

## EE-559 – Deep learning

### 4b. PyTorch modules, batch processing

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`torch.nn`

PyTorch provides a vast collection of functions and “modules” which can be combined into complicated architectures. We will look at what is needed to build our first convolutional neural network:

- `torch.nn.functional.relu`
- `torch.nn.functional.max_pool2d`
- `torch.nn.Conv2d`
- `torch.nn.Linear`
- `torch.nn.MSELoss`

Elements from `torch.nn.functional` are autograd-compliant functions which compute a result from provided arguments alone. This is usually imported as `F`.

Subclasses of `torch.nn.Module` are losses and network components. The latter embed `torch.nn.Parameter`s to be optimized during training.



Since they are almost exclusively used with autograd, elements from `torch.nn` only process `Variable`s.

The term “tensor” is used for both `Tensor`s and `Variable`s in what follows.



Functions and modules from `torch.nn` process only batches of inputs stored in a tensor with an additional first dimension to index them, and produce a corresponding tensor with an additional dimension.

*E.g.* a fully connected layer  $\mathbb{R}^C \rightarrow \mathbb{R}^D$  expects as input a tensor of size  $N \times C$  and compute a tensor of size  $N \times D$ , where  $N$  is the number of samples.

```
torch.nn.functional.relu(input, inplace=False)
```

Takes a tensor of any size as input, applies ReLU on each value to produce a result tensor of same size.

```
>>> x = Variable(Tensor(2, 5).normal_())
>>> x
Variable containing:
-0.2066 -1.7997 -0.0653  0.6481  0.0253
 1.0239  3.0324  1.6431 -1.8925  0.0890
[torch.FloatTensor of size 2x5]

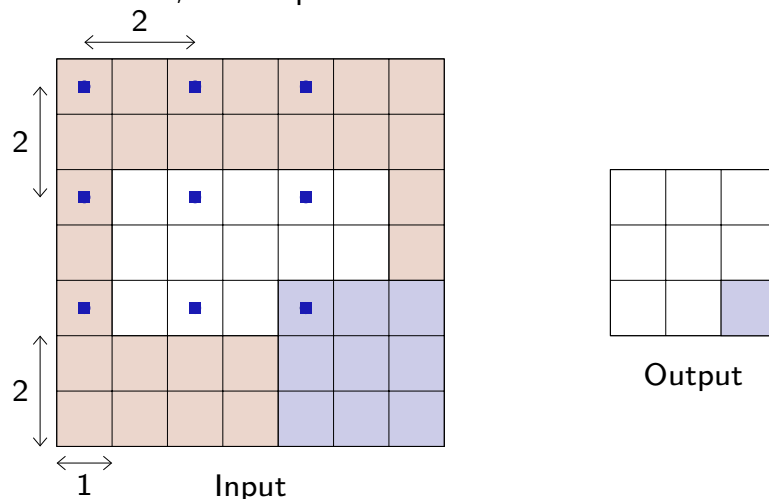
>>> torch.nn.functional.relu(x)
Variable containing:
 0.0000  0.0000  0.0000  0.6481  0.0253
 1.0239  3.0324  1.6431  0.0000  0.0890
[torch.FloatTensor of size 2x5]
```

`inplace` indicates if the operation should modify the argument itself. This may be desirable to reduce the memory footprint of the processing.

For what follows, note that pooling and convolution have two additional standard parameters:

- The **padding** specifies the size of a zeroed frame added around the input,
- the **stride** specifies a step size when moving the filter across the signal.

Here with  $C \times 3 \times 5$  as input, a padding of (2, 1), a stride of (2, 2), and a kernel of size  $C \times 3 \times 3$ , the output is  $1 \times 3 \times 3$ .



Pooling operations have a default stride equal to their kernel size, and convolutions have a default stride of 1. Padding is zero by default, and is useful for instance to generate an output of same size as the input.

```
torch.nn.functional.max_pool2d(input, kernel_size,
                                stride=None, padding=0, dilation=1,
                                ceil_mode=False, return_indices=False)
```

Takes as input a  $N \times C \times H \times W$  tensor, and a kernel size  $(h, w)$  or  $k$  interpreted as  $(k, k)$ , applies the max-pooling on each channel of each sample separately, and produce if the padding is 0 a  $N \times C \times \lfloor H/h \rfloor \times \lfloor W/w \rfloor$  output.

```
>>> x = Variable(Tensor(1, 2, 3, 6).random_(3))
>>> x
Variable containing:
(0 ,0 ,...) =
  1  2  0  1  1  0
  2  2  1  2  2  2
  0  2  0  1  1  0

(0 ,1 ,...) =
  1  0  0  2  0  2
  0  0  0  1  0  2
  1  1  1  1  1  0
[torch.FloatTensor of size 1x2x3x6]

>>> torch.nn.functional.max_pool2d(x, (1, 2))
Variable containing:
(0 ,0 ,...) =
  2  1  1
  2  2  2
  2  1  1

(0 ,1 ,...) =
  1  2  2
  0  1  2
  1  1  1
[torch.FloatTensor of size 1x2x3x3]
```

```
class torch.nn.Linear(in_features, out_features, bias=True)
```

Implements a  $\mathbb{R}^C \rightarrow \mathbb{R}^D$  fully-connected layer. It takes as input a tensor of size  $N \times C$  and produce a tensor of size  $N \times D$ .

```
>>> f = torch.nn.Linear(in_features = 10, out_features = 4)
>>> f.weight.size()
torch.Size([4, 10])
>>> f.bias.size()
torch.Size([4])
>>> x = Variable(Tensor(523, 10).normal_())
>>> y = f(x)
>>> y.size()
torch.Size([523, 4])
```



The weights and biases are automatically randomized at creation. We will come back to that later.

```
torch.nn.Conv2d(in_channels, out_channels,
                 kernel_size,
                 stride=1, padding=0, dilation=1, groups=1, bias=True)
```

Implements a standard 2d convolutional layer. The kernel size is either a pair  $(h, w)$  or a single value  $k$  interpreted as  $(k, k)$ .

It takes as input a  $N \times C \times H \times W$  tensor and returns a tensor  $N \times D \times (H - h + 1) \times (W - w + 1)$

```
>>> l = torch.nn.Conv2d(in_channels = 4, out_channels = 5, kernel_size = (2, 3))
>>> l.weight.size()
torch.Size([5, 4, 2, 3])
>>> l.bias.size()
torch.Size([5])
>>> x = Variable(Tensor(117, 4, 10, 3).normal_())
>>> y = l(x)
>>> y.size()
torch.Size([117, 5, 9, 1])
```

As for the fully connected layer, weights and biases are randomized.

```

mnist_train = datasets.MNIST('./data/mnist/', train = True, download = True)

# Take the 13th example, shape it as a batch of a single one-channel image
x = mnist_train.train_data[12].float().view(1, 1, 28, 28)

f = torch.nn.Conv2d(1, 5, kernel_size=3)

f.bias.data.zero_()

f.weight.data[0] = Tensor([ [ 0, 0, 0 ],
                             [ 0, 1, 0 ],
                             [ 0, 0, 0 ] ])

f.weight.data[1] = Tensor([ [ 1, 1, 1 ],
                             [ 1, 1, 1 ],
                             [ 1, 1, 1 ] ])

f.weight.data[2] = Tensor([ [ -1, 0, 1 ],
                             [ -1, 0, 1 ],
                             [ -1, 0, 1 ] ])

f.weight.data[3] = Tensor([ [ -1, -1, -1 ],
                             [ 0, 0, 0 ],
                             [ 1, 1, 1 ] ])

f.weight.data[4] = Tensor([ [ 0, -1, 0 ],
                             [ -1, 4, -1 ],
                             [ 0, -1, 0 ] ])

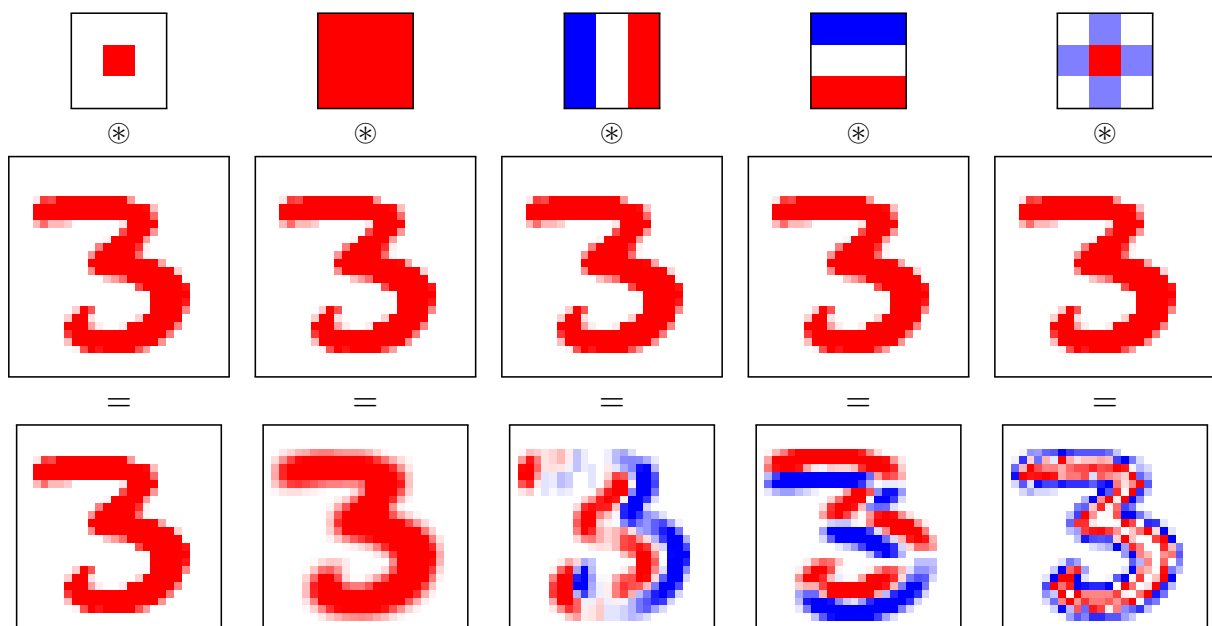
y = f(Variable(x)).data

save_2d_tensor_as_image(f.weight.data[0], 'conv-filters-{:d}.png',
                        signed = True)

save_2d_tensor_as_image(x[0], 'conv-mnist-orig.png', signed = True)

save_2d_tensor_as_image(y[0], 'conv-mnist-results-{:d}.png',
                        signed = True)

```



```
torch.nn.MSELoss()
```

Implements the Mean Square Error loss: the sum of the component-wise squared difference, **divided by the total number of components in the tensors**.

```
>>> f = torch.nn.MSELoss()
>>> x = Variable(Tensor([[ 3 ]]))
>>> y = Variable(Tensor([[ 0 ]]))
>>> f(x, y)
Variable containing:
  9
[torch.FloatTensor of size 1]

>>> x = Variable(Tensor([[ 3, 0, 0, 0 ]]))
>>> y = Variable(Tensor([[ 0, 0, 0, 0 ]]))
>>> f(x, y)
Variable containing:
  2.2500
[torch.FloatTensor of size 1]
```

The first parameter of a loss is traditionally called the **input** and the second the **target**. These two quantities may be of different dimensions or even types for some losses (e.g. for classification).

Remember that **Module**s' inputs and outputs are **Variable**s. **Data Tensor**s should be wrapped before forwarding them into a **Module**.

```
>>> import torchvision
>>> mnist = torchvision.datasets.MNIST('./data/mnist/')
>>> x = mnist.train_data.float()
>>> x = x.view(x.size(0), -1)
>>> l = nn.Linear(x.size(1), 10)
>>> y = l(x)
/.../
RuntimeError: addmm(): argument 'mat1' (position 1) must be Variable, not torch.
FloatTensor
>>> x = torch.autograd.Variable(x)
>>> y = l(x)
```

Conversely, results are also `Variables`, so to retrieve a loss as an actual standard python float, one has to do

```
>>> f = torch.nn.L1Loss()
>>> u = f(Variable(Tensor([1, 2, 3])), Variable(Tensor([1, 2, 9])))
>>> u
Variable containing:
  2
[torch.FloatTensor of size 1]

>>> u.data[0]
2.0
```



Criteria do not compute the gradient with respect to the target, and will not accept a `Variable` with `requires_grad` to `True` as the target.

```
>>> f = torch.nn.MSELoss()
>>> x = Variable(Tensor([ 3, 2 ]), requires_grad = True)
>>> y = Variable(Tensor([ 0, -2 ]), requires_grad = True)
>>> f(x, y)
/.../
AssertionError: nn criterions don't compute the gradient w.r.t. targets - please mark
these variables as volatile or not requiring gradients
```



We can use the MSE loss for training, even though this is classification.

To do so, given a training set

$$(x_n, y_n) \in \mathbb{R}^D \times \{1, \dots, C\}, \quad n = 1, \dots, N,$$

we will consider an output with as many units as there are classes, and the target will be a tensor  $z \in \mathbb{R}^{N \times C}$ , with  $-1$  everywhere but for the correct labels:

$$\forall n, z_{n,m} = \begin{cases} 1 & \text{if } m = y_n \\ -1 & \text{otherwise.} \end{cases}$$

For instance, with  $N = 5$  and  $C = 3$ , we would have

$$\begin{pmatrix} 2 \\ 1 \\ 1 \\ 3 \\ 2 \end{pmatrix} \Rightarrow \begin{pmatrix} -1 & 1 & -1 \\ 1 & -1 & -1 \\ 1 & -1 & -1 \\ -1 & -1 & 1 \\ -1 & 1 & -1 \end{pmatrix}.$$

Although MSE is a regression loss, using it like this gives excellent results.

Both the convolutional and pooling layers take as input batches of samples, each one being itself a 3d tensor  $C \times H \times W$ .

The output has the same structure, and tensors have to be explicitly reshaped before being forwarded to a fully connected layer.

```
>>> mnist = datasets.MNIST('./data/mnist/', train = True, download = True)
>>> d = mnist.train_data
>>> d.size()
torch.Size([60000, 28, 28])
>>> x = d.view(d.size(0), 1, d.size(1), d.size(2))
>>> x.size()
torch.Size([60000, 1, 28, 28])
>>> x = x.view(x.size(0), -1)
>>> x.size()
torch.Size([60000, 784])
```

We can now put all this together and define our first convolutional network for MNIST, with two convolutional layers, and two fully-connected layers:

Input sizes / operations	Nb. parameters	Nb. products
$1 \times 28 \times 28$		
<code>nn.Conv2d(1, 32, kernel_size=5)</code>	$32 \times (5^2 + 1) = 832$	$32 \times 24^2 \times 5^2 = 460,800$
$32 \times 24 \times 24$		
<code>F.max_pool2d(x, kernel_size=3)</code>	0	0
$32 \times 8 \times 8$		
<code>F.relu</code>	0	0
$32 \times 8 \times 8$		
<code>nn.Conv2d(32, 64, kernel_size=5)</code>	$64 \times (32 \times 5^2 + 1) = 51,264$	$32 \times 64 \times 4^2 \times 5^2 = 819,200$
$64 \times 4 \times 4$		
<code>F.max_pool2d(x, kernel_size=2)</code>	0	0
$64 \times 2 \times 2$		
<code>F.relu</code>	0	0
$64 \times 2 \times 2$		
<code>x.view(-1, 256)</code>	0	0
256		
<code>nn.Linear(256, 200)</code>	$200 \times (256 + 1) = 51,400$	$200 \times 256 = 51,200$
200		
<code>F.relu</code>	0	0
200		
<code>nn.Linear(200, 10)</code>	$10 \times (200 + 1) = 2,010$	$10 \times 200 = 2,000$
10		

Total 105,506 parameters and 1,333,200 products for the forward pass.

## Creating a module

To create a `Module`, one has to inherit from the base class and implement the constructor `__init__(self, ...)` and the forward pass `forward(self, x)`.

```
class Net(nn.Module):
    def __init__(self):
        super(Net, self).__init__()
        self.conv1 = nn.Conv2d(1, 32, kernel_size=5)
        self.conv2 = nn.Conv2d(32, 64, kernel_size=5)
        self.fc1 = nn.Linear(256, 200)
        self.fc2 = nn.Linear(200, 10)

    def forward(self, x):
        x = F.relu(F.max_pool2d(self.conv1(x), kernel_size=3, stride=3))
        x = F.relu(F.max_pool2d(self.conv2(x), kernel_size=2, stride=2))
        x = x.view(-1, 256)
        x = F.relu(self.fc1(x))
        x = self.fc2(x)
        return x
```

As long as you use autograd-compliant operations, the backward pass is implemented automatically.

`Module`s added as attributes are seen by `Module.parameters()`, which returns an iterator over the model's parameters for optimization.

```
class Net(nn.Module):
    def __init__(self):
        super(Net, self).__init__()
        self.conv1 = nn.Conv2d(1, 32, kernel_size=5)
        self.conv2 = nn.Conv2d(32, 64, kernel_size=5)
        self.fc1 = nn.Linear(256, 200)
        self.fc2 = nn.Linear(200, 10)

model = Net()

for k in model.parameters():
    print(k.size())
```

prints

```
torch.Size([32, 1, 5, 5])
torch.Size([32])
torch.Size([64, 32, 5, 5])
torch.Size([64])
torch.Size([200, 256])
torch.Size([200])
torch.Size([10, 200])
torch.Size([10])
```

Parameter's added as attributes are also seen by `Module.parameters()`.



Parameters added in dictionaries or arrays are not seen.

```
class Buggy(nn.Module):
    def __init__(self):
        super(Buggy, self).__init__()
        self.conv = nn.Conv2d(1, 32, kernel_size=5)
        self.param = Parameter(Tensor(123, 456))
        self.ouch = {}
        self.ouch[0] = nn.Linear(543, 21)

model = Buggy()

for k in model.parameters():
    print(k.size())
```

prints

```
torch.Size([123, 456])
torch.Size([32, 1, 5, 5])
torch.Size([32])
```

The proper policy then is to use `Module.add_module(name, module)`

```
class NotBuggyAnymore(nn.Module):
    def __init__(self):
        super(NotBuggyAnymore, self).__init__()
        self.conv = nn.Conv2d(1, 32, kernel_size=5)
        self.param = Parameter(Tensor(123, 456))
        self.add_module('ahhh_0', nn.Linear(543, 21))

model = NotBuggyAnymore()

for k in model.parameters():
    print(k.size())
```

prints

```
torch.Size([123, 456])
torch.Size([32, 1, 5, 5])
torch.Size([32])
torch.Size([21, 543])
torch.Size([21])
```

These modules are added as attributes, and can be accessed with `getattr`.

`Module.register_parameter(name, parameter)` allows to similarly register Parameter's explicitly.

Another option is to add modules in a field of type `nn.ModuleList`, which is a list of modules properly dealt with by PyTorch's machinery.

```
class AnotherNotBuggy(nn.Module):
    def __init__(self):
        super(AnotherNotBuggy, self).__init__()
        self.conv = nn.Conv2d(1, 32, kernel_size=5)
        self.param = Parameter(Tensor(123, 456))
        self.other_stuff = nn.ModuleList()
        self.other_stuff.append(nn.Linear(50, 75))
        self.other_stuff.append(nn.Linear(125, 999))

model = AnotherNotBuggy()

for k in model.parameters():
    print(k.size())
```

prints

```
torch.Size([123, 456])
torch.Size([32, 1, 5, 5])
torch.Size([32])
torch.Size([75, 50])
torch.Size([75])
torch.Size([999, 125])
torch.Size([999])
```

## Batch processing

We saw that elements from `torch.nn` take as input a batch of samples, that is a tensor whose first index is the sample's index.

However we have formalized the fully connected layers and back-prop with column vectors e.g.

$$\forall l, n, w^{(l)} \in \mathbb{R}^{d_l \times d_{l-1}}, x_n^{(l-1)} \in \mathbb{R}^{d_{l-1}}, s_n^{(l)} = w^{(l)} x_n^{(l-1)}.$$

From now on, we will use row vectors, so that we can represent a series of samples as a 2d array with the first index being the sample's index.

$$x = \begin{pmatrix} x_{1,1} & \dots & x_{1,D} \\ \vdots & \ddots & \vdots \\ x_{N,1} & \dots & x_{N,D} \end{pmatrix} = \begin{pmatrix} (x_1)^T \\ \vdots \\ (x_N)^T \end{pmatrix},$$

which is an element of  $\mathbb{R}^{N \times D}$ .

To make all sample row vectors and apply a linear operator, we want

$$\forall n, s_n^{(l)} = \left( w^{(l)} \left( x_n^{(l-1)} \right)^T \right)^T = x_n^{(l-1)} \left( w^{(l)} \right)^T$$

which gives a tensorial expression for the full batch

$$s^{(l)} = x^{(l-1)} \left( w^{(l)} \right)^T.$$

And in `torch/nn/functional.py`

```
def linear(input, weight, bias=None):
    if input.dim() == 2 and bias is not None:
        # fused op is marginally faster
        return torch.addmm(bias, input, weight.t())

    output = input.matmul(weight.t())
    if bias is not None:
        output += bias
    return output
```

Similarly for the backward pass of a linear layer we get

$$\left[ \frac{\partial \mathcal{L}}{\partial \mathbf{w}^{(l)}} \right] = \left[ \frac{\partial \mathcal{L}}{\partial \mathbf{x}^{(l)}} \right]^T \mathbf{x}^{(l-1)},$$

and

$$\left[ \frac{\partial \mathcal{L}}{\partial \mathbf{x}^{(l)}} \right] = \left[ \frac{\partial \ell}{\partial \mathbf{x}^{(l+1)}} \right] \mathbf{w}^{(l+1)}.$$

Batch processing allows to use efficient matrix product implementations, which in particular deal properly with cache memory

```
import torch, time

def timing(x, w, nb = 51):
    t = torch.FloatTensor(nb)

    for u in range(t.size(0)):
        t0 = time.perf_counter()
        # Batch processing
        y = x.mm(w.t())
        y.is_cuda and torch.cuda.synchronize()
        t[u] = time.perf_counter() - t0
    tb = t.median()[0][0]

    for u in range(t.size(0)):
        t0 = time.perf_counter()
        # Ugly loop
        for k in range(y.size(0)): y[k] = w.mv(x[k])
        y.is_cuda and torch.cuda.synchronize()
        t[u] = time.perf_counter() - t0
    t1 = t.median()[0][0]

    print('{:s} batch vs. loop speed ratio {:.01f}'
          .format((y.is_cuda and 'GPU') or 'CPU', t1 / tb))

x = torch.FloatTensor(2500, 1000).normal_()
w = torch.FloatTensor(1500, 1000).normal_()
timing(x, w)

x = torch.cuda.FloatTensor(2500, 1000).normal_()
w = torch.cuda.FloatTensor(1500, 1000).normal_()
timing(x, w)
```

Prints:

```
CPU batch vs. loop speed ratio 10.0
GPU batch vs. loop speed ratio 80.7
```

Practical session:

<https://fleuret.org/dlc/dlc-practical-4.pdf>