is typically stored in a Tensor of shape N x C x H x W, where:

- N is the number of datapoints
- C is the number of channels
- H is the height of the intermediate feature map in pixels
- W is the height of the intermediate feature map in pixels

This is the right way to represent the data when we are doing something like a 2D convolution, that needs spatial understanding of where the intermediate features are relative to each other. When we use fully connected affine layers to process the image, however, we want each datapoint to be represented by a single vector -- it's no longer useful to segregate the different channels, rows, and columns of the data. So, we use a "flatten" operation to collapse the `C x H x W` values per representation into a single long vector. The flatten function below first reads in the N, C, H, and W values from a given batch of data, and then returns a "view" of that data. "View" is analogous to numpy's "reshape" method: it reshapes x's dimensions to be N x ??, where ?? is allowed to be anything (in this case, it will be C x H x W, but we don't need to specify that explicitly).

In [4]:

```
def flatten(x):
    N = x.shape[0] # read in N, C, H, W
    return x.view(N, -1)  # "flatten" the C * H * W values into a single vector
 per image

def test_flatten():
    x = torch.arange(12).view(2, 1, 3, 2)
    print('Before flattening: ', x)
    print('After flattening: ', flatten(x))

test_flatten()
```

```
Before flattening:  tensor([[[[ 0,  1],
          [ 2,  3],
          [ 4,  5]]],


        [[[ 6,  7],
          [ 8,  9],
          [10, 11]]]])
After flattening:  tensor([[ 0,  1,  2,  3,  4,  5],
        [ 6,  7,  8,  9, 10, 11]])
```

Barebones PyTorch: Two-Layer Network

Here we define a function `two_layer_fc` which performs the forward pass of a two-layer fully-connected ReLU network on a batch of image data. After defining the forward pass we check that it doesn't crash and that it produces outputs of the right shape by running zeros through the network.

You don't have to write any code here, but it's important that you read and understand the implementation.

In [5]:

```
import torch.nn.functional as F  # useful stateless functions

def two_layer_fc(x, params):
    """
    A fully-connected neural networks; the architecture is:
    NN is fully connected -> ReLU -> fully connected layer.
    Note that this function only defines the forward pass;
    PyTorch will take care of the backward pass for us.

    The input to the network will be a minibatch of data, of shape
    (N, d1, ..., dM) where d1 * ... * dM = D. The hidden layer will have H unit
s,
    and the output layer will produce scores for C classes.

    Inputs:
    - x: A PyTorch Tensor of shape (N, d1, ..., dM) giving a minibatch of
      input data.
    - params: A list [w1, w2] of PyTorch Tensors giving weights for the network;
      w1 has shape (D, H) and w2 has shape (H, C).

    Returns:
    - scores: A PyTorch Tensor of shape (N, C) giving classification scores for
      the input data x.
    """
    # first we flatten the image
    x = flatten(x)  # shape: [batch_size, C x H x W]

    w1, w2 = params

    # Forward pass: compute predicted y using operations on Tensors. Since w1 an
d
    # w2 have requires_grad=True, operations involving these Tensors will cause
    # PyTorch to build a computational graph, allowing automatic computation of
    # gradients. Since we are no longer implementing the backward pass by hand w
e
    # don't need to keep references to intermediate values.
    # you can also use `.clamp(min=0)`, equivalent to F.relu()
    x = F.relu(x.mm(w1))
    x = x.mm(w2)
    return x


def two_layer_fc_test():
    hidden_layer_size = 42
    x = torch.zeros((64, 50), dtype=dtype)  # minibatch size 64, feature dimensi
on 50
    w1 = torch.zeros((50, hidden_layer_size), dtype=dtype)
    w2 = torch.zeros((hidden_layer_size, 10), dtype=dtype)
    scores = two_layer_fc(x, [w1, w2])
    print(scores.size())  # you should see [64, 10]

two_layer_fc_test()
```

```
torch.Size([64, 10])
```

Barebones PyTorch: Three-Layer ConvNet

Here you will complete the implementation of the function `three_layer_convnet`, which will perform the forward pass of a three-layer convolutional network. Like above, we can immediately test our implementation by passing zeros through the network. The network should have the following architecture:

1. A convolutional layer (with bias) with `channel_1` filters, each with shape `KW1 x KH1`, and zero-padding of two
2. ReLU nonlinearity
3. A convolutional layer (with bias) with `channel_2` filters, each with shape `KW2 x KH2`, and zero-padding of one
4. ReLU nonlinearity
5. Fully-connected layer with bias, producing scores for C classes.

HINT: For convolutions: http://pytorch.org/docs/stable/nn.html#torch.nn.functional.conv2d (http://pytorch.org/docs/stable/nn.html#torch.nn.functional.conv2d); pay attention to the shapes of convolutional filters!

In [6]:

```
def three_layer_convnet(x, params):
    """
    Performs the forward pass of a three-layer convolutional network with the
    architecture defined above.

    Inputs:
    - x: A PyTorch Tensor of shape (N, 3, H, W) giving a minibatch of images
    - params: A list of PyTorch Tensors giving the weights and biases for the
      network; should contain the following:
      - conv_w1: PyTorch Tensor of shape (channel_1, 3, KH1, KW1) giving weights
        for the first convolutional layer
      - conv_b1: PyTorch Tensor of shape (channel_1,) giving biases for the firs
t
        convolutional layer
      - conv_w2: PyTorch Tensor of shape (channel_2, channel_1, KH2, KW2) giving
        weights for the second convolutional layer
      - conv_b2: PyTorch Tensor of shape (channel_2,) giving biases for the seco
nd
        convolutional layer
      - fc_w: PyTorch Tensor giving weights for the fully-connected layer. Can y
ou
        figure out what the shape should be?
      - fc_b: PyTorch Tensor giving biases for the fully-connected layer. Can yo
u
        figure out what the shape should be?

    Returns:
    - scores: PyTorch Tensor of shape (N, C) giving classification scores for x
    """
    conv_w1, conv_b1, conv_w2, conv_b2, fc_w, fc_b = params
    scores = None
    ################################################################################
####
    # Implement the forward pass for the three-layer ConvNet.
   #
    ################################################################################
####
    scores = F.relu(F.conv2d(x, conv_w1, bias=conv_b1, padding=2))
    scores = F.relu(F.conv2d(scores, conv_w2, bias=conv_b2, padding=1))
    scores = flatten(scores)
    scores = scores.mm(fc_w) + fc_b
    ################################################################################
####
    #                                END OF YOUR CODE
   #
    ################################################################################
####
    return scores
```

After defining the forward pass of the ConvNet above, run the following cell to test your implementation.

When you run this function, scores should have shape (64, 10).

In [7]:

```
def three_layer_convnet_test():
    x = torch.zeros((64, 3, 32, 32), dtype=dtype)  # minibatch size 64, image si
ze [3, 32, 32]

    conv_w1 = torch.zeros((6, 3, 5, 5), dtype=dtype)  # [out_channel, in_channe
l, kernel_H, kernel_W]
    conv_b1 = torch.zeros((6,))  # out_channel
    conv_w2 = torch.zeros((9, 6, 3, 3), dtype=dtype)  # [out_channel, in_channe
l, kernel_H, kernel_W]
    conv_b2 = torch.zeros((9,))  # out_channel

    # you must calculate the shape of the tensor after two conv layers, before t
he fully-connected layer
    fc_w = torch.zeros((9 * 32 * 32, 10))
    fc_b = torch.zeros(10)

    scores = three_layer_convnet(x, [conv_w1, conv_b1, conv_w2, conv_b2, fc_w, f
c_b])
    print(scores.size())  # you should see [64, 10]
three_layer_convnet_test()
```

```
torch.Size([64, 10])
```

Barebones PyTorch: Initialization

Let's write a couple utility methods to initialize the weight matrices for our models.

- `random_weight(shape)` initializes a weight tensor with the Kaiming normalization method.
- `zero_weight(shape)` initializes a weight tensor with all zeros. Useful for instantiating bias parameters.

The `random_weight` function uses the Kaiming normal initialization method, described in:

He et al, *Delving Deep into Rectifiers: Surpassing Human-Level Performance on ImageNet Classification*, ICCV 2015, https://arxiv.org/abs/1502.01852 (https://arxiv.org/abs/1502.01852)

In [8]:

```
def random_weight(shape):
    """
    Create random Tensors for weights; setting requires_grad=True means that we
    want to compute gradients for these Tensors during the backward pass.
    We use Kaiming normalization: sqrt(2 / fan_in)
    """
    if len(shape) == 2:  # FC weight
        fan_in = shape[0]
    else:
        fan_in = np.prod(shape[1:]) # conv weight [out_channel, in_channel, kH,
 kW]
    # randn is standard normal distribution generator.
    w = torch.randn(shape, device=device, dtype=dtype) * np.sqrt(2. / fan_in)
    w.requires_grad = True
    return w

def zero_weight(shape):
    return torch.zeros(shape, device=device, dtype=dtype, requires_grad=True)

# create a weight of shape [3 x 5]
# you should see the type `torch.cuda.FloatTensor` if you use GPU.
# Otherwise it should be `torch.FloatTensor`
random_weight((3, 5))
```

Out[8]:

```
tensor([[-0.6855, -0.1454,  0.0237,  0.7164,  0.0976],
        [ 0.9279,  0.1883, -0.4779, -0.6781,  0.2719],
        [-0.9527, -0.1321, -1.1824, -0.0096, -2.3456]], requires_gra
d=True)
```

Barebones PyTorch: Check Accuracy

When training the model we will use the following function to check the accuracy of our model on the training or validation sets.

When checking accuracy we don't need to compute any gradients; as a result we don't need PyTorch to build a computational graph for us when we compute scores. To prevent a graph from being built we scope our computation under a `torch.no_grad()` context manager.

In [9]:

```
def check_accuracy_part2(loader, model_fn, params):
    """
    Check the accuracy of a classification model.

    Inputs:
    - loader: A DataLoader for the data split we want to check
    - model_fn: A function that performs the forward pass of the model,
      with the signature scores = model_fn(x, params)
    - params: List of PyTorch Tensors giving parameters of the model

    Returns: Nothing, but prints the accuracy of the model
    """
    split = 'val' if loader.dataset.train else 'test'
    print('Checking accuracy on the %s set' % split)
    num_correct, num_samples = 0, 0
    with torch.no_grad():
        for x, y in loader:
            x = x.to(device=device, dtype=dtype)  # move to device, e.g. GPU
            y = y.to(device=device, dtype=torch.int64)
            scores = model_fn(x, params)
            _, preds = scores.max(1)
            num_correct += (preds == y).sum()
            num_samples += preds.size(0)
        acc = float(num_correct) / num_samples
        print('Got %d / %d correct (%.2f%%)' % (num_correct, num_samples, 100 *
acc))
```

BareBones PyTorch: Training Loop

We can now set up a basic training loop to train our network. We will train the model using stochastic gradient descent without momentum. We will use `torch.functional.cross_entropy` to compute the loss; you can read about it here (http://pytorch.org/docs/stable/nn.html#cross-entropy).

The training loop takes as input the neural network function, a list of initialized parameters (`[w1, w2]` in our example), and learning rate.

In [10]:

```
def train_part2(model_fn, params, learning_rate):
    """
    Train a model on CIFAR-10.

    Inputs:
    - model_fn: A Python function that performs the forward pass of the model.
      It should have the signature scores = model_fn(x, params) where x is a
      PyTorch Tensor of image data, params is a list of PyTorch Tensors giving
      model weights, and scores is a PyTorch Tensor of shape (N, C) giving
      scores for the elements in x.
    - params: List of PyTorch Tensors giving weights for the model
    - learning_rate: Python scalar giving the learning rate to use for SGD

    Returns: Nothing
    """
    for t, (x, y) in enumerate(loader_train):
        # Move the data to the proper device (GPU or CPU)
        x = x.to(device=device, dtype=dtype)
        y = y.to(device=device, dtype=torch.long)

        # Forward pass: compute scores and loss
        scores = model_fn(x, params)
        loss = F.cross_entropy(scores, y)

        # Backward pass: PyTorch figures out which Tensors in the computational
        # graph has requires_grad=True and uses backpropagation to compute the
        # gradient of the loss with respect to these Tensors, and stores the
        # gradients in the .grad attribute of each Tensor.
        loss.backward()

        # Update parameters. We don't want to backpropagate through the
        # parameter updates, so we scope the updates under a torch.no_grad()
        # context manager to prevent a computational graph from being built.
        with torch.no_grad():
            for w in params:
                w -= learning_rate * w.grad

                # Manually zero the gradients after running the backward pass
                w.grad.zero_()

        if t % print_every == 0:
            print('Iteration %d, loss = %.4f' % (t, loss.item()))
            check_accuracy_part2(loader_val, model_fn, params)
            print()
```

BareBones PyTorch: Train a Two-Layer Network

Now we are ready to run the training loop. We need to explicitly allocate tensors for the fully connected weights, `w1` and `w2`.

Each minibatch of CIFAR has 64 examples, so the tensor shape is `[64, 3, 32, 32]`.

After flattening, `x` shape should be `[64, 3 * 32 * 32]`. This will be the size of the first dimension of `w1`. The second dimension of `w1` is the hidden layer size, which will also be the first dimension of `w2`.

Finally, the output of the network is a 10-dimensional vector that represents the probability distribution over 10 classes.

You don't need to tune any hyperparameters but you should see accuracies above 40% after training for one epoch.

In [11]:

```
hidden_layer_size = 4000
learning_rate = 1e-2

w1 = random_weight((3 * 32 * 32, hidden_layer_size))
w2 = random_weight((hidden_layer_size, 10))

train_part2(two_layer_fc, [w1, w2], learning_rate)
```

```
Iteration 0, loss = 3.1784
Checking accuracy on the val set
Got 147 / 1000 correct (14.70%)

Iteration 100, loss = 2.9780
Checking accuracy on the val set
Got 330 / 1000 correct (33.00%)

Iteration 200, loss = 2.0169
Checking accuracy on the val set
Got 395 / 1000 correct (39.50%)

Iteration 300, loss = 1.7327
Checking accuracy on the val set
Got 416 / 1000 correct (41.60%)

Iteration 400, loss = 1.7351
Checking accuracy on the val set
Got 418 / 1000 correct (41.80%)

Iteration 500, loss = 1.9948
Checking accuracy on the val set
Got 413 / 1000 correct (41.30%)

Iteration 600, loss = 1.4242
Checking accuracy on the val set
Got 435 / 1000 correct (43.50%)

Iteration 700, loss = 1.5007
Checking accuracy on the val set
Got 436 / 1000 correct (43.60%)
```

BareBones PyTorch: Training a ConvNet

In the below you should use the functions defined above to train a three-layer convolutional network on CIFAR. The network should have the following architecture:

1. Convolutional layer (with bias) with 32 5x5 filters, with zero-padding of 2
2. ReLU
3. Convolutional layer (with bias) with 16 3x3 filters, with zero-padding of 1
4. ReLU
5. Fully-connected layer (with bias) to compute scores for 10 classes

You should initialize your weight matrices using the `random_weight` function defined above, and you should initialize your bias vectors using the `zero_weight` function above.

You don't need to tune any hyperparameters, but if everything works correctly you should achieve an accuracy above 42% after one epoch.

In [12]:

```
learning_rate = 3e-3

channel_1 = 32
channel_2 = 16

conv_w1 = None
conv_b1 = None
conv_w2 = None
conv_b2 = None
fc_w = None
fc_b = None

################################################################################
# Initialize the parameters of a three-layer ConvNet.                          #
################################################################################
conv_w1 = random_weight((channel_1, 3, 5, 5))
conv_b1 = zero_weight((channel_1, ))
conv_w2 = random_weight((channel_2, channel_1, 3, 3))
conv_b2 = zero_weight((channel_2, ))
fc_w = random_weight((32 * 32 * channel_2, 10))
fc_b = zero_weight((10, ))
################################################################################
#                                 END OF YOUR CODE                             #
################################################################################

params = [conv_w1, conv_b1, conv_w2, conv_b2, fc_w, fc_b]
train_part2(three_layer_convnet, params, learning_rate)
```

```
Iteration 0, loss = 3.2312
Checking accuracy on the val set
Got 132 / 1000 correct (13.20%)

Iteration 100, loss = 1.7888
Checking accuracy on the val set
Got 352 / 1000 correct (35.20%)

Iteration 200, loss = 1.8299
Checking accuracy on the val set
Got 425 / 1000 correct (42.50%)

Iteration 300, loss = 1.7949
Checking accuracy on the val set
Got 426 / 1000 correct (42.60%)

Iteration 400, loss = 1.6536
Checking accuracy on the val set
Got 455 / 1000 correct (45.50%)

Iteration 500, loss = 1.5480
Checking accuracy on the val set
Got 452 / 1000 correct (45.20%)

Iteration 600, loss = 1.4917
Checking accuracy on the val set
Got 457 / 1000 correct (45.70%)

Iteration 700, loss = 1.5277
Checking accuracy on the val set
Got 484 / 1000 correct (48.40%)
```

Part III. PyTorch Module API

Barebone PyTorch requires that we track all the parameter tensors by hand. This is fine for small networks with a few tensors, but it would be extremely inconvenient and error-prone to track tens or hundreds of tensors in larger networks.

PyTorch provides the `nn.Module` API for you to define arbitrary network architectures, while tracking every learnable parameters for you. In Part II, we implemented SGD ourselves. PyTorch also provides the `torch.optim` package that implements all the common optimizers, such as RMSProp, Adagrad, and Adam. It even supports approximate second-order methods like L-BFGS! You can refer to the doc (http://pytorch.org/docs/master/optim.html) for the exact specifications of each optimizer.

To use the Module API, follow the steps below:

1. Subclass `nn.Module`. Give your network class an intuitive name like `TwoLayerFC`.
2. In the constructor `__init__()`, define all the layers you need as class attributes. Layer objects like `nn.Linear` and `nn.Conv2d` are themselves `nn.Module` subclasses and contain learnable parameters, so that you don't have to instantiate the raw tensors yourself. `nn.Module` will track these internal parameters for you. Refer to the doc (http://pytorch.org/docs/master/nn.html) to learn more about the dozens of builtin layers. **Warning**: don't forget to call the `super().__init__()` first!
3. In the `forward()` method, define the *connectivity* of your network. You should use the attributes defined in `__init__` as function calls that take tensor as input and output the "transformed" tensor. Do *not* create any new layers with learnable parameters in `forward()`! All of them must be declared upfront in `__init__`.

After you define your Module subclass, you can instantiate it as an object and call it just like the NN forward function in part II.

Module API: Two-Layer Network

Here is a concrete example of a 2-layer fully connected network:

In [13]:

```
class TwoLayerFC(nn.Module):
    def __init__(self, input_size, hidden_size, num_classes):
        super().__init__()
        # assign layer objects to class attributes
        self.fc1 = nn.Linear(input_size, hidden_size)
        # nn.init package contains convenient initialization methods
        # http://pytorch.org/docs/master/nn.html#torch-nn-init
        nn.init.kaiming_normal_(self.fc1.weight)
        self.fc2 = nn.Linear(hidden_size, num_classes)
        nn.init.kaiming_normal_(self.fc2.weight)

    def forward(self, x):
        # forward always defines connectivity
        x = flatten(x)
        scores = self.fc2(F.relu(self.fc1(x)))
        return scores

def test_TwoLayerFC():
    input_size = 50
    x = torch.zeros((64, input_size), dtype=dtype)  # minibatch size 64, feature
 dimension 50
    model = TwoLayerFC(input_size, 42, 10)
    scores = model(x)
    print(scores.size())  # you should see [64, 10]
test_TwoLayerFC()
```

```
torch.Size([64, 10])
```

Module API: Three-Layer ConvNet

It's your turn to implement a 3-layer ConvNet followed by a fully connected layer. The network architecture should be the same as in Part II:

1. Convolutional layer with `channel_1` 5x5 filters with zero-padding of 2
2. ReLU
3. Convolutional layer with `channel_2` 3x3 filters with zero-padding of 1
4. ReLU
5. Fully-connected layer to `num_classes` classes

You should initialize the weight matrices of the model using the Kaiming normal initialization method.

HINT: http://pytorch.org/docs/stable/nn.html#conv2d (http://pytorch.org/docs/stable/nn.html#conv2d)

After you implement the three-layer ConvNet, the `test_ThreeLayerConvNet` function will run your implementation; it should print `(64, 10)` for the shape of the output scores.

In [14]:

```
class ThreeLayerConvNet(nn.Module):
    def __init__(self, in_channel, channel_1, channel_2, num_classes):
        super().__init__()
        ########################################################################
        # Set up the layers you need for a three-layer ConvNet with the        #
        # architecture defined above.                                          #
        ########################################################################
        self.conv1 = nn.Conv2d(in_channel, channel_1, (5, 5), padding=2, bias=Tr
ue)
        nn.init.kaiming_normal_(self.conv1.weight)
        nn.init.constant_(self.conv1.bias, 0)

        self.conv2 = nn.Conv2d(channel_1, channel_2, (3, 3), padding=1, bias=Tru
e)
        nn.init.kaiming_normal_(self.conv2.weight)
        nn.init.constant_(self.conv2.bias, 0)

        self.fc = nn.Linear(32 * 32 * channel_2, num_classes)
        nn.init.kaiming_normal_(self.fc.weight)
        nn.init.constant_(self.fc.bias, 0)
        ########################################################################
        #                           END OF YOUR CODE                           #

        ########################################################################

    def forward(self, x):
        scores = None
        ########################################################################
        # Implement the forward function for a 3-layer ConvNet. you            #
        # should use the layers you defined in __init__ and specify the        #
        # connectivity of those layers in forward()                            #
        ########################################################################
        scores = F.relu(self.conv2(F.relu(self.conv1(x))))
        scores = self.fc(flatten(scores))
        ########################################################################
        #                                END OF YOUR CODE                      #
        ########################################################################
        return scores


def test_ThreeLayerConvNet():
    x = torch.zeros((64, 3, 32, 32), dtype=dtype)  # minibatch size 64, image si
ze [3, 32, 32]
    model = ThreeLayerConvNet(in_channel=3, channel_1=12, channel_2=8, num_class
es=10)
    scores = model(x)
    print(scores.size())  # you should see [64, 10]
test_ThreeLayerConvNet()
```

```
torch.Size([64, 10])
```

Module API: Check Accuracy

Given the validation or test set, we can check the classification accuracy of a neural network.

This version is slightly different from the one in part II. You don't manually pass in the parameters anymore.

In [15]:

```
def check_accuracy_part34(loader, model):
    if loader.dataset.train:
        print('Checking accuracy on validation set')
    else:
        print('Checking accuracy on test set')
    num_correct = 0
    num_samples = 0
    model.eval()  # set model to evaluation mode
    with torch.no_grad():
        for x, y in loader:
            x = x.to(device=device, dtype=dtype)  # move to device, e.g. GPU
            y = y.to(device=device, dtype=torch.long)
            scores = model(x)
            _, preds = scores.max(1)
            num_correct += (preds == y).sum()
            num_samples += preds.size(0)
        acc = float(num_correct) / num_samples
        print('Got %d / %d correct (%.2f)' % (num_correct, num_samples, 100 * ac
c))
```

Module API: Training Loop

We also use a slightly different training loop. Rather than updating the values of the weights ourselves, we use an Optimizer object from the `torch.optim` package, which abstract the notion of an optimization algorithm and provides implementations of most of the algorithms commonly used to optimize neural networks.

In [16]:

```
def train_part34(model, optimizer, epochs=1):
    """
    Train a model on CIFAR-10 using the PyTorch Module API.

    Inputs:
    - model: A PyTorch Module giving the model to train.
    - optimizer: An Optimizer object we will use to train the model
    - epochs: (Optional) A Python integer giving the number of epochs to train f
or

    Returns: Nothing, but prints model accuracies during training.
    """
    model = model.to(device=device)  # move the model parameters to CPU/GPU
    for e in range(epochs):
        for t, (x, y) in enumerate(loader_train):
            model.train()  # put model to training mode
            x = x.to(device=device, dtype=dtype)  # move to device, e.g. GPU
            y = y.to(device=device, dtype=torch.long)

            scores = model(x)
            loss = F.cross_entropy(scores, y)

            # Zero out all of the gradients for the variables which the optimize
r
            # will update.
            optimizer.zero_grad()

            # This is the backwards pass: compute the gradient of the loss with
            # respect to each  parameter of the model.
            loss.backward()

            # Actually update the parameters of the model using the gradients
            # computed by the backwards pass.
            optimizer.step()

            if t % print_every == 0:
                print('Iteration %d, loss = %.4f' % (t, loss.item()))
                check_accuracy_part34(loader_val, model)
                print()
```

Module API: Train a Two-Layer Network

Now we are ready to run the training loop. In contrast to part II, we don't explicitly allocate parameter tensors anymore.

Simply pass the input size, hidden layer size, and number of classes (i.e. output size) to the constructor of `TwoLayerFC`.

You also need to define an optimizer that tracks all the learnable parameters inside `TwoLayerFC`.

You don't need to tune any hyperparameters, but you should see model accuracies above 40% after training for one epoch.

In [17]:

```
hidden_layer_size = 4000
learning_rate = 1e-2
model = TwoLayerFC(3 * 32 * 32, hidden_layer_size, 10)
optimizer = optim.SGD(model.parameters(), lr=learning_rate)

train_part34(model, optimizer)
```

```
Iteration 0, loss = 4.2267
Checking accuracy on validation set
Got 147 / 1000 correct (14.70)

Iteration 100, loss = 2.1651
Checking accuracy on validation set
Got 308 / 1000 correct (30.80)

Iteration 200, loss = 2.2587
Checking accuracy on validation set
Got 376 / 1000 correct (37.60)

Iteration 300, loss = 2.4077
Checking accuracy on validation set
Got 388 / 1000 correct (38.80)

Iteration 400, loss = 1.9853
Checking accuracy on validation set
Got 422 / 1000 correct (42.20)

Iteration 500, loss = 1.9451
Checking accuracy on validation set
Got 441 / 1000 correct (44.10)

Iteration 600, loss = 1.8323
Checking accuracy on validation set
Got 414 / 1000 correct (41.40)

Iteration 700, loss = 1.7594
Checking accuracy on validation set
Got 459 / 1000 correct (45.90)
```

Module API: Train a Three-Layer ConvNet

You should now use the Module API to train a three-layer ConvNet on CIFAR. This should look very similar to training the two-layer network! You don't need to tune any hyperparameters, but you should achieve above above 45% after training for one epoch.

You should train the model using stochastic gradient descent without momentum.

In [18]:

```
learning_rate = 3e-3
channel_1 = 32
channel_2 = 16

model = None
optimizer = None
################################################################################
# Instantiate your ThreeLayerConvNet model and a corresponding optimizer       #
################################################################################
model = ThreeLayerConvNet(3, channel_1, channel_2, 10)
optimizer = optim.SGD(model.parameters(), lr=learning_rate)
################################################################################
#                                END OF YOUR CODE                              
################################################################################

train_part34(model, optimizer)
```

```
Iteration 0, loss = 3.5877
Checking accuracy on validation set
Got 117 / 1000 correct (11.70)

Iteration 100, loss = 1.7804
Checking accuracy on validation set
Got 357 / 1000 correct (35.70)

Iteration 200, loss = 1.9044
Checking accuracy on validation set
Got 403 / 1000 correct (40.30)

Iteration 300, loss = 1.5300
Checking accuracy on validation set
Got 431 / 1000 correct (43.10)

Iteration 400, loss = 1.4116
Checking accuracy on validation set
Got 448 / 1000 correct (44.80)

Iteration 500, loss = 1.4439
Checking accuracy on validation set
Got 468 / 1000 correct (46.80)

Iteration 600, loss = 1.3790
Checking accuracy on validation set
Got 481 / 1000 correct (48.10)

Iteration 700, loss = 1.1597
Checking accuracy on validation set
Got 476 / 1000 correct (47.60)
```

Part IV. PyTorch Sequential API

Part III introduced the PyTorch Module API, which allows you to define arbitrary learnable layers and their connectivity.

For simple models like a stack of feed forward layers, you still need to go through 3 steps: subclass `nn.Module`, assign layers to class attributes in `__init__`, and call each layer one by one in `forward()`. Is there a more convenient way?

Fortunately, PyTorch provides a container Module called `nn.Sequential`, which merges the above steps into one. It is not as flexible as `nn.Module`, because you cannot specify more complex topology than a feed-forward stack, but it's good enough for many use cases.

Sequential API: Two-Layer Network

Let's see how to rewrite our two-layer fully connected network example with `nn.Sequential`, and train it using the training loop defined above.

Again, you don't need to tune any hyperparameters here, but you shoud achieve above 40% accuracy after one epoch of training.

In [19]:

```
# We need to wrap `flatten` function in a module in order to stack it
# in nn.Sequential
class Flatten(nn.Module):
    def forward(self, x):
        return flatten(x)

hidden_layer_size = 4000
learning_rate = 1e-2

model = nn.Sequential(
    Flatten(),
    nn.Linear(3 * 32 * 32, hidden_layer_size),
    nn.ReLU(),
    nn.Linear(hidden_layer_size, 10),
)

# you can use Nesterov momentum in optim.SGD
optimizer = optim.SGD(model.parameters(), lr=learning_rate,
                      momentum=0.9, nesterov=True)

train_part34(model, optimizer)
```

```
Iteration 0, loss = 2.3080
Checking accuracy on validation set
Got 184 / 1000 correct (18.40)

Iteration 100, loss = 1.6887
Checking accuracy on validation set
Got 402 / 1000 correct (40.20)

Iteration 200, loss = 1.5311
Checking accuracy on validation set
Got 403 / 1000 correct (40.30)

Iteration 300, loss = 1.8126
Checking accuracy on validation set
Got 425 / 1000 correct (42.50)

Iteration 400, loss = 1.7005
Checking accuracy on validation set
Got 432 / 1000 correct (43.20)

Iteration 500, loss = 1.9567
Checking accuracy on validation set
Got 427 / 1000 correct (42.70)

Iteration 600, loss = 1.6717
Checking accuracy on validation set
Got 416 / 1000 correct (41.60)

Iteration 700, loss = 1.8908
Checking accuracy on validation set
Got 448 / 1000 correct (44.80)
```

Sequential API: Three-Layer ConvNet

Here you should use `nn.Sequential` to define and train a three-layer ConvNet with the same architecture we used in Part III:

1. Convolutional layer (with bias) with 32 5x5 filters, with zero-padding of 2
2. ReLU
3. Convolutional layer (with bias) with 16 3x3 filters, with zero-padding of 1
4. ReLU
5. Fully-connected layer (with bias) to compute scores for 10 classes

You should initialize your weight matrices using the `random_weight` function defined above, and you should initialize your bias vectors using the `zero_weight` function above.

You should optimize your model using stochastic gradient descent with Nesterov momentum 0.9.

Again, you don't need to tune any hyperparameters but you should see accuracy above 55% after one epoch of training.

In [20]:

```
channel_1 = 32
channel_2 = 16
learning_rate = 1e-2

model = None
optimizer = None

################################################################################
# Rewrite the 2-layer ConvNet with bias from Part III with the                 #
# Sequential API.                                                              #
################################################################################
model = nn.Sequential(
    nn.Conv2d(3, channel_1, (5, 5), padding=2, bias=True),
    nn.ReLU(),
    nn.Conv2d(channel_1, channel_2, (3, 3), padding=1, bias=True),
    nn.ReLU(),
    Flatten(),
    nn.Linear(32 * 32 * channel_2, 10)
)
optimizer = optim.SGD(model.parameters(), lr=learning_rate,
                      momentum=0.9, nesterov=True)

def init_weights(m):
    if type(m) == nn.Conv2d or type(m) == nn.Linear:
        random_weight(m.weight.size())
        zero_weight(m.bias.size())

model.apply(init_weights)
################################################################################
#                                 END OF YOUR CODE
################################################################################

train_part34(model, optimizer)
```

```
Iteration 0, loss = 2.3100
Checking accuracy on validation set
Got 152 / 1000 correct (15.20)

Iteration 100, loss = 1.5689
Checking accuracy on validation set
Got 451 / 1000 correct (45.10)

Iteration 200, loss = 1.1855
Checking accuracy on validation set
Got 455 / 1000 correct (45.50)

Iteration 300, loss = 1.6346
Checking accuracy on validation set
Got 481 / 1000 correct (48.10)

Iteration 400, loss = 1.3025
Checking accuracy on validation set
Got 515 / 1000 correct (51.50)

Iteration 500, loss = 1.3820
Checking accuracy on validation set
Got 553 / 1000 correct (55.30)

Iteration 600, loss = 1.5002
Checking accuracy on validation set
Got 563 / 1000 correct (56.30)

Iteration 700, loss = 1.3821
Checking accuracy on validation set
Got 561 / 1000 correct (56.10)
```

Part V. CIFAR-10 open-ended challenge

In this section, you can experiment with whatever ConvNet architecture you'd like on CIFAR-10.

Now it's your job to experiment with architectures, hyperparameters, loss functions, and optimizers to train a model that achieves **at least 70%** accuracy on the CIFAR-10 **validation** set within 10 epochs. You can use the check_accuracy and train functions from above. You can use either `nn.Module` or `nn.Sequential` API.

Describe what you did at the end of this notebook.

Here are the official API documentation for each component. One note: what we call in the class "spatial batch norm" is called "BatchNorm2D" in PyTorch.

- Layers in torch.nn package: http://pytorch.org/- (http://pytorch.org/-) **Filter size**: Above we used 5x5; would smaller filters be more efficient? docs/stable/nn.html
- Activations: http://pytorch.org/docs/stable/nn.html#non-linear-activations (http://pytorch.org/docs/stable/nn.html#non-linear-activations)
- Loss functions: http://pytorch.org/docs/stable/nn.html#loss-functions (http://pytorch.org/docs/stable/nn.html#loss-functions)
- Optimizers: http://pytorch.org/docs/stable/optim.html (http://pytorch.org/docs/stable/optim.html)

Things you might try:

- **Number of filters**: Above we used 32 filters. Do more or fewer do better?
- **Pooling vs Strided Convolution**: Do you use max pooling or just stride convolutions?
- **Batch normalization**: Try adding spatial batch normalization after convolution layers and vanilla batch normalization after affine layers. Do your networks train faster?
- **Network architecture**: The network above has two layers of trainable parameters. Can you do better with a deep network? Good architectures to try include:
  - [conv-relu-pool]xN -> [affine]xM -> [softmax or SVM]
  - [conv-relu-conv-relu-pool]xN -> [affine]xM -> [softmax or SVM]
  - [batchnorm-relu-conv]xN -> [affine]xM -> [softmax or SVM]
- **Global Average Pooling**: Instead of flattening and then having multiple affine layers, perform convolutions until your image gets small (7x7 or so) and then perform an average pooling operation to get to a 1x1 image picture (1, 1 , Filter#), which is then reshaped into a (Filter#) vector. This is used in Google's Inception Network (https://arxiv.org/abs/1512.00567) (See Table 1 for their architecture).
- **Regularization**: Add l2 weight regularization, or perhaps use Dropout.

Tips for training

For each network architecture that you try, you should tune the learning rate and other hyperparameters. When doing this there are a couple important things to keep in mind:

- If the parameters are working well, you should see improvement within a few hundred iterations
- Remember the coarse-to-fine approach for hyperparameter tuning: start by testing a large range of hyperparameters for just a few training iterations to find the combinations of parameters that are working at all.
- Once you have found some sets of parameters that seem to work, search more finely around these parameters. You may need to train for more epochs.
- You should use the validation set for hyperparameter search, and save your test set for evaluating your architecture on the best parameters as selected by the validation set.

Going above and beyond

If you are feeling adventurous there are many other features you can implement to try and improve your performance. You are **not required** to implement any of these, but don't miss the fun if you have time!

- Alternative optimizers: you can try Adam, Adagrad, RMSprop, etc.
- Alternative activation functions such as leaky ReLU, parametric ReLU, ELU, or MaxOut.
- Model ensembles
- Data augmentation
- New Architectures
  - ResNets (https://arxiv.org/abs/1512.03385) where the input from the previous layer is added to the output.
  - DenseNets (https://arxiv.org/abs/1608.06993) where inputs into previous layers are concatenated together.
  - This blog has an in-depth overview (https://chatbotslife.com/resnets-highwaynets-and-densenets-oh-my-9bb15918ee32)

Have fun and happy training!

In [21]:

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

# Experiment with any architectures, optimizers, and hyperparameters.          #
# Achieve AT LEAST 70% accuracy on the *validation set* within 10 epochs.      #
#                                                                              #
# Note that you can use the check_accuracy function to evaluate on either      #
# the test set or the validation set, by passing either loader_test or         #
# loader_val as the second argument to check_accuracy. You should not touch    #
# the test set until you have finished your architecture and  hyperparameter   #
# tuning, and only run the test set once at the end to report a final value.   #
################################################################################

# [conv -> batchnorm -> relu -> maxpool] * 3 --> [affine -> batchnorm -> relu] -
-> [affine] --> softmax
layer1 = nn.Sequential(
    nn.Conv2d(3, 16, (5, 5), padding=2, bias=True),
    nn.BatchNorm2d(16),
    nn.ReLU(),
    nn.MaxPool2d((2, 2))
)

layer2 = nn.Sequential(
    nn.Conv2d(16, 32, (3, 3), padding=1, bias=True),
    nn.BatchNorm2d(32),
    nn.ReLU(),
    nn.MaxPool2d((2, 2))
)

layer3 = nn.Sequential(
    nn.Conv2d(32, 64, (3, 3), padding=1, bias=True),
    nn.BatchNorm2d(64),
    nn.ReLU(),
    nn.MaxPool2d((2, 2))
)

layer4 = nn.Sequential(
    Flatten(),
    nn.Linear(64*4*4, 512),
    nn.BatchNorm1d(512),
    nn.ReLU(),
    nn.Linear(512, 10)
)

model = nn.Sequential(
    layer1,
    layer2,
    layer3,
    layer4
)

model.apply(init_weights)

learning_rate = 3e-3
optimizer = optim.Adam(model.parameters(), lr=learning_rate)

print_every = 300
################################################################################
#                                END OF YOUR CODE
################################################################################
```

```
# You should get at least 70% accuracy
train_part34(model, optimizer, epochs=10)
```

```
Iteration 0, loss = 2.3147
Checking accuracy on validation set
Got 134 / 1000 correct (13.40)

Iteration 300, loss = 1.1148
Checking accuracy on validation set
Got 572 / 1000 correct (57.20)

Iteration 600, loss = 0.8930
Checking accuracy on validation set
Got 584 / 1000 correct (58.40)

Iteration 0, loss = 0.8716
Checking accuracy on validation set
Got 660 / 1000 correct (66.00)

Iteration 300, loss = 0.9413
Checking accuracy on validation set
Got 684 / 1000 correct (68.40)

Iteration 600, loss = 0.8604
Checking accuracy on validation set
Got 700 / 1000 correct (70.00)

Iteration 0, loss = 0.5265
Checking accuracy on validation set
Got 730 / 1000 correct (73.00)

Iteration 300, loss = 0.7088
Checking accuracy on validation set
Got 735 / 1000 correct (73.50)

Iteration 600, loss = 0.8336
Checking accuracy on validation set
Got 721 / 1000 correct (72.10)

Iteration 0, loss = 0.4219
Checking accuracy on validation set
Got 764 / 1000 correct (76.40)

Iteration 300, loss = 0.6169
Checking accuracy on validation set
Got 748 / 1000 correct (74.80)

Iteration 600, loss = 0.3343
Checking accuracy on validation set
Got 757 / 1000 correct (75.70)

Iteration 0, loss = 0.3600
Checking accuracy on validation set
Got 744 / 1000 correct (74.40)

Iteration 300, loss = 0.3582
Checking accuracy on validation set
Got 771 / 1000 correct (77.10)

Iteration 600, loss = 0.4167
Checking accuracy on validation set
Got 769 / 1000 correct (76.90)

Iteration 0, loss = 0.2609
```

```
Checking accuracy on validation set
Got 762 / 1000 correct (76.20)

Iteration 300, loss = 0.5303
Checking accuracy on validation set
Got 753 / 1000 correct (75.30)

Iteration 600, loss = 0.2754
Checking accuracy on validation set
Got 755 / 1000 correct (75.50)

Iteration 0, loss = 0.2815
Checking accuracy on validation set
Got 775 / 1000 correct (77.50)

Iteration 300, loss = 0.2299
Checking accuracy on validation set
Got 790 / 1000 correct (79.00)

Iteration 600, loss = 0.2238
Checking accuracy on validation set
Got 780 / 1000 correct (78.00)

Iteration 0, loss = 0.2573
Checking accuracy on validation set
Got 744 / 1000 correct (74.40)

Iteration 300, loss = 0.1981
Checking accuracy on validation set
Got 776 / 1000 correct (77.60)

Iteration 600, loss = 0.2487
Checking accuracy on validation set
Got 757 / 1000 correct (75.70)

Iteration 0, loss = 0.2890
Checking accuracy on validation set
Got 780 / 1000 correct (78.00)

Iteration 300, loss = 0.1595
Checking accuracy on validation set
Got 764 / 1000 correct (76.40)

Iteration 600, loss = 0.2360
Checking accuracy on validation set
Got 769 / 1000 correct (76.90)

Iteration 0, loss = 0.0659
Checking accuracy on validation set
Got 758 / 1000 correct (75.80)

Iteration 300, loss = 0.0950
Checking accuracy on validation set
Got 758 / 1000 correct (75.80)

Iteration 600, loss = 0.0626
Checking accuracy on validation set
Got 755 / 1000 correct (75.50)
```

Describe what you did

In the cell below you should write an explanation of what you did, any additional features that you implemented, and/or any graphs that you made in the process of training and evaluating your network.

TODO: Describe what you did

Test set -- run this only once

Now that we've gotten a result we're happy with, we test our final model on the test set (which you should store in best_model). Think about how this compares to your validation set accuracy.

In [22]:

```
best_model = model
check_accuracy_part34(loader_test, best_model)
```

```
Checking accuracy on test set
Got 7535 / 10000 correct (75.35)
```

What's this TensorFlow business?

You've written a lot of code in this assignment to provide a whole host of neural network functionality. Dropout, Batch Norm, and 2D convolutions are some of the workhorses of deep learning in computer vision. You've also worked hard to make your code efficient and vectorized.

For the last part of this assignment, though, we're going to leave behind your beautiful codebase and instead migrate to one of two popular deep learning frameworks: in this instance, TensorFlow (or PyTorch, if you switch over to that notebook)

What is it?

TensorFlow is a system for executing computational graphs over Tensor objects, with native support for performing backpropogation for its Variables. In it, we work with Tensors which are n-dimensional arrays analogous to the numpy ndarray.

Why?

- Our code will now run on GPUs! Much faster training. Writing your own modules to run on GPUs is beyond the scope of this class, unfortunately.
- We want you to be ready to use one of these frameworks for your project so you can experiment more efficiently than if you were writing every feature you want to use by hand.
- We want you to stand on the shoulders of giants! TensorFlow and PyTorch are both excellent frameworks that will make your lives a lot easier, and now that you understand their guts, you are free to use them :)
- We want you to be exposed to the sort of deep learning code you might run into in academia or industry.

How will I learn TensorFlow?

TensorFlow has many excellent tutorials available, including those from Google themselves (https://www.tensorflow.org/get_started/get_started).

Otherwise, this notebook will walk you through much of what you need to do to train models in TensorFlow. See the end of the notebook for some links to helpful tutorials if you want to learn more or need further clarification on topics that aren't fully explained here.

Table of Contents

This notebook has 5 parts. We will walk through TensorFlow at three different levels of abstraction, which should help you better understand it and prepare you for working on your project.

1. Preparation: load the CIFAR-10 dataset.
2. Barebone TensorFlow: we will work directly with low-level TensorFlow graphs.
3. Keras Model API: we will use `tf.keras.Model` to define arbitrary neural network architecture.
4. Keras Sequential API: we will use `tf.keras.Sequential` to define a linear feed-forward network very conveniently.
5. CIFAR-10 open-ended challenge: please implement your own network to get as high accuracy as possible on CIFAR-10. You can experiment with any layer, optimizer, hyperparameters or other advanced features.

Here is a table of comparison:

API	Flexibility	Convenience
Barebone	High	Low
`tf.keras.Model`	High	Medium
`tf.keras.Sequential`	Low	High

Part I: Preparation

First, we load the CIFAR-10 dataset. This might take a few minutes to download the first time you run it, but after that the files should be cached on disk and loading should be faster.

In previous parts of the assignment we used CS231N-specific code to download and read the CIFAR-10 dataset; however the `tf.keras.datasets` package in TensorFlow provides prebuilt utility functions for loading many common datasets.

For the purposes of this assignment we will still write our own code to preprocess the data and iterate through it in minibatches. The `tf.data` package in TensorFlow provides tools for automating this process, but working with this package adds extra complication and is beyond the scope of this notebook. However using `tf.data` can be much more efficient than the simple approach used in this notebook, so you should consider using it for your project.

In [1]:

```
import os
import tensorflow as tf
import numpy as np
import math
import timeit
import matplotlib.pyplot as plt

%matplotlib inline
```

In [2]:

```
def load_cifar10(num_training=49000, num_validation=1000, num_test=10000):
    """
    Fetch the CIFAR-10 dataset from the web and perform preprocessing to prepare
    it for the two-layer neural net classifier. These are the same steps as
    we used for the SVM, but condensed to a single function.
    """
    # Load the raw CIFAR-10 dataset and use appropriate data types and shapes
    cifar10 = tf.keras.datasets.cifar10.load_data()
    (X_train, y_train), (X_test, y_test) = cifar10
    X_train = np.asarray(X_train, dtype=np.float32)
    y_train = np.asarray(y_train, dtype=np.int32).flatten()
    X_test = np.asarray(X_test, dtype=np.float32)
    y_test = np.asarray(y_test, dtype=np.int32).flatten()

    # 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 pixel and divide by std
    mean_pixel = X_train.mean(axis=(0, 1, 2), keepdims=True)
    std_pixel = X_train.std(axis=(0, 1, 2), keepdims=True)
    X_train = (X_train - mean_pixel) / std_pixel
    X_val = (X_val - mean_pixel) / std_pixel
    X_test = (X_test - mean_pixel) / std_pixel

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


# Invoke the above function to get our data.
NHW = (0, 1, 2)
X_train, y_train, X_val, y_val, X_test, y_test = load_cifar10()
print('Train data shape: ', X_train.shape)
print('Train labels shape: ', y_train.shape, y_train.dtype)
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, 32, 32, 3)
Train labels shape:  (49000,) int32
Validation data shape:  (1000, 32, 32, 3)
Validation labels shape:  (1000,)
Test data shape:  (10000, 32, 32, 3)
Test labels shape:  (10000,)
```

Preparation: Dataset object

For our own convenience we'll define a lightweight `Dataset` class which lets us iterate over data and labels. This is not the most flexible or most efficient way to iterate through data, but it will serve our purposes.

In [3]:

```
class Dataset(object):
    def __init__(self, X, y, batch_size, shuffle=False):
        """
        Construct a Dataset object to iterate over data X and labels y

        Inputs:
        - X: Numpy array of data, of any shape
        - y: Numpy array of labels, of any shape but with y.shape[0] == X.shape
[0]
        - batch_size: Integer giving number of elements per minibatch
        - shuffle: (optional) Boolean, whether to shuffle the data on each epoch
        """
        assert X.shape[0] == y.shape[0], 'Got different numbers of data and labe
ls'
        self.X, self.y = X, y
        self.batch_size, self.shuffle = batch_size, shuffle

    def __iter__(self):
        N, B = self.X.shape[0], self.batch_size
        idxs = np.arange(N)
        if self.shuffle:
            np.random.shuffle(idxs)
        return iter((self.X[i:i+B], self.y[i:i+B]) for i in range(0, N, B))


train_dset = Dataset(X_train, y_train, batch_size=64, shuffle=True)
val_dset = Dataset(X_val, y_val, batch_size=64, shuffle=False)
test_dset = Dataset(X_test, y_test, batch_size=64)
```

In [4]:

```
# We can iterate through a dataset like this:
for t, (x, y) in enumerate(train_dset):
    print(t, x.shape, y.shape)
    if t > 5: break
```

```
0 (64, 32, 32, 3) (64,)
1 (64, 32, 32, 3) (64,)
2 (64, 32, 32, 3) (64,)
3 (64, 32, 32, 3) (64,)
4 (64, 32, 32, 3) (64,)
5 (64, 32, 32, 3) (64,)
6 (64, 32, 32, 3) (64,)
```

You can optionally **use GPU by setting the flag to True below**. It's not neccessary to use a GPU for this assignment; if you are working on Google Cloud then we recommend that you do not use a GPU, as it will be significantly more expensive.

In [5]:

```
# Set up some global variables
USE_GPU = False

if USE_GPU:
    device = '/device:GPU:0'
else:
    device = '/cpu:0'

# Constant to control how often we print when training models
print_every = 100

print('Using device: ', device)
```

```
Using device:  /cpu:0
```

Part II: Barebone TensorFlow

TensorFlow ships with various high-level APIs which make it very convenient to define and train neural networks; we will cover some of these constructs in Part III and Part IV of this notebook. In this section we will start by building a model with basic TensorFlow constructs to help you better understand what's going on under the hood of the higher-level APIs.

TensorFlow is primarily a framework for working with **static computational graphs**. Nodes in the computational graph are Tensors which will hold n-dimensional arrays when the graph is run; edges in the graph represent functions that will operate on Tensors when the graph is run to actually perform useful computation.

This means that a typical TensorFlow program is written in two distinct phases:

1. Build a computational graph that describes the computation that you want to perform. This stage doesn't actually perform any computation; it just builds up a symbolic representation of your computation. This stage will typically define one or more `placeholder` objects that represent inputs to the computational graph.
2. Run the computational graph many times. Each time the graph is run you will specify which parts of the graph you want to compute, and pass a `feed_dict` dictionary that will give concrete values to any `placeholder`s in the graph.

TensorFlow warmup: Flatten Function

We can see this in action by defining a simple `flatten` function that will reshape image data for use in a fully-connected network.

In TensorFlow, data for convolutional feature maps is typically stored in a Tensor of shape N x H x W x C where:

- N is the number of datapoints (minibatch size)
- H is the height of the feature map
- W is the width of the feature map
- C is the number of channels in the feature map

This is the right way to represent the data when we are doing something like a 2D convolution, that needs spatial understanding of where the intermediate features are relative to each other. When we use fully connected affine layers to process the image, however, we want each datapoint to be represented by a single vector -- it's no longer useful to segregate the different channels, rows, and columns of the data. So, we use a "flatten" operation to collapse the `H x W x C` values per representation into a single long vector. The flatten function below first reads in the value of N from a given batch of data, and then returns a "view" of that data. "View" is analogous to numpy's "reshape" method: it reshapes x's dimensions to be N x ??, where ?? is allowed to be anything (in this case, it will be H x W x C, but we don't need to specify that explicitly).

NOTE: TensorFlow and PyTorch differ on the default Tensor layout; TensorFlow uses N x H x W x C but PyTorch uses N x C x H x W.

In [6]:

```
def flatten(x):
    """
    Input:
    - TensorFlow Tensor of shape (N, D1, ..., DM)

    Output:
    - TensorFlow Tensor of shape (N, D1 * ... * DM)
    """
    N = tf.shape(x)[0]
    return tf.reshape(x, (N, -1))
```

In [7]:

```
def test_flatten():
    # Clear the current TensorFlow graph.
    tf.reset_default_graph()

    # Stage I: Define the TensorFlow graph describing our computation.
    # In this case the computation is trivial: we just want to flatten
    # a Tensor using the flatten function defined above.

    # Our computation will have a single input, x. We don't know its
    # value yet, so we define a placeholder which will hold the value
    # when the graph is run. We then pass this placeholder Tensor to
    # the flatten function; this gives us a new Tensor which will hold
    # a flattened view of x when the graph is run. The tf.device
    # context manager tells TensorFlow whether to place these Tensors
    # on CPU or GPU.
    with tf.device(device):
        x = tf.placeholder(tf.float32)
        x_flat = flatten(x)

    # At this point we have just built the graph describing our computation,
    # but we haven't actually computed anything yet. If we print x and x_flat
    # we see that they don't hold any data; they are just TensorFlow Tensors
    # representing values that will be computed when the graph is run.
    print('x: ', type(x), x)
    print('x_flat: ', type(x_flat), x_flat)
    print()

    # We need to use a TensorFlow Session object to actually run the graph.
    with tf.Session() as sess:
        # Construct concrete values of the input data x using numpy
        x_np = np.arange(24).reshape((2, 3, 4))
        print('x_np:\n', x_np, '\n')

        # Run our computational graph to compute a concrete output value.
        # The first argument to sess.run tells TensorFlow which Tensor
        # we want it to compute the value of; the feed_dict specifies
        # values to plug into all placeholder nodes in the graph. The
        # resulting value of x_flat is returned from sess.run as a
        # numpy array.
        x_flat_np = sess.run(x_flat, feed_dict={x: x_np})
        print('x_flat_np:\n', x_flat_np, '\n')

        # We can reuse the same graph to perform the same computation
        # with different input data
        x_np = np.arange(12).reshape((2, 3, 2))
        print('x_np:\n', x_np, '\n')
        x_flat_np = sess.run(x_flat, feed_dict={x: x_np})
        print('x_flat_np:\n', x_flat_np)
test_flatten()
```

```
x:  <class 'tensorflow.python.framework.ops.Tensor'> Tensor("Placeho
lder:0", dtype=float32, device=/device:CPU:0)
x_flat:  <class 'tensorflow.python.framework.ops.Tensor'> Tensor("Re
shape:0", shape=(?, ?), dtype=float32, device=/device:CPU:0)

x_np:
 [[[ 0  1  2  3]
  [ 4  5  6  7]
  [ 8  9 10 11]]

 [[12 13 14 15]
  [16 17 18 19]
  [20 21 22 23]]]

x_flat_np:
 [[ 0.  1.  2.  3.  4.  5.  6.  7.  8.  9. 10. 11.]
 [12. 13. 14. 15. 16. 17. 18. 19. 20. 21. 22. 23.]]

x_np:
 [[[ 0  1]
  [ 2  3]
  [ 4  5]]

 [[ 6  7]
  [ 8  9]
  [10 11]]]

x_flat_np:
 [[ 0.  1.  2.  3.  4.  5.]
 [ 6.  7.  8.  9. 10. 11.]]
```

Barebones TensorFlow: Two-Layer Network

We will now implement our first neural network with TensorFlow: a fully-connected ReLU network with two hidden layers and no biases on the CIFAR10 dataset. For now we will use only low-level TensorFlow operators to define the network; later we will see how to use the higher-level abstractions provided by `tf.keras` to simplify the process.

We will define the forward pass of the network in the function `two_layer_fc`; this will accept TensorFlow Tensors for the inputs and weights of the network, and return a TensorFlow Tensor for the scores. It's important to keep in mind that calling the `two_layer_fc` function **does not** perform any computation; instead it just sets up the computational graph for the forward computation. To actually run the network we need to enter a TensorFlow Session and feed data to the computational graph.

After defining the network architecture in the `two_layer_fc` function, we will test the implementation by setting up and running a computational graph, feeding zeros to the network and checking the shape of the output.

It's important that you read and understand this implementation.

In [8]:

```
def two_layer_fc(x, params):
    """
    A fully-connected neural network; the architecture is:
    fully-connected layer -> ReLU -> fully connected layer.
    Note that we only need to define the forward pass here; TensorFlow will take
    care of computing the gradients for us.

    The input to the network will be a minibatch of data, of shape
    (N, d1, ..., dM) where d1 * ... * dM = D. The hidden layer will have H unit
s,
    and the output layer will produce scores for C classes.

    Inputs:
    - x: A TensorFlow Tensor of shape (N, d1, ..., dM) giving a minibatch of
      input data.
    - params: A list [w1, w2] of TensorFlow Tensors giving weights for the
      network, where w1 has shape (D, H) and w2 has shape (H, C).

    Returns:
    - scores: A TensorFlow Tensor of shape (N, C) giving classification scores
      for the input data x.
    """
    w1, w2 = params  # Unpack the parameters
    x = flatten(x)   # Flatten the input; now x has shape (N, D)
    h = tf.nn.relu(tf.matmul(x, w1)) # Hidden layer: h has shape (N, H)
    scores = tf.matmul(h, w2)        # Compute scores of shape (N, C)
    return scores
```

In [9]:

```
def two_layer_fc_test():
    # TensorFlow's default computational graph is essentially a hidden global
    # variable. To avoid adding to this default graph when you rerun this cell,
    # we clear the default graph before constructing the graph we care about.
    tf.reset_default_graph()
    hidden_layer_size = 42

    # Scoping our computational graph setup code under a tf.device context
    # manager lets us tell TensorFlow where we want these Tensors to be
    # placed.
    with tf.device(device):
        # Set up a placehoder for the input of the network, and constant
        # zero Tensors for the network weights. Here we declare w1 and w2
        # using tf.zeros instead of tf.placeholder as we've seen before - this
        # means that the values of w1 and w2 will be stored in the computational
        # graph itself and will persist across multiple runs of the graph; in
        # particular this means that we don't have to pass values for w1 and w2
        # using a feed_dict when we eventually run the graph.
        x = tf.placeholder(tf.float32)
        w1 = tf.zeros((32 * 32 * 3, hidden_layer_size))
        w2 = tf.zeros((hidden_layer_size, 10))

        # Call our two_layer_fc function to set up the computational
        # graph for the forward pass of the network.
        scores = two_layer_fc(x, [w1, w2])

    # Use numpy to create some concrete data that we will pass to the
    # computational graph for the x placeholder.
    x_np = np.zeros((64, 32, 32, 3))
    with tf.Session() as sess:
        # The calls to tf.zeros above do not actually instantiate the values
        # for w1 and w2; the following line tells TensorFlow to instantiate
        # the values of all Tensors (like w1 and w2) that live in the graph.
        sess.run(tf.global_variables_initializer())

        # Here we actually run the graph, using the feed_dict to pass the
        # value to bind to the placeholder for x; we ask TensorFlow to compute
        # the value of the scores Tensor, which it returns as a numpy array.
        scores_np = sess.run(scores, feed_dict={x: x_np})
        print(scores_np.shape)

two_layer_fc_test()
```

```
(64, 10)
```

Barebones TensorFlow: Three-Layer ConvNet

Here you will complete the implementation of the function `three_layer_convnet` which will perform the forward pass of a three-layer convolutional network. The network should have the following architecture:

1. A convolutional layer (with bias) with `channel_1` filters, each with shape `KW1 x KH1`, and zero-padding of two
2. ReLU nonlinearity
3. A convolutional layer (with bias) with `channel_2` filters, each with shape `KW2 x KH2`, and zero-padding of one
4. ReLU nonlinearity
5. Fully-connected layer with bias, producing scores for `C` classes.

HINT: For convolutions: https://www.tensorflow.org/api_docs/python/tf/nn/conv2d (https://www.tensorflow.org/api_docs/python/tf/nn/conv2d); be careful with padding!

HINT: For biases: https://www.tensorflow.org/performance/xla/broadcasting (https://www.tensorflow.org/performance/xla/broadcasting)

In [10]:

```
def three_layer_convnet(x, params):
    """
    A three-layer convolutional network with the architecture described above.

    Inputs:
    - x: A TensorFlow Tensor of shape (N, H, W, 3) giving a minibatch of images
    - params: A list of TensorFlow Tensors giving the weights and biases for the
      network; should contain the following:
      - conv_w1: TensorFlow Tensor of shape (KH1, KW1, 3, channel_1) giving
        weights for the first convolutional layer.
      - conv_b1: TensorFlow Tensor of shape (channel_1,) giving biases for the
        first convolutional layer.
      - conv_w2: TensorFlow Tensor of shape (KH2, KW2, channel_1, channel_2)
        giving weights for the second convolutional layer
      - conv_b2: TensorFlow Tensor of shape (channel_2,) giving biases for the
        second convolutional layer.
      - fc_w: TensorFlow Tensor giving weights for the fully-connected layer.
        Can you figure out what the shape should be?
      - fc_b: TensorFlow Tensor giving biases for the fully-connected layer.
        Can you figure out what the shape should be?
    """
    conv_w1, conv_b1, conv_w2, conv_b2, fc_w, fc_b = params
    scores = None
    ################################################################################
    # Implement the forward pass for the three-layer ConvNet.                      #
    ################################################################################
    x_padded = tf.pad(x, [[0, 0], [2, 2], [2, 2], [0, 0]], mode='CONSTANT')
    scores = tf.nn.relu(tf.nn.conv2d(x_padded, conv_w1, strides=[1,1,1,1], paddi
ng="VALID") + conv_b1)
    scores = tf.pad(scores, [[0, 0], [1, 1], [1, 1], [0, 0]], mode='CONSTANT')
    scores = tf.nn.relu(tf.nn.conv2d(scores, conv_w2, strides=[1,1,1,1], padding
="VALID") + conv_b2)
    scores = flatten(scores)
    scores = tf.matmul(scores, fc_w) + fc_b
    ################################################################################
    #                                END OF YOUR CODE                              #
    ################################################################################
    return scores
```

After defing the forward pass of the three-layer ConvNet above, run the following cell to test your implementation. Like the two-layer network, we use the `three_layer_convnet` function to set up the computational graph, then run the graph on a batch of zeros just to make sure the function doesn't crash, and produces outputs of the correct shape.

When you run this function, `scores_np` should have shape `(64, 10)`.

In [11]:

```
def three_layer_convnet_test():
    tf.reset_default_graph()

    with tf.device(device):
        x = tf.placeholder(tf.float32)
        conv_w1 = tf.zeros((5, 5, 3, 6))
        conv_b1 = tf.zeros((6,))
        conv_w2 = tf.zeros((3, 3, 6, 9))
        conv_b2 = tf.zeros((9,))
        fc_w = tf.zeros((32 * 32 * 9, 10))
        fc_b = tf.zeros((10,))
        params = [conv_w1, conv_b1, conv_w2, conv_b2, fc_w, fc_b]
        scores = three_layer_convnet(x, params)

    # Inputs to convolutional layers are 4-dimensional arrays with shape
    # [batch_size, height, width, channels]
    x_np = np.zeros((64, 32, 32, 3))

    with tf.Session() as sess:
        sess.run(tf.global_variables_initializer())
        scores_np = sess.run(scores, feed_dict={x: x_np})
        print('scores_np has shape: ', scores_np.shape)

with tf.device('/cpu:0'):
    three_layer_convnet_test()
```

```
scores_np has shape:  (64, 10)
```

Barebones TensorFlow: Training Step

We now define the `training_step` function which sets up the part of the computational graph that performs a single training step. This will take three basic steps:

1. Compute the loss
2. Compute the gradient of the loss with respect to all network weights
3. Make a weight update step using (stochastic) gradient descent.

Note that the step of updating the weights is itself an operation in the computational graph - the calls to `tf.assign_sub` in `training_step` return TensorFlow operations that mutate the weights when they are executed. There is an important bit of subtlety here - when we call `sess.run`, TensorFlow does not execute all operations in the computational graph; it only executes the minimal subset of the graph necessary to compute the outputs that we ask TensorFlow to produce. As a result, naively computing the loss would not cause the weight update operations to execute, since the operations needed to compute the loss do not depend on the output of the weight update. To fix this problem, we insert a **control dependency** into the graph, adding a duplicate `loss` node to the graph that does depend on the outputs of the weight update operations; this is the object that we actually return from the `training_step` function. As a result, asking TensorFlow to evaluate the value of the `loss` returned from `training_step` will also implicitly update the weights of the network using that minibatch of data.

We need to use a few new TensorFlow functions to do all of this:

- For computing the cross-entropy loss we'll use `tf.nn.sparse_softmax_cross_entropy_with_logits`: https://www.tensorflow.org/api_docs/python/tf/nn/sparse_softmax_cross_entropy_with_logits (https://www.tensorflow.org/api_docs/python/tf/nn/sparse_softmax_cross_entropy_with_logits)
- For averaging the loss across a minibatch of data we'll use `tf.reduce_mean`: https://www.tensorflow.org/api_docs/python/tf/reduce_mean (https://www.tensorflow.org/api_docs/python/tf/reduce_mean)
- For computing gradients of the loss with respect to the weights we'll use `tf.gradients`: https://www.tensorflow.org/api_docs/python/tf/gradients (https://www.tensorflow.org/api_docs/python/tf/gradients)
- We'll mutate the weight values stored in a TensorFlow Tensor using `tf.assign_sub`: https://www.tensorflow.org/api_docs/python/tf/assign_sub (https://www.tensorflow.org/api_docs/python/tf/assign_sub)
- We'll add a control dependency to the graph using `tf.control_dependencies`: https://www.tensorflow.org/api_docs/python/tf/control_dependencies (https://www.tensorflow.org/api_docs/python/tf/control_dependencies)

In [12]:

```
def training_step(scores, y, params, learning_rate):
    """
    Set up the part of the computational graph which makes a training step.

    Inputs:
    - scores: TensorFlow Tensor of shape (N, C) giving classification scores for
      the model.
    - y: TensorFlow Tensor of shape (N,) giving ground-truth labels for scores;
      y[i] == c means that c is the correct class for scores[i].
    - params: List of TensorFlow Tensors giving the weights of the model
    - learning_rate: Python scalar giving the learning rate to use for gradient
      descent step.

    Returns:
    - loss: A TensorFlow Tensor of shape () (scalar) giving the loss for this
      batch of data; evaluating the loss also performs a gradient descent step
      on params (see above).
    """
    # First compute the loss; the first line gives losses for each example in
    # the minibatch, and the second averages the losses acros the batch
    losses = tf.nn.sparse_softmax_cross_entropy_with_logits(labels=y, logits=sco
res)
    loss = tf.reduce_mean(losses)

    # Compute the gradient of the loss with respect to each parameter of the the
    # network. This is a very magical function call: TensorFlow internally
    # traverses the computational graph starting at loss backward to each elemen
t
    # of params, and uses backpropagation to figure out how to compute gradient
s;
    # it then adds new operations to the computational graph which compute the
    # requested gradients, and returns a list of TensorFlow Tensors that will
    # contain the requested gradients when evaluated.
    grad_params = tf.gradients(loss, params)

    # Make a gradient descent step on all of the model parameters.
    new_weights = []
    for w, grad_w in zip(params, grad_params):
        new_w = tf.assign_sub(w, learning_rate * grad_w)
        new_weights.append(new_w)

    # Insert a control dependency so that evaluting the loss causes a weight
    # update to happen; see the discussion above.
    with tf.control_dependencies(new_weights):
        return tf.identity(loss)
```

Barebones TensorFlow: Training Loop

Now we set up a basic training loop using low-level TensorFlow operations. We will train the model using stochastic gradient descent without momentum. The `training_step` function sets up the part of the computational graph that performs the training step, and the function `train_part2` iterates through the training data, making training steps on each minibatch, and periodically evaluates accuracy on the validation set.

In [13]:

```
def train_part2(model_fn, init_fn, learning_rate):
    """
    Train a model on CIFAR-10.

    Inputs:
    - model_fn: A Python function that performs the forward pass of the model
      using TensorFlow; it should have the following signature:
      scores = model_fn(x, params) where x is a TensorFlow Tensor giving a
      minibatch of image data, params is a list of TensorFlow Tensors holding
      the model weights, and scores is a TensorFlow Tensor of shape (N, C)
      giving scores for all elements of x.
    - init_fn: A Python function that initializes the parameters of the model.
      It should have the signature params = init_fn() where params is a list
      of TensorFlow Tensors holding the (randomly initialized) weights of the
      model.
    - learning_rate: Python float giving the learning rate to use for SGD.
    """
    # First clear the default graph
    tf.reset_default_graph()
    is_training = tf.placeholder(tf.bool, name='is_training')
    # Set up the computational graph for performing forward and backward passes,
    # and weight updates.
    with tf.device(device):
        # Set up placeholders for the data and labels
        x = tf.placeholder(tf.float32, [None, 32, 32, 3])
        y = tf.placeholder(tf.int32, [None])
        params = init_fn()           # Initialize the model parameters
        scores = model_fn(x, params) # Forward pass of the model
        loss = training_step(scores, y, params, learning_rate)

    # Now we actually run the graph many times using the training data
    with tf.Session() as sess:
        # Initialize variables that will live in the graph
        sess.run(tf.global_variables_initializer())
        for t, (x_np, y_np) in enumerate(train_dset):
            # Run the graph on a batch of training data; recall that asking
            # TensorFlow to evaluate loss will cause an SGD step to happen.
            feed_dict = {x: x_np, y: y_np}
            loss_np = sess.run(loss, feed_dict=feed_dict)

            # Periodically print the loss and check accuracy on the val set
            if t % print_every == 0:
                print('Iteration %d, loss = %.4f' % (t, loss_np))
                check_accuracy(sess, val_dset, x, scores, is_training)
```

Barebones TensorFlow: Check Accuracy

When training the model we will use the following function to check the accuracy of our model on the training or validation sets. Note that this function accepts a TensorFlow Session object as one of its arguments; this is needed since the function must actually run the computational graph many times on the data that it loads from the dataset `dset`.

Also note that we reuse the same computational graph both for taking training steps and for evaluating the model; however since the `check_accuracy` function never evalutes the `loss` value in the computational graph, the part of the graph that updates the weights of the graph do not execute on the validation data.

In [14]:

```
def check_accuracy(sess, dset, x, scores, is_training=None):
    """
    Check accuracy on a classification model.

    Inputs:
    - sess: A TensorFlow Session that will be used to run the graph
    - dset: A Dataset object on which to check accuracy
    - x: A TensorFlow placeholder Tensor where input images should be fed
    - scores: A TensorFlow Tensor representing the scores output from the
      model; this is the Tensor we will ask TensorFlow to evaluate.

    Returns: Nothing, but prints the accuracy of the model
    """
    num_correct, num_samples = 0, 0
    for x_batch, y_batch in dset:
        feed_dict = {x: x_batch, is_training: 0}
        scores_np = sess.run(scores, feed_dict=feed_dict)
        y_pred = scores_np.argmax(axis=1)
        num_samples += x_batch.shape[0]
        num_correct += (y_pred == y_batch).sum()
    acc = float(num_correct) / num_samples
    print('Got %d / %d correct (%.2f%%)' % (num_correct, num_samples, 100 * acc
))
```

Barebones TensorFlow: Initialization

We'll use the following utility method to initialize the weight matrices for our models using Kaiming's normalization method.

[1] He et al, *Delving Deep into Rectifiers: Surpassing Human-Level Performance on ImageNet Classification*, ICCV 2015, https://arxiv.org/abs/1502.01852 (https://arxiv.org/abs/1502.01852)

In [15]:

```
def kaiming_normal(shape):
    if len(shape) == 2:
        fan_in, fan_out = shape[0], shape[1]
    elif len(shape) == 4:
        fan_in, fan_out = np.prod(shape[:3]), shape[3]
    return tf.random_normal(shape) * np.sqrt(2.0 / fan_in)
```

Barebones TensorFlow: Train a Two-Layer Network

We are finally ready to use all of the pieces defined above to train a two-layer fully-connected network on CIFAR-10.

We just need to define a function to initialize the weights of the model, and call `train_part2`.

Defining the weights of the network introduces another important piece of TensorFlow API: `tf.Variable`. A TensorFlow Variable is a Tensor whose value is stored in the graph and persists across runs of the computational graph; however unlike constants defined with `tf.zeros` or `tf.random_normal`, the values of a Variable can be mutated as the graph runs; these mutations will persist across graph runs. Learnable parameters of the network are usually stored in Variables.

You don't need to tune any hyperparameters, but you should achieve accuracies above 40% after one epoch of training.

In [16]:

```
def two_layer_fc_init():
    """
    Initialize the weights of a two-layer network, for use with the
    two_layer_network function defined above.

    Inputs: None

    Returns: A list of:
    - w1: TensorFlow Variable giving the weights for the first layer
    - w2: TensorFlow Variable giving the weights for the second layer
    """
    hidden_layer_size = 4000
    w1 = tf.Variable(kaiming_normal((3 * 32 * 32, 4000)))
    w2 = tf.Variable(kaiming_normal((4000, 10)))
    return [w1, w2]

learning_rate = 1e-2
train_part2(two_layer_fc, two_layer_fc_init, learning_rate)
```

```
Iteration 0, loss = 2.9349
Got 108 / 1000 correct (10.80%)
Iteration 100, loss = 1.9784
Got 392 / 1000 correct (39.20%)
Iteration 200, loss = 1.4357
Got 393 / 1000 correct (39.30%)
Iteration 300, loss = 1.8257
Got 369 / 1000 correct (36.90%)
Iteration 400, loss = 1.8686
Got 424 / 1000 correct (42.40%)
Iteration 500, loss = 1.7931
Got 437 / 1000 correct (43.70%)
Iteration 600, loss = 1.8467
Got 423 / 1000 correct (42.30%)
Iteration 700, loss = 1.9089
Got 434 / 1000 correct (43.40%)
```

Barebones TensorFlow: Train a three-layer ConvNet

We will now use TensorFlow to train a three-layer ConvNet on CIFAR-10.

You need to implement the `three_layer_convnet_init` function. Recall that the architecture of the network is:

1. Convolutional layer (with bias) with 32 5x5 filters, with zero-padding 2
2. ReLU
3. Convolutional layer (with bias) with 16 3x3 filters, with zero-padding 1
4. ReLU
5. Fully-connected layer (with bias) to compute scores for 10 classes

You don't need to do any hyperparameter tuning, but you should see accuracies above 43% after one epoch of training.

In [17]:

```
def three_layer_convnet_init():
    """
    Initialize the weights of a Three-Layer ConvNet, for use with the
    three_layer_convnet function defined above.

    Inputs: None

    Returns a list containing:
    - conv_w1: TensorFlow Variable giving weights for the first conv layer
    - conv_b1: TensorFlow Variable giving biases for the first conv layer
    - conv_w2: TensorFlow Variable giving weights for the second conv layer
    - conv_b2: TensorFlow Variable giving biases for the second conv layer
    - fc_w: TensorFlow Variable giving weights for the fully-connected layer
    - fc_b: TensorFlow Variable giving biases for the fully-connected layer
    """
    params = None
    ############################################################################
    # Initialize the parameters of the three-layer network.                    #
    ############################################################################
    conv_w1 = tf.Variable(kaiming_normal((5, 5, 3, 32)))
    conv_b1 = tf.Variable(np.zeros([32]), dtype=tf.float32)
    conv_w2 = tf.Variable(kaiming_normal((3, 3, 32, 16)))
    conv_b2 = tf.Variable(np.zeros([16]), dtype=tf.float32)
    fc_w = tf.Variable(kaiming_normal((16 * 32 * 32, 10)))
    fc_b = tf.Variable(np.zeros([10]), dtype=tf.float32)
    params = [conv_w1, conv_b1, conv_w2, conv_b2, fc_w, fc_b]
    ############################################################################
    #                                 END OF YOUR CODE                         #
    ############################################################################
    return params

learning_rate = 3e-3
train_part2(three_layer_convnet, three_layer_convnet_init, learning_rate)
```

```
Iteration 0, loss = 3.3693
Got 155 / 1000 correct (15.50%)
Iteration 100, loss = 1.9058
Got 352 / 1000 correct (35.20%)
Iteration 200, loss = 1.6226
Got 414 / 1000 correct (41.40%)
Iteration 300, loss = 1.7225
Got 421 / 1000 correct (42.10%)
Iteration 400, loss = 1.7039
Got 453 / 1000 correct (45.30%)
Iteration 500, loss = 1.6228
Got 454 / 1000 correct (45.40%)
Iteration 600, loss = 1.6709
Got 476 / 1000 correct (47.60%)
Iteration 700, loss = 1.6309
Got 471 / 1000 correct (47.10%)
```

Part III: Keras Model API

Implementing a neural network using the low-level TensorFlow API is a good way to understand how TensorFlow works, but it's a little inconvenient - we had to manually keep track of all Tensors holding learnable parameters, and we had to use a control dependency to implement the gradient descent update step. This was fine for a small network, but could quickly become unweildy for a large complex model.

Fortunately TensorFlow provides higher-level packages such as `tf.keras` and `tf.layers` which make it easy to build models out of modular, object-oriented layers; `tf.train` allows you to easily train these models using a variety of different optimization algorithms.

In this part of the notebook we will define neural network models using the `tf.keras.Model` API. To implement your own model, you need to do the following:

1. Define a new class which subclasses `tf.keras.model`. Give your class an intuitive name that describes it, like `TwoLayerFC` or `ThreeLayerConvNet`.
2. In the initializer `__init__()` for your new class, define all the layers you need as class attributes. The `tf.layers` package provides many common neural-network layers, like `tf.layers.Dense` for fully-connected layers and `tf.layers.Conv2D` for convolutional layers. Under the hood, these layers will construct `Variable` Tensors for any learnable parameters. **Warning**: Don't forget to call `super().__init__()` as the first line in your initializer!
3. Implement the `call()` method for your class; this implements the forward pass of your model, and defines the *connectivity* of your network. Layers defined in `__init__()` implement `__call__()` so they can be used as function objects that transform input Tensors into output Tensors. Don't define any new layers in `call()`; any layers you want to use in the forward pass should be defined in `__init__()`.

After you define your `tf.keras.Model` subclass, you can instantiate it and use it like the model functions from Part II.

Module API: Two-Layer Network

Here is a concrete example of using the `tf.keras.Model` API to define a two-layer network. There are a few new bits of API to be aware of here:

We use an `Initializer` object to set up the initial values of the learnable parameters of the layers; in particular `tf.variance_scaling_initializer` gives behavior similar to the Kaiming initialization method we used in Part II. You can read more about it here:
https://www.tensorflow.org/api_docs/python/tf/variance_scaling_initializer (https://www.tensorflow.org/api_docs/python/tf/variance_scaling_initializer)

We construct `tf.layers.Dense` objects to represent the two fully-connected layers of the model. In addition to multiplying their input by a weight matrix and adding a bias vector, these layer can also apply a nonlinearity for you. For the first layer we specify a ReLU activation function by passing `activation=tf.nn.relu` to the constructor; the second layer does not apply any activation function.

Unfortunately the `flatten` function we defined in Part II is not compatible with the `tf.keras.Model` API; fortunately we can use `tf.layers.flatten` to perform the same operation. The issue with our `flatten` function from Part II has to do with static vs dynamic shapes for Tensors, which is beyond the scope of this notebook; you can read more about the distinction in the documentation (https://www.tensorflow.org/programmers_guide/faq#tensor_shapes).

In [18]:

```
class TwoLayerFC(tf.keras.Model):
    def __init__(self, hidden_size, num_classes):
        super().__init__()
        initializer = tf.variance_scaling_initializer(scale=2.0)
        self.fc1 = tf.layers.Dense(hidden_size, activation=tf.nn.relu,
                                   kernel_initializer=initializer)
        self.fc2 = tf.layers.Dense(num_classes,
                                   kernel_initializer=initializer)
    def call(self, x, training=None):
        x = tf.layers.flatten(x)
        x = self.fc1(x)
        x = self.fc2(x)
        return x


def test_TwoLayerFC():
    """ A small unit test to exercise the TwoLayerFC model above. """
    tf.reset_default_graph()
    input_size, hidden_size, num_classes = 50, 42, 10

    # As usual in TensorFlow, we first need to define our computational graph.
    # To this end we first construct a TwoLayerFC object, then use it to constru
ct
    # the scores Tensor.
    model = TwoLayerFC(hidden_size, num_classes)
    with tf.device(device):
        x = tf.zeros((64, input_size))
        scores = model(x)

    # Now that our computational graph has been defined we can run the graph
    with tf.Session() as sess:
        sess.run(tf.global_variables_initializer())
        scores_np = sess.run(scores)
        print(scores_np.shape)

test_TwoLayerFC()
```

```
(64, 10)
```

Funtional API: Two-Layer Network

The `tf.layers` package provides two different higher-level APIs for defining neural network models. In the example above we used the **object-oriented API**, where each layer of the neural network is represented as a Python object (like `tf.layers.Dense`). Here we showcase the **functional API**, where each layer is a Python function (like `tf.layers.dense`) which inputs and outputs TensorFlow Tensors, and which internally sets up Tensors in the computational graph to hold any learnable weights.

To construct a network, one needs to pass the input tensor to the first layer, and construct the subsequent layers sequentially. Here's an example of how to construct the same two-layer nework with the functional API.

In [19]:

```
def two_layer_fc_functional(inputs, hidden_size, num_classes):
    initializer = tf.variance_scaling_initializer(scale=2.0)
    flattened_inputs = tf.layers.flatten(inputs)
    fc1_output = tf.layers.dense(flattened_inputs, hidden_size, activation=tf.nn
.relu,
                                 kernel_initializer=initializer)
    scores = tf.layers.dense(fc1_output, num_classes,
                             kernel_initializer=initializer)
    return scores

def test_two_layer_fc_functional():
    """ A small unit test to exercise the TwoLayerFC model above. """
    tf.reset_default_graph()
    input_size, hidden_size, num_classes = 50, 42, 10

    # As usual in TensorFlow, we first need to define our computational graph.
    # To this end we first construct a two layer network graph by calling the
    # two_layer_network() function. This function constructs the computation
    # graph and outputs the score tensor.
    with tf.device(device):
        x = tf.zeros((64, input_size))
        scores = two_layer_fc_functional(x, hidden_size, num_classes)

    # Now that our computational graph has been defined we can run the graph
    with tf.Session() as sess:
        sess.run(tf.global_variables_initializer())
        scores_np = sess.run(scores)
        print(scores_np.shape)

test_two_layer_fc_functional()
```

```
(64, 10)
```

Keras Model API: Three-Layer ConvNet

Now it's your turn to implement a three-layer ConvNet using the `tf.keras.Model` API. Your model should have the same architecture used in Part II:

1. Convolutional layer with 5 x 5 kernels, with zero-padding of 2
2. ReLU nonlinearity
3. Convolutional layer with 3 x 3 kernels, with zero-padding of 1
4. ReLU nonlinearity
5. Fully-connected layer to give class scores

You should initialize the weights of your network using the same initialization method as was used in the two-layer network above.

Hint: Refer to the documentation for `tf.layers.Conv2D` and `tf.layers.Dense`:

https://www.tensorflow.org/api_docs/python/tf/layers/Conv2D (https://www.tensorflow.org/api_docs/python/tf/layers/Conv2D)

https://www.tensorflow.org/api_docs/python/tf/layers/Dense (https://www.tensorflow.org/api_docs/python/tf/layers/Dense)

In [20]:

```
class ThreeLayerConvNet(tf.keras.Model):
    def __init__(self, channel_1, channel_2, num_classes):
        super().__init__()
        ########################################################################
        # Implement the __init__ method for a three-layer ConvNet. You        #
        # should instantiate layer objects to be used in the forward pass.     #
        ########################################################################
        initializer = tf.variance_scaling_initializer(scale=2.0)
        self.conv1 = tf.layers.Conv2D(channel_1, [5, 5], [1, 1], padding='valid'
,
                                      activation=tf.nn.relu, kernel_initializer=
initializer)
        self.conv2 = tf.layers.Conv2D(channel_2, [3, 3], [1, 1], padding='valid'
,
                                      activation=tf.nn.relu, kernel_initializer=
initializer)
        self.fc = tf.layers.Dense(num_classes, kernel_initializer=initializer)

        ########################################################################
        #                              END OF YOUR CODE                        #
        ########################################################################

    def call(self, x, training=None):
        scores = None
        ########################################################################
        # Implement the forward pass for a three-layer ConvNet. You            #
        # should use the layer objects defined in the __init__ method.         #
        ########################################################################
        scores = tf.pad(x, [[0, 0], [2, 2], [2, 2], [0, 0]], mode='CONSTANT')
        scores = self.conv1(scores)
        scores = tf.pad(scores, [[0, 0], [1, 1], [1, 1], [0, 0]], mode='CONSTAN
T')
        scores = self.conv2(scores)
        scores = tf.layers.flatten(scores)
        scores = self.fc(scores)
        ########################################################################
        #                              END OF YOUR CODE                        #
        ########################################################################

        return scores
```

Once you complete the implementation of the `ThreeLayerConvNet` above you can run the following to ensure that your implementation does not crash and produces outputs of the expected shape.

In [21]:

```
def test_ThreeLayerConvNet():
    tf.reset_default_graph()

    channel_1, channel_2, num_classes = 12, 8, 10
    model = ThreeLayerConvNet(channel_1, channel_2, num_classes)
    with tf.device(device):
        x = tf.zeros((64, 3, 32, 32))
        scores = model(x)

    with tf.Session() as sess:
        sess.run(tf.global_variables_initializer())
        scores_np = sess.run(scores)
        print(scores_np.shape)

test_ThreeLayerConvNet()
```

```
(64, 10)
```

Keras Model API: Training Loop

We need to implement a slightly different training loop when using the `tf.keras.Model` API. Instead of computing gradients and updating the weights of the model manually, we use an `Optimizer` object from the `tf.train` package which takes care of these details for us. You can read more about `Optimizer` s here: https://www.tensorflow.org/api_docs/python/tf/train/Optimizer (https://www.tensorflow.org/api_docs/python/tf/train/Optimizer)

In [22]:

```
def train_part34(model_init_fn, optimizer_init_fn, num_epochs=1):
    """
    Simple training loop for use with models defined using tf.keras. It trains
    a model for one epoch on the CIFAR-10 training set and periodically checks
    accuracy on the CIFAR-10 validation set.

    Inputs:
    - model_init_fn: A function that takes no parameters; when called it
      constructs the model we want to train: model = model_init_fn()
    - optimizer_init_fn: A function which takes no parameters; when called it
      constructs the Optimizer object we will use to optimize the model:
      optimizer = optimizer_init_fn()
    - num_epochs: The number of epochs to train for

    Returns: Nothing, but prints progress during trainingn
    """
    tf.reset_default_graph()
    with tf.device(device):
        # Construct the computational graph we will use to train the model. We
        # use the model_init_fn to construct the model, declare placeholders for
        # the data and labels
        x = tf.placeholder(tf.float32, [None, 32, 32, 3])
        y = tf.placeholder(tf.int32, [None])

        # We need a place holder to explicitly specify if the model is in the tr
aining
        # phase or not. This is because a number of layers behaves differently i
n
        # training and in testing, e.g., dropout and batch normalization.
        # We pass this variable to the computation graph through feed_dict as sh
own below.
        is_training = tf.placeholder(tf.bool, name='is_training')

        # Use the model function to build the forward pass.
        scores = model_init_fn(x, is_training)

        # Compute the loss like we did in Part II
        loss = tf.nn.sparse_softmax_cross_entropy_with_logits(labels=y, logits=s
cores)
        loss = tf.reduce_mean(loss)

        # Use the optimizer_fn to construct an Optimizer, then use the optimizer
        # to set up the training step. Asking TensorFlow to evaluate the
        # train_op returned by optimizer.minimize(loss) will cause us to make a
        # single update step using the current minibatch of data.

        # Note that we use tf.control_dependencies to force the model to run
        # the tf.GraphKeys.UPDATE_OPS at each training step. tf.GraphKeys.UPDATE
_OPS
        # holds the operators that update the states of the network.
        # For example, the tf.layers.batch_normalization function adds the runni
ng mean
        # and variance update operators to tf.GraphKeys.UPDATE_OPS.
        optimizer = optimizer_init_fn()
        update_ops = tf.get_collection(tf.GraphKeys.UPDATE_OPS)
        with tf.control_dependencies(update_ops):
            train_op = optimizer.minimize(loss)

    # Now we can run the computational graph many times to train the model.
```

```
    # When we call sess.run we ask it to evaluate train_op, which causes the
    # model to update.
    with tf.Session() as sess:
        sess.run(tf.global_variables_initializer())
        t = 0
        for epoch in range(num_epochs):
            print('Starting epoch %d' % epoch)
            for x_np, y_np in train_dset:
                feed_dict = {x: x_np, y: y_np, is_training:1}
                loss_np, _ = sess.run([loss, train_op], feed_dict=feed_dict)
                if t % print_every == 0:
                    print('Iteration %d, loss = %.4f' % (t, loss_np))
                    check_accuracy(sess, val_dset, x, scores, is_training=is_tra
ining)
                    print()
                t += 1
```

Keras Model API: Train a Two-Layer Network

We can now use the tools defined above to train a two-layer network on CIFAR-10. We define the `model_init_fn` and `optimizer_init_fn` that construct the model and optimizer respectively when called. Here we want to train the model using stochastic gradient descent with no momentum, so we construct a `tf.train.GradientDescentOptimizer` function; you can read about it here (https://www.tensorflow.org/api_docs/python/tf/train/GradientDescentOptimizer).

You don't need to tune any hyperparameters here, but you should achieve accuracies above 40% after one epoch of training.

In [23]:

```
hidden_size, num_classes = 4000, 10
learning_rate = 1e-2

def model_init_fn(inputs, is_training):
    return TwoLayerFC(hidden_size, num_classes)(inputs)

def optimizer_init_fn():
    return tf.train.GradientDescentOptimizer(learning_rate)

train_part34(model_init_fn, optimizer_init_fn)
```

```
Starting epoch 0
Iteration 0, loss = 2.9681
Got 137 / 1000 correct (13.70%)

Iteration 100, loss = 1.8324
Got 390 / 1000 correct (39.00%)

Iteration 200, loss = 1.4157
Got 402 / 1000 correct (40.20%)

Iteration 300, loss = 1.8077
Got 375 / 1000 correct (37.50%)

Iteration 400, loss = 1.8419
Got 447 / 1000 correct (44.70%)

Iteration 500, loss = 1.8408
Got 453 / 1000 correct (45.30%)

Iteration 600, loss = 1.8319
Got 441 / 1000 correct (44.10%)

Iteration 700, loss = 1.9328
Got 444 / 1000 correct (44.40%)
```

Keras Model API: Train a Two-Layer Network (functional API)

Similarly, we train the two-layer network constructed using the functional API.

In [24]:

```
hidden_size, num_classes = 4000, 10
learning_rate = 1e-2

def model_init_fn(inputs, is_training):
    return two_layer_fc_functional(inputs, hidden_size, num_classes)

def optimizer_init_fn():
    return tf.train.GradientDescentOptimizer(learning_rate)

train_part34(model_init_fn, optimizer_init_fn)
```

```
Starting epoch 0
Iteration 0, loss = 2.9580
Got 130 / 1000 correct (13.00%)

Iteration 100, loss = 1.8524
Got 363 / 1000 correct (36.30%)

Iteration 200, loss = 1.3765
Got 363 / 1000 correct (36.30%)

Iteration 300, loss = 1.7311
Got 375 / 1000 correct (37.50%)

Iteration 400, loss = 1.7597
Got 417 / 1000 correct (41.70%)

Iteration 500, loss = 1.8954
Got 418 / 1000 correct (41.80%)

Iteration 600, loss = 1.9135
Got 412 / 1000 correct (41.20%)

Iteration 700, loss = 1.9359
Got 438 / 1000 correct (43.80%)
```

Keras Model API: Train a Three-Layer ConvNet

Here you should use the tools we've defined above to train a three-layer ConvNet on CIFAR-10. Your ConvNet should use 32 filters in the first convolutional layer and 16 filters in the second layer.

To train the model you should use gradient descent with Nesterov momentum 0.9.

HINT: https://www.tensorflow.org/api_docs/python/tf/train/MomentumOptimizer (https://www.tensorflow.org/api_docs/python/tf/train/MomentumOptimizer)

You don't need to perform any hyperparameter tuning, but you should achieve accuracies above 45% after training for one epoch.

In [25]:

```
learning_rate = 3e-3
channel_1, channel_2, num_classes = 32, 16, 10

def model_init_fn(inputs, is_training):
    model = None
    ################################################################################
    # Complete the implementation of model_fn.                                     #
    ################################################################################
    model = ThreeLayerConvNet(channel_1, channel_2, num_classes)
    ################################################################################
    #                                END OF YOUR CODE                              #
    ################################################################################
    return model(inputs)

def optimizer_init_fn():
    optimizer = None
    ################################################################################
    # Complete the implementation of model_fn.                                     #
    ################################################################################
    optimizer = tf.train.MomentumOptimizer(learning_rate, 0.9, use_nesterov=True
)
    ################################################################################
    #                                END OF YOUR CODE                              #
    ################################################################################
    return optimizer

train_part34(model_init_fn, optimizer_init_fn)
```

```
Starting epoch 0
Iteration 0, loss = 2.7454
Got 87 / 1000 correct (8.70%)

Iteration 100, loss = 1.7118
Got 432 / 1000 correct (43.20%)

Iteration 200, loss = 1.3744
Got 497 / 1000 correct (49.70%)

Iteration 300, loss = 1.3454
Got 512 / 1000 correct (51.20%)

Iteration 400, loss = 1.2740
Got 537 / 1000 correct (53.70%)

Iteration 500, loss = 1.4667
Got 542 / 1000 correct (54.20%)

Iteration 600, loss = 1.3584
Got 568 / 1000 correct (56.80%)

Iteration 700, loss = 1.2022
Got 565 / 1000 correct (56.50%)
```

Part IV: Keras Sequential API

In Part III we introduced the `tf.keras.Model` API, which allows you to define models with any number of learnable layers and with arbitrary connectivity between layers.

However for many models you don't need such flexibility - a lot of models can be expressed as a sequential stack of layers, with the output of each layer fed to the next layer as input. If your model fits this pattern, then there is an even easier way to define your model: using `tf.keras.Sequential`. You don't need to write any custom classes; you simply call the `tf.keras.Sequential` constructor with a list containing a sequence of layer objects.

One complication with `tf.keras.Sequential` is that you must define the shape of the input to the model by passing a value to the `input_shape` of the first layer in your model.

Keras Sequential API: Two-Layer Network

Here we rewrite the two-layer fully-connected network using `tf.keras.Sequential`, and train it using the training loop defined above.

You don't need to perform any hyperparameter tuning here, but you should see accuracies above 40% after training for one epoch.

In [26]:

```
learning_rate = 1e-2

def model_init_fn(inputs, is_training):
    input_shape = (32, 32, 3)
    hidden_layer_size, num_classes = 4000, 10
    initializer = tf.variance_scaling_initializer(scale=2.0)
    layers = [
        tf.layers.Flatten(input_shape=input_shape),
        tf.layers.Dense(hidden_layer_size, activation=tf.nn.relu,
                        kernel_initializer=initializer),
        tf.layers.Dense(num_classes, kernel_initializer=initializer),
    ]
    model = tf.keras.Sequential(layers)
    return model(inputs)

def optimizer_init_fn():
    return tf.train.GradientDescentOptimizer(learning_rate)

train_part34(model_init_fn, optimizer_init_fn)
```

```
Starting epoch 0
Iteration 0, loss = 2.8860
Got 128 / 1000 correct (12.80%)

Iteration 100, loss = 1.8906
Got 359 / 1000 correct (35.90%)

Iteration 200, loss = 1.3435
Got 398 / 1000 correct (39.80%)

Iteration 300, loss = 1.8195
Got 381 / 1000 correct (38.10%)

Iteration 400, loss = 1.8523
Got 419 / 1000 correct (41.90%)

Iteration 500, loss = 1.7718
Got 423 / 1000 correct (42.30%)

Iteration 600, loss = 1.8750
Got 409 / 1000 correct (40.90%)

Iteration 700, loss = 1.9625
Got 443 / 1000 correct (44.30%)
```

Keras Sequential API: Three-Layer ConvNet

Here you should use `tf.keras.Sequential` to reimplement the same three-layer ConvNet architecture used in Part II and Part III. As a reminder, your model should have the following architecture:

1. Convolutional layer with 16 5x5 kernels, using zero padding of 2
2. ReLU nonlinearity
3. Convolutional layer with 32 3x3 kernels, using zero padding of 1
4. ReLU nonlinearity
5. Fully-connected layer giving class scores

You should initialize the weights of the model using a `tf.variance_scaling_initializer` as above.

You should train the model using Nesterov momentum 0.9.

You don't need to perform any hyperparameter search, but you should achieve accuracy above 45% after training for one epoch.

In [27]:

```
def model_init_fn(inputs, is_training):
    model = None
    ##############################################################################
    # Construct a three-layer ConvNet using tf.keras.Sequential.                 #
    ##############################################################################
    input_shape = (32, 32, 3)
    channel_1, channel_2, num_classes = 32, 16, 10
    initializer = tf.variance_scaling_initializer(scale=2.0)
    layers = [
        tf.keras.layers.InputLayer(input_shape=input_shape),
        tf.layers.Conv2D(channel_1, [5, 5], [1, 1], padding='same', activation=t
f.nn.relu, kernel_initializer=initializer),
        tf.layers.Conv2D(channel_2, [3, 3], [1, 1], padding='same', activation=t
f.nn.relu, kernel_initializer=initializer),
        tf.layers.Flatten(),
        tf.layers.Dense(num_classes, kernel_initializer=initializer),
    ]
    model = tf.keras.Sequential(layers)
    ##############################################################################
    #                               END OF YOUR CODE                             #
    ##############################################################################
    return model(inputs)

learning_rate = 5e-4
def optimizer_init_fn():
    optimizer = None
    ##############################################################################
    # Complete the implementation of model_fn.                                   #
    ##############################################################################
    optimizer = tf.train.MomentumOptimizer(learning_rate, 0.9, use_nesterov=True
)
    ##############################################################################
    #                               END OF YOUR CODE                             #
    ##############################################################################
    return optimizer

train_part34(model_init_fn, optimizer_init_fn)
```

```
Starting epoch 0
Iteration 0, loss = 3.3274
Got 107 / 1000 correct (10.70%)

Iteration 100, loss = 1.8492
Got 357 / 1000 correct (35.70%)

Iteration 200, loss = 1.4910
Got 407 / 1000 correct (40.70%)

Iteration 300, loss = 1.6574
Got 417 / 1000 correct (41.70%)

Iteration 400, loss = 1.6128
Got 443 / 1000 correct (44.30%)

Iteration 500, loss = 1.6004
Got 455 / 1000 correct (45.50%)

Iteration 600, loss = 1.7066
Got 464 / 1000 correct (46.40%)

Iteration 700, loss = 1.5346
Got 493 / 1000 correct (49.30%)
```

Part V: CIFAR-10 open-ended challenge

In this section you can experiment with whatever ConvNet architecture you'd like on CIFAR-10.

You should experiment with architectures, hyperparameters, loss functions, regularization, or anything else you can think of to train a model that achieves **at least 70%** accuracy on the **validation** set within 10 epochs. You can use the `check_accuracy` and `train` functions from above, or you can implement your own training loop.

Describe what you did at the end of the notebook.

Some things you can try:

- **Filter size**: Above we used 5x5 and 3x3; is this optimal?
- **Number of filters**: Above we used 16 and 32 filters. Would more or fewer do better?
- **Pooling**: We didn't use any pooling above. Would this improve the model?
- **Normalization**: Would your model be improved with batch normalization, layer normalization, group normalization, or some other normalization strategy?
- **Network architecture**: The ConvNet above has only three layers of trainable parameters. Would a deeper model do better?
- **Global average pooling**: Instead of flattening after the final convolutional layer, would global average pooling do better? This strategy is used for example in Google's Inception network and in Residual Networks.
- **Regularization**: Would some kind of regularization improve performance? Maybe weight decay or dropout?

WARNING: Batch Normalization / Dropout

Batch Normalization and Dropout **WILL NOT WORK CORRECTLY** if you use the `train_part34()` function with the object-oriented `tf.keras.Model` or `tf.keras.Sequential` APIs; if you want to use these layers with this training loop then you **must use the tf.layers functional API**.

We wrote `train_part34()` to explicitly demonstrate how TensorFlow works; however there are some subtleties that make it tough to handle the object-oriented batch normalization layer in a simple training loop. In practice both `tf.keras` and `tf` provide higher-level APIs which handle the training loop for you, such as keras.fit (https://keras.io/models/sequential/) and tf.Estimator (https://www.tensorflow.org/programmers_guide/estimators), both of which will properly handle batch normalization when using the object-oriented API.

Tips for training

For each network architecture that you try, you should tune the learning rate and other hyperparameters. When doing this there are a couple important things to keep in mind:

- If the parameters are working well, you should see improvement within a few hundred iterations
- Remember the coarse-to-fine approach for hyperparameter tuning: start by testing a large range of hyperparameters for just a few training iterations to find the combinations of parameters that are working at all.
- Once you have found some sets of parameters that seem to work, search more finely around these parameters. You may need to train for more epochs.
- You should use the validation set for hyperparameter search, and save your test set for evaluating your architecture on the best parameters as selected by the validation set.

Going above and beyond

If you are feeling adventurous there are many other features you can implement to try and improve your performance. You are **not required** to implement any of these, but don't miss the fun if you have time!

- Alternative optimizers: you can try Adam, Adagrad, RMSprop, etc.
- Alternative activation functions such as leaky ReLU, parametric ReLU, ELU, or MaxOut.
- Model ensembles
- Data augmentation
- New Architectures
  - ResNets (https://arxiv.org/abs/1512.03385) where the input from the previous layer is added to the output.
  - DenseNets (https://arxiv.org/abs/1608.06993) where inputs into previous layers are concatenated together.
  - This blog has an in-depth overview (https://chatbotslife.com/resnets-highwaynets-and-densenets-oh-my-9bb15918ee32)

Have fun and happy training!

In [ ]:

```
def model_init_fn(inputs, is_training):
    model = None
    ##############################################################################
    # Construct a model that performs well on CIFAR-10                           #
    ##############################################################################

    ##############################################################################
    #                               END OF YOUR CODE                             #
    ##############################################################################
    return net

def optimizer_init_fn():
    optimizer = None
    ##############################################################################
    # Construct an optimizer that performs well on CIFAR-10                      #
    ##############################################################################
    optimizer = tf.train.AdamOptimizer(learning_rate)
    ##############################################################################
    #                               END OF YOUR CODE                             #
    ##############################################################################
    return optimizer

device = '/gpu:0'
print_every = 700
num_epochs = 10
train_part34(model_init_fn, optimizer_init_fn, num_epochs)
```

Describe what you did

In the cell below you should write an explanation of what you did, any additional features that you implemented, and/or any graphs that you made in the process of training and evaluating your network.

TODO: Tell us what you did