

# 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 \(https://github.com/jcjohnson/pytorch-examples\)](https://github.com/jcjohnson/pytorch-examples) for PyTorch.

You can also find the detailed [API doc \(http://pytorch.org/docs/stable/index.html\)](http://pytorch.org/docs/stable/index.html) here. If you have other questions that are not addressed by the API docs, the [PyTorch forum \(https://discuss.pytorch.org/\)](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
<code>nn.Module</code>	High	Medium
<code>nn.Sequential</code>	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 [3]: 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

import os
os.environ['KMP_DUPLICATE_LIB_OK']='True'
```

```

In [4]: 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('./cs682/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('./cs682/datasets', train=True, download=True,
                           transform=transform)
loader_val = DataLoader(cifar10_val, batch_size=64,
                       sampler=sampler.SubsetRandomSampler(range(NUM_TRAIN, 50000)))

cifar10_test = dset.CIFAR10('./cs682/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 [5]: 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  $N \times C \times H \times W$ , 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 width 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  $C \times H \times W$  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  $N \times ??$ , where  $??$  is allowed to be anything (in this case, it will be  $C \times H \times W$ , but we don't need to specify that explicitly).

```
In [6]: 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 [7]: 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 units,
    and the output layer will produce scores for C classes.

    Inputs:
    - x: A PyTorch Tensor of shape (N, d1, ..., dM) giving a minibatch o
    f
        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 sco
    res 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. Sin
    ce w1 and
    # w2 have requires_grad=True, operations involving these Tensors wil
    l cause
    # PyTorch to build a computational graph, allowing automatic computa
    tion of
    # gradients. Since we are no longer implementing the backward pass b
    y hand we
    # 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
    dimension 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 [24]: 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 first
            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 second
            convolutional layer
            - fc_w: PyTorch Tensor giving weights for the fully-connected layer. Can you
            figure out what the shape should be?
            - fc_b: PyTorch Tensor giving biases for the fully-connected layer. Can you
            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
        #####
        # TODO: Implement the forward pass for the three-layer ConvNet.
        #
        #####
        z1 = F.conv2d(x, conv_w1, bias=conv_b1, padding=2)
        z2 = F.relu(z1)
        # print("z2", z2.shape)
        z3 = F.conv2d(z2, conv_w2, bias=conv_b2, padding=1)
        z4 = F.relu(z3)
        z4 = flatten(z4)
        # print("z4", z4.shape)
        scores = z4.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 [25]: def three_layer_convnet_test():  
        x = torch.zeros((64, 3, 32, 32), dtype=dtype) # minibatch size 64,  
        image size [3, 32, 32]  
  
        conv_w1 = torch.zeros((6, 3, 5, 5), dtype=dtype) # [out_channel, in  
        _channel, kernel_H, kernel_W]  
        conv_b1 = torch.zeros((6,)) # out_channel  
        conv_w2 = torch.zeros((9, 6, 3, 3), dtype=dtype) # [out_channel, in  
        _channel, kernel_H, kernel_W]  
        conv_b2 = torch.zeros((9,)) # out_channel  
  
        # you must calculate the shape of the tensor after two conv layers,  
        before the 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, fc_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 [26]: 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 pas
          s.
          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_chann
              el, kH, kW]
          # randn is standard normal distribution generator.
          w = torch.randn(shape, device=device, dtype=dtype) * np.sqrt(2. / fa
              n_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[26]: tensor([[ -0.8634,  1.2359,  0.0678, -1.0635,  1.6025],
                  [ 0.2004, -0.5486, -0.5235,  0.0680,  1.0950],
                  [-0.9561,  0.4455,  0.5152,  0.2006,  1.0745]], requires_grad=T
          rue)
```

## 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 [27]: 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 \(http://pytorch.org/docs/stable/nn.html#cross-entropy\)](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 [28]: 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) givi
            ng
            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 S
        GD

        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 comput
            ational
            # graph has requires_grad=True and uses backpropagation to compu
            te 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_gr
            ad()
            # context manager to prevent a computational graph from being bu
            ilt.

            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,  $w_1$  and  $w_2$ .

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  $w_1$ . The second dimension of  $w_1$  is the hidden layer size, which will also be the first dimension of  $w_2$ .

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 [29]: 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 = 3.5956
Checking accuracy on the val set
Got 103 / 1000 correct (10.30%)
```

```
Iteration 100, loss = 2.4938
Checking accuracy on the val set
Got 290 / 1000 correct (29.00%)
```

```
Iteration 200, loss = 1.7095
Checking accuracy on the val set
Got 393 / 1000 correct (39.30%)
```

```
Iteration 300, loss = 2.1934
Checking accuracy on the val set
Got 370 / 1000 correct (37.00%)
```

```
Iteration 400, loss = 1.8438
Checking accuracy on the val set
Got 383 / 1000 correct (38.30%)
```

```
Iteration 500, loss = 1.7035
Checking accuracy on the val set
Got 414 / 1000 correct (41.40%)
```

```
Iteration 600, loss = 1.8732
Checking accuracy on the val set
Got 437 / 1000 correct (43.70%)
```

```
Iteration 700, loss = 1.5101
Checking accuracy on the val set
Got 419 / 1000 correct (41.90%)
```



## 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 [30]: 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

#####
#####
# TODO: Initialize the parameters of a three-layer ConvNet.
#
#####
#####
# 3 x 32 x 32
conv_w1 = random_weight ((channel_1, 3, 5, 5))
conv_b1 = zero_weight ((channel_1))
# after 1st conv layer (pad=2) => channel_1 x 32 x 32
conv_w2 = random_weight ((channel_2, channel_1, 3, 3))
conv_b2 = zero_weight ((channel_2))
# after 2nd conv layer (pad=1) => channel_2 x 32 x 32
fc_w = random_weight ((channel_2 * 32 * 32, 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 = 3.4746  
Checking accuracy on the val set  
Got 128 / 1000 correct (12.80%)

Iteration 100, loss = 2.1287  
Checking accuracy on the val set  
Got 357 / 1000 correct (35.70%)

Iteration 200, loss = 1.7476  
Checking accuracy on the val set  
Got 419 / 1000 correct (41.90%)

Iteration 300, loss = 1.4640  
Checking accuracy on the val set  
Got 410 / 1000 correct (41.00%)

Iteration 400, loss = 1.5675  
Checking accuracy on the val set  
Got 457 / 1000 correct (45.70%)

Iteration 500, loss = 1.6361  
Checking accuracy on the val set  
Got 458 / 1000 correct (45.80%)

Iteration 600, loss = 1.4654  
Checking accuracy on the val set  
Got 470 / 1000 correct (47.00%)

Iteration 700, loss = 1.6182  
Checking accuracy on the val set  
Got 478 / 1000 correct (47.80%)

## 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 \(http://pytorch.org/docs/master/optim.html\)](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 \(http://pytorch.org/docs/master/nn.html\)](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 [31]: 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 [34]: class ThreeLayerConvNet(nn.Module):
    def __init__(self, in_channel, channel_1, channel_2, num_classes):
        super().__init__()
        #####
        # TODO: 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)
        nn.init.kaiming_normal_(self.conv1.weight)
        self.conv2 = nn.Conv2d (channel_1, channel_2, (3,3), padding=1)
        nn.init.kaiming_normal_(self.conv2.weight)
        self.fc = nn.Linear (channel_2*32*32, num_classes)
        #####
        #
        #                                     END OF YOUR CODE
        #
        #####
        def forward(self, x):
            scores = None
            #####
            # TODO: 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()
            #
            #####
            z1 = F.relu(self.conv1(x))
            z2 = F.relu(self.conv2(z1))
            scores = self.fc(flatten(z2))
            #####
            #
            #                                     END OF YOUR CODE
            #
            #####
            return scores

def test_ThreeLayerConvNet():
    x = torch.zeros((64, 3, 32, 32), dtype=dtype) # minibatch size 64,
    image size [3, 32, 32]
    model = ThreeLayerConvNet(in_channel=3, channel_1=12, channel_2=8, num_classes=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 [35]: 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 * acc))
```

## 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 [36]: 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 for

        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
optimizer
                # will update.
                optimizer.zero_grad()

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

                # Actually update the parameters of the model using the grad
ients
                # 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 [37]: 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 = 3.7192
Checking accuracy on validation set
Got 138 / 1000 correct (13.80)
```

```
Iteration 100, loss = 2.3288
Checking accuracy on validation set
Got 333 / 1000 correct (33.30)
```

```
Iteration 200, loss = 1.7268
Checking accuracy on validation set
Got 357 / 1000 correct (35.70)
```

```
Iteration 300, loss = 2.5014
Checking accuracy on validation set
Got 399 / 1000 correct (39.90)
```

```
Iteration 400, loss = 1.9137
Checking accuracy on validation set
Got 442 / 1000 correct (44.20)
```

```
Iteration 500, loss = 1.9807
Checking accuracy on validation set
Got 408 / 1000 correct (40.80)
```

```
Iteration 600, loss = 1.7959
Checking accuracy on validation set
Got 434 / 1000 correct (43.40)
```

```
Iteration 700, loss = 1.8260
Checking accuracy on validation set
Got 441 / 1000 correct (44.10)
```

## **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 45% after training for one epoch.

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

```

In [38]: learning_rate = 3e-3
channel_1 = 32
channel_2 = 16

model = None
optimizer = None
#####
#####
# TODO: Instantiate your ThreeLayerConvNet model and a corresponding opt
imizer #
#####
#####
model = ThreeLayerConvNet(in_channel=3, channel_1=20, channel_2=20, num_
classes=10)
optimizer = optim.Adam(model.parameters(), lr=1e-3)
#####
#####
#
#                                     END OF YOUR CODE
#####
#####

train_part34(model, optimizer)

```

```

Iteration 0, loss = 2.3925
Checking accuracy on validation set
Got 129 / 1000 correct (12.90)

```

```

Iteration 100, loss = 1.6374
Checking accuracy on validation set
Got 430 / 1000 correct (43.00)

```

```

Iteration 200, loss = 1.6120
Checking accuracy on validation set
Got 487 / 1000 correct (48.70)

```

```

Iteration 300, loss = 1.2784
Checking accuracy on validation set
Got 514 / 1000 correct (51.40)

```

```

Iteration 400, loss = 1.4642
Checking accuracy on validation set
Got 542 / 1000 correct (54.20)

```

```

Iteration 500, loss = 1.3801
Checking accuracy on validation set
Got 547 / 1000 correct (54.70)

```

```

Iteration 600, loss = 1.1941
Checking accuracy on validation set
Got 570 / 1000 correct (57.00)

```

```

Iteration 700, loss = 1.2486
Checking accuracy on validation set
Got 597 / 1000 correct (59.70)

```

## 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 should achieve above 40% accuracy after one epoch of training.

```

In [39]: # 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 = 2.3838
Checking accuracy on validation set
Got 182 / 1000 correct (18.20)

```

```

Iteration 100, loss = 1.7808
Checking accuracy on validation set
Got 391 / 1000 correct (39.10)

```

```

Iteration 200, loss = 1.7499
Checking accuracy on validation set
Got 367 / 1000 correct (36.70)

```

```

Iteration 300, loss = 1.9528
Checking accuracy on validation set
Got 404 / 1000 correct (40.40)

```

```

Iteration 400, loss = 1.8237
Checking accuracy on validation set
Got 415 / 1000 correct (41.50)

```

```

Iteration 500, loss = 1.5825
Checking accuracy on validation set
Got 441 / 1000 correct (44.10)

```

```

Iteration 600, loss = 1.6609
Checking accuracy on validation set
Got 436 / 1000 correct (43.60)

```

```

Iteration 700, loss = 1.7796
Checking accuracy on validation set
Got 432 / 1000 correct (43.20)

```

## 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 [44]: channel_1 = 32
channel_2 = 16
learning_rate = 1e-2

model = None
optimizer = None

#####
#####
# TODO: Rewrite the 2-layer ConvNet with bias from Part III with the
#
# Sequential API.
#
#####
#####
model = nn.Sequential(
    nn.Conv2d(3, 20, (5,5),padding=2),
    nn.ReLU(),
    nn.Conv2d(20, 20, (3,3),padding=1),
    nn.ReLU(),
    Flatten(),
    nn.Linear(20*32*32, 10),
)

optimizer = optim.Adam(model.parameters(), lr=1e-3)
#####
#####
#
#                               END OF YOUR CODE
#####
#####

train_part34(model, optimizer)

```

Iteration 0, loss = 2.3349  
Checking accuracy on validation set  
Got 129 / 1000 correct (12.90)

Iteration 100, loss = 1.9342  
Checking accuracy on validation set  
Got 473 / 1000 correct (47.30)

Iteration 200, loss = 1.5828  
Checking accuracy on validation set  
Got 487 / 1000 correct (48.70)

Iteration 300, loss = 1.4545  
Checking accuracy on validation set  
Got 532 / 1000 correct (53.20)

Iteration 400, loss = 1.2852  
Checking accuracy on validation set  
Got 556 / 1000 correct (55.60)

Iteration 500, loss = 1.5161  
Checking accuracy on validation set  
Got 554 / 1000 correct (55.40)

Iteration 600, loss = 1.0615  
Checking accuracy on validation set  
Got 566 / 1000 correct (56.60)

Iteration 700, loss = 1.3529  
Checking accuracy on validation set  
Got 586 / 1000 correct (58.60)



# 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/docs/stable/nn.html> (<http://pytorch.org/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:

- **Filter size:** Above we used 5x5; would smaller filters be more efficient?
- **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 \(https://arxiv.org/abs/1512.00567\)](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 \(https://arxiv.org/abs/1512.03385\)](https://arxiv.org/abs/1512.03385) where the input from the previous layer is added to the output.
  - [DenseNets \(https://arxiv.org/abs/1608.06993\)](https://arxiv.org/abs/1608.06993) where inputs into previous layers are concatenated together.
  - [This blog has an in-depth overview \(https://chatbotlife.com/resnets-highwaynets-and-densenets-oh-my-9bb15918ee32\)](https://chatbotlife.com/resnets-highwaynets-and-densenets-oh-my-9bb15918ee32).

```

In [60]: #####
#####
# TODO:
#
# Experiment with any architectures, optimizers, and hyperparameters.
#
# Achieve AT LEAST 70% accuracy on the *validation set* within 10 epoch
s.      #
#
#
# Note that you can use the check_accuracy function to evaluate on eithe
r      #
# 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 to
uch    #
# the test set until you have finished your architecture and hyperparam
eter   #
# tuning, and only run the test set once at the end to report a final va
lue.   #
#####
#####
model = None
optimizer = None

model = nn.Sequential(
    nn.Conv2d(3, 20, (5,5),padding=2),
    nn.BatchNorm2d(20),
    nn.ReLU(),
    nn.MaxPool2d((2,2)), # 32x32 => 16x16
    nn.Conv2d(20, 50, (5,5),padding=2),
    nn.BatchNorm2d(50),
    nn.ReLU(),
    nn.MaxPool2d((2,2)), # 16x16 => 8x8
    nn.Conv2d(50, 50, (3,3),padding=1),
    nn.BatchNorm2d(50),
    nn.ReLU(),
    Flatten(),
    nn.Linear(50*8*8, 1024),
    nn.Linear(1024,10)
)

optimizer = optim.Adam(model.parameters(), lr=1e-3)
#####
#####
#
#                                     END OF YOUR CODE
#####
#####

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

```

Iteration 0, loss = 2.3497  
Checking accuracy on validation set  
Got 109 / 1000 correct (10.90)

Iteration 100, loss = 1.6936  
Checking accuracy on validation set  
Got 454 / 1000 correct (45.40)

Iteration 200, loss = 1.4230  
Checking accuracy on validation set  
Got 514 / 1000 correct (51.40)

Iteration 300, loss = 1.1730  
Checking accuracy on validation set  
Got 554 / 1000 correct (55.40)

Iteration 400, loss = 1.1308  
Checking accuracy on validation set  
Got 557 / 1000 correct (55.70)

Iteration 500, loss = 1.3258  
Checking accuracy on validation set  
Got 570 / 1000 correct (57.00)

Iteration 600, loss = 1.4640  
Checking accuracy on validation set  
Got 574 / 1000 correct (57.40)

Iteration 700, loss = 1.0723  
Checking accuracy on validation set  
Got 602 / 1000 correct (60.20)

Iteration 0, loss = 0.9848  
Checking accuracy on validation set  
Got 614 / 1000 correct (61.40)

Iteration 100, loss = 1.1298  
Checking accuracy on validation set  
Got 578 / 1000 correct (57.80)

Iteration 200, loss = 1.0836  
Checking accuracy on validation set  
Got 617 / 1000 correct (61.70)

Iteration 300, loss = 0.8377  
Checking accuracy on validation set  
Got 628 / 1000 correct (62.80)

Iteration 400, loss = 0.9715  
Checking accuracy on validation set  
Got 640 / 1000 correct (64.00)

Iteration 500, loss = 0.9843  
Checking accuracy on validation set  
Got 656 / 1000 correct (65.60)

Iteration 600, loss = 0.9773

Checking accuracy on validation set  
Got 622 / 1000 correct (62.20)

Iteration 700, loss = 0.6761  
Checking accuracy on validation set  
Got 629 / 1000 correct (62.90)

Iteration 0, loss = 0.8370  
Checking accuracy on validation set  
Got 636 / 1000 correct (63.60)

Iteration 100, loss = 0.9479  
Checking accuracy on validation set  
Got 671 / 1000 correct (67.10)

Iteration 200, loss = 0.8476  
Checking accuracy on validation set  
Got 675 / 1000 correct (67.50)

Iteration 300, loss = 0.8792  
Checking accuracy on validation set  
Got 681 / 1000 correct (68.10)

Iteration 400, loss = 1.0242  
Checking accuracy on validation set  
Got 692 / 1000 correct (69.20)

Iteration 500, loss = 0.9149  
Checking accuracy on validation set  
Got 696 / 1000 correct (69.60)

Iteration 600, loss = 0.8583  
Checking accuracy on validation set  
Got 693 / 1000 correct (69.30)

Iteration 700, loss = 0.6781  
Checking accuracy on validation set  
Got 693 / 1000 correct (69.30)

Iteration 0, loss = 0.6042  
Checking accuracy on validation set  
Got 698 / 1000 correct (69.80)

Iteration 100, loss = 0.6293  
Checking accuracy on validation set  
Got 703 / 1000 correct (70.30)

Iteration 200, loss = 0.7063  
Checking accuracy on validation set  
Got 701 / 1000 correct (70.10)

Iteration 300, loss = 0.7640  
Checking accuracy on validation set  
Got 687 / 1000 correct (68.70)

Iteration 400, loss = 0.6097  
Checking accuracy on validation set

Got 695 / 1000 correct (69.50)

Iteration 500, loss = 0.6942  
Checking accuracy on validation set  
Got 712 / 1000 correct (71.20)

Iteration 600, loss = 0.5115  
Checking accuracy on validation set  
Got 699 / 1000 correct (69.90)

Iteration 700, loss = 0.5922  
Checking accuracy on validation set  
Got 694 / 1000 correct (69.40)

Iteration 0, loss = 0.5485  
Checking accuracy on validation set  
Got 714 / 1000 correct (71.40)

Iteration 100, loss = 0.4997  
Checking accuracy on validation set  
Got 702 / 1000 correct (70.20)

Iteration 200, loss = 0.5262  
Checking accuracy on validation set  
Got 736 / 1000 correct (73.60)

Iteration 300, loss = 0.5172  
Checking accuracy on validation set  
Got 712 / 1000 correct (71.20)

Iteration 400, loss = 0.6746  
Checking accuracy on validation set  
Got 744 / 1000 correct (74.40)

Iteration 500, loss = 0.5279  
Checking accuracy on validation set  
Got 724 / 1000 correct (72.40)

Iteration 600, loss = 0.5852  
Checking accuracy on validation set  
Got 739 / 1000 correct (73.90)

Iteration 700, loss = 0.6247  
Checking accuracy on validation set  
Got 741 / 1000 correct (74.10)

Iteration 0, loss = 0.7368  
Checking accuracy on validation set  
Got 732 / 1000 correct (73.20)

Iteration 100, loss = 0.4470  
Checking accuracy on validation set  
Got 735 / 1000 correct (73.50)

Iteration 200, loss = 0.6347  
Checking accuracy on validation set  
Got 759 / 1000 correct (75.90)

Iteration 300, loss = 0.8925  
Checking accuracy on validation set  
Got 724 / 1000 correct (72.40)

Iteration 400, loss = 0.7596  
Checking accuracy on validation set  
Got 731 / 1000 correct (73.10)

Iteration 500, loss = 0.5915  
Checking accuracy on validation set  
Got 733 / 1000 correct (73.30)

Iteration 600, loss = 0.4848  
Checking accuracy on validation set  
Got 710 / 1000 correct (71.00)

Iteration 700, loss = 0.5966  
Checking accuracy on validation set  
Got 712 / 1000 correct (71.20)

Iteration 0, loss = 0.4044  
Checking accuracy on validation set  
Got 755 / 1000 correct (75.50)

Iteration 100, loss = 0.5634  
Checking accuracy on validation set  
Got 729 / 1000 correct (72.90)

Iteration 200, loss = 0.6137  
Checking accuracy on validation set  
Got 759 / 1000 correct (75.90)

Iteration 300, loss = 0.4423  
Checking accuracy on validation set  
Got 759 / 1000 correct (75.90)

Iteration 400, loss = 0.4145  
Checking accuracy on validation set  
Got 721 / 1000 correct (72.10)

Iteration 500, loss = 0.4775  
Checking accuracy on validation set  
Got 751 / 1000 correct (75.10)

Iteration 600, loss = 0.4411  
Checking accuracy on validation set  
Got 748 / 1000 correct (74.80)

Iteration 700, loss = 0.4563  
Checking accuracy on validation set  
Got 731 / 1000 correct (73.10)

Iteration 0, loss = 0.2930  
Checking accuracy on validation set  
Got 766 / 1000 correct (76.60)

Iteration 100, loss = 0.5990  
Checking accuracy on validation set  
Got 729 / 1000 correct (72.90)

Iteration 200, loss = 0.4143  
Checking accuracy on validation set  
Got 718 / 1000 correct (71.80)

Iteration 300, loss = 0.2678  
Checking accuracy on validation set  
Got 754 / 1000 correct (75.40)

Iteration 400, loss = 0.4067  
Checking accuracy on validation set  
Got 723 / 1000 correct (72.30)

Iteration 500, loss = 0.4766  
Checking accuracy on validation set  
Got 736 / 1000 correct (73.60)

Iteration 600, loss = 0.5136  
Checking accuracy on validation set  
Got 750 / 1000 correct (75.00)

Iteration 700, loss = 0.3405  
Checking accuracy on validation set  
Got 754 / 1000 correct (75.40)

Iteration 0, loss = 0.3297  
Checking accuracy on validation set  
Got 751 / 1000 correct (75.10)

Iteration 100, loss = 0.5637  
Checking accuracy on validation set  
Got 753 / 1000 correct (75.30)

Iteration 200, loss = 0.3968  
Checking accuracy on validation set  
Got 754 / 1000 correct (75.40)

Iteration 300, loss = 0.2474  
Checking accuracy on validation set  
Got 747 / 1000 correct (74.70)

Iteration 400, loss = 0.5851  
Checking accuracy on validation set  
Got 760 / 1000 correct (76.00)

Iteration 500, loss = 0.6267  
Checking accuracy on validation set  
Got 750 / 1000 correct (75.00)

Iteration 600, loss = 0.5335  
Checking accuracy on validation set  
Got 758 / 1000 correct (75.80)

Iteration 700, loss = 0.4673



```
Checking accuracy on validation set  
Got 754 / 1000 correct (75.40)
```

```
Iteration 0, loss = 0.2662  
Checking accuracy on validation set  
Got 754 / 1000 correct (75.40)
```

```
Iteration 100, loss = 0.5627  
Checking accuracy on validation set  
Got 743 / 1000 correct (74.30)
```

```
Iteration 200, loss = 0.5520  
Checking accuracy on validation set  
Got 753 / 1000 correct (75.30)
```

```
Iteration 300, loss = 0.3652  
Checking accuracy on validation set  
Got 757 / 1000 correct (75.70)
```

```
Iteration 400, loss = 0.3019  
Checking accuracy on validation set  
Got 771 / 1000 correct (77.10)
```

```
Iteration 500, loss = 0.2220  
Checking accuracy on validation set  
Got 730 / 1000 correct (73.00)
```

```
Iteration 600, loss = 0.4130  
Checking accuracy on validation set  
Got 756 / 1000 correct (75.60)
```

```
Iteration 700, loss = 0.3751  
Checking accuracy on validation set  
Got 738 / 1000 correct (73.80)
```

## 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.

Answer:

I started with a basic conv-batchnorm-relu-pool set followed by a fully connected layer. I was able to get close to 65% accuracy with it. I then incrementally added another conv-batchnorm-relu-pool set and then another fully connected layer after which the model was able to get above 75% accuracy on the validation set.

## 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 [61]: best_model = model  
         check_accuracy_part34(loader_test, best_model)
```

```
Checking accuracy on test set  
Got 7340 / 10000 correct (73.40)
```

```
In [ ]:
```