COSE474-2024F: DEEP LEARNING HW2

2022320338 데이터과학과 신민서

Chp7. Convolutional Neural Network

7.1. From Fully Connected Layers to Convolutions

7.1.1 Discussion

- CNNs systemize the idea of spatial invariance, learning useful representations with fewer paramters

Overall design of the network:

- Translation invariance: network should respond similarly to the same patch, no matter where in the image
- Locality: earliest layers should focus on local regions -> aggregate to make predictions at the whole image level
- deeper layers should be able to capture longer-range features

7.1.2. Discussion

$$\begin{aligned}[\mathbf{H}]_{i,j} &= [\mathbf{U}]_{i,j} + \sum_k \sum_l [\mathbf{W}]_{i,j,k,l} [\mathbf{X}]_{k,l} \\ &= [\mathbf{U}]_{i,j} + \sum_a \sum_b [\mathbf{V}]_{i,j,a,b} [\mathbf{X}]_{i+a,j+b} .\end{aligned}$$

- Translation Invariance:

$$[\mathbf{H}]_{i,j} = u + \sum_a \sum_b [\mathbf{V}]_{a,b} [\mathbf{X}]_{i+a,j+b}$$

- Locality:

$$[\mathbf{H}]_{i,j} = u + \sum_{a=-\Delta}^{\Delta} \sum_{b=-\Delta}^{\Delta} [\mathbf{V}]_{a,b} [\mathbf{X}]_{i+a,j+b}$$

7.1.3. Discussion

$$(f * g)(i) = \sum_a f(a) g(i-a)$$

7.1.4. Discussion

- images are third-order tensors: H x W x channel (RGB):

$$[\mathbf{V}]_{a,b,c}$$

- To support multiple channels in both inputs (X) and hidden representations (H), add a fourth coordinate:

$$[\mathbf{V}]_{a,b,c,d}$$

- This makes:

$$[\mathbf{H}]_{i,j,d} = u + \sum_{a=-\Delta}^{\Delta} \sum_{b=-\Delta}^{\Delta} \sum_c [\mathbf{V}]_{a,b,c,d} [\mathbf{X}]_{i+a,j+b}$$

7.2. Convolutions for Images

```
!pip install d2l==1.0.3
```

```
Collecting d2l==1.0.3
  Downloading d2l-1.0.3-py3-none-any.whl.metadata (556 bytes)
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Downloading matplotlib_inline-0.1.6-py3-none-any.whl (9.4 kB)
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albumentations 1.4.15 requires numpy>=1.24.4, but you have numpy 1.23.5 which is incompatible.
bigframes 1.21.0 requires numpy>=1.24.0, but you have numpy 1.23.5 which is incompatible.
chex 0.1.87 requires numpy>=1.24.1, but you have numpy 1.23.5 which is incompatible.
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jax 0.4.33 requires numpy>=1.24, but you have numpy 1.23.5 which is incompatible.
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mizani 0.11.4 requires pandas>=2.1.0, but you have pandas 2.0.3 which is incompatible.
plotnine 0.13.6 requires pandas<3.0.0,>=2.1.0, but you have pandas 2.0.3 which is incompatible.
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WARNING: The following packages were previously imported in this runtime:
  [matplotlib,matplotlib_inline,mpl_toolkits,numpy]
You must restart the runtime in order to use newly installed versions.
```

RESTART SESSION

```python
import torch
from torch import nn
from d2l import torch as d2l
```

7.2.1. Cross-Correlation Operation

```python
def corr2d(X, K):
  # Compute 2D cross-correlaiton
  h, w = K.shape
  Y = torch.zeros( (X.shape[0] - h + 1, X.shape[1] - w + 1) )
  for i in range(Y.shape[0]):
    for j in range(Y.shape[1]):
      Y[i, j] = (X[i:i + h, j:j + w] * K).sum()
  return Y
```

```python
X = torch.tensor([[0.01, 1.0, 2.0], [3.0, 4.0, 5.0], [6.0, 7.0, 8.0]])
K = torch.tensor([[0.0, 1.0], [2.0, 3.0]])
corr2d(X, K)

```

```
tensor([[19., 25.],
        [37., 43.]])
```

7.2.2. Convolutional Layers

```python
class Conv2D(nn.Module):
  def __init__(self, kernel_size):
    super().__init__()
    self.weight = nn.Paramter(torch.rand(kernel_size))
    self.bias = nn.Parameter(torch.zeros(1))

  def forward(self,x):
    return corr2d(x, self.weight) + self.bias

```

7.2.3. Object Edge Detection

```python
X = torch.ones((6,8)) #image of 6x8 pixels
X[:, 2:6] = 0
X
```

```
tensor([[1., 1., 0., 0., 0., 0., 1., 1.],
        [1., 1., 0., 0., 0., 0., 1., 1.],
        [1., 1., 0., 0., 0., 0., 1., 1.],
        [1., 1., 0., 0., 0., 0., 1., 1.],
        [1., 1., 0., 0., 0., 0., 1., 1.],
        [1., 1., 0., 0., 0., 0., 1., 1.]])
```

```python
#contruct kernel K of 1x2
K = torch.tensor([[1.0, -1.0]])
```

```python
Y = corr2d(X,K)
Y
```

```
tensor([[ 0.,  1.,  0.,  0.,  0., -1.,  0.],
        [ 0.,  1.,  0.,  0.,  0., -1.,  0.],
        [ 0.,  1.,  0.,  0.,  0., -1.,  0.],
        [ 0.,  1.,  0.,  0.,  0., -1.,  0.],
        [ 0.,  1.,  0.,  0.,  0., -1.,  0.],
        [ 0.,  1.,  0.,  0.,  0., -1.,  0.]])
```

```python
corr2d(X.t(), K)
```

```
tensor([[0., 0., 0., 0., 0.],
        [0., 0., 0., 0., 0.],
        [0., 0., 0., 0., 0.],
        [0., 0., 0., 0., 0.],
        [0., 0., 0., 0., 0.],
        [0., 0., 0., 0., 0.],
        [0., 0., 0., 0., 0.],
        [0., 0., 0., 0., 0.]])
```

7.2.4. Learning a Kernel

```
conv2d = nn.LazyConv2d(1, kernel_size=(1,2), bias=False)

X = X.reshape((1,1,6,8))
Y = Y.reshape((1,1,6,7))

lr = 3e-2 #learning rate

for i in range(10):
  Y_hat = conv2d(X)
  l = (Y_hat - Y) ** 2
  conv2d.zero_grad()
  l.sum().backward()
  conv2d.weight.data[:] -= lr * conv2d.weight.grad
  if (i+1) % 2 == 0:
    print(f'epoch {i+1}, loss {l.sum():.3f}')
```

```
epoch 2, loss 7.683
epoch 4, loss 1.290
epoch 6, loss 0.217
epoch 8, loss 0.036
epoch 10, loss 0.006
```

```
conv2d.weight.data.reshape((1,2))
```

```
tensor([[ 0.9847, -0.9865]])
```

7.2.5. Discussion

- since kernels are learned from data in DL, the outputs of convolutional layers remain unaffected no matter such layers perform either the strict convolution operations or the cross-correlation operations
- When the convolutional layer performs strict convolution for an input, the same output will be ontained (cross-correlation of the input and K)
-

7.2.6 Discussion

- Feature map: convolutional layer output of features in spatial dimensions (WxH)
- Receptive field: elements from all the previous layers that may affect the calculation of x during the forward propagation

7.3. Padding and Stride

```
import torch
from torch import nn
```

7.3.1. Padding (discussion)

- Padding: adding extra pixels (usually zeros) around the edges of an input image
- Why? To prevent shrinking of the feature map
- If we add a total of Ph rows of padding and Pw columns of padding, the output shape will be:

$$(n_h - k_h + p_h + 1) * (n_w - k_w + p_w + 1)$$

- height and width increase by ph and pw
- usually use convolution kernels with odd height and width values

```
def comp_conv2d(conv2d, X):
  X = X.reshape((1,1) + X.shape)
  Y = conv2d(X)
  return Y.reshape(Y.shape[2:])

conv2d = nn.LazyConv2d(1, kernel_size=3, padding=1)
X = torch.rand(size=(8,8))
comp_conv2d(conv2d, X).shape
```

```
torch.Size([8, 8])
```

```
conv2d = nn.LazyConv2d(1, kernel_size=(5,3), padding=(2,1))
comp_conv2d(conv2d, X).shape
```

```
torch.Size([8, 8])
```

7.3.2. Stride (discussion)

- Stride: number of rows and columns traversed per slide
- generally, the output shape with Sh and Sw is:

$$\left\lfloor \frac{n_h - k_h + p_h + s_h}{s_h} \right\rfloor \times \left\lfloor \frac{n_w - k_w + p_w + s_w}{s_w} \right\rfloor$$

```
conv2d = nn.LazyConv2d(1, kernel_size=3, padding = 1, stride = 2)
comp_conv2d(conv2d, X).shape
```

```
torch.Size([4, 4])
```

```
conv2d = nn.LazyConv2d(1, kernel_size=(3,5), padding=(0,1), stride=(3,4))
comp_conv2d(conv2d, X).shape
```

```
torch.Size([2, 2])
```

7.3 Discussion

- **Padding**
- > increases height and width of the output
- > in order to avoid undesirable shrinkage of the output
- > ensures that all pizels are used equally frequently
- > usually use symmetric padding on both sides
- **Stride**
- > reduces the resolution of the output

7.4. Multiple Input and Multiple Output Channels

```
import torch
from d2l import torch as d2l
```

7.4.1. Multiple input channels (Discussion)

- If the number of channels for input data is c_i, then the number of input channels of the convolution kernel should also be If the number of channels for input data is c_i
- Given c_i > 1, the shape is: $c_i * k_h * k_w$
-

```
def corr2d_multi_in(X,K):
  return sum(d2l.corr2d(x, k) for x, k in zip(X,K))
```

```
X = torch.tensor([[[0.0,1.0,2.0],[3.0,4.0,5.0],[6.0,7.0,8.0]],[[1.0,2.0,3.0],[4.0,5.0,6.0],[7.0,8.0,9.0]]])
K = torch.tensor([[[0.0,1.0],[2.0,3.0]],[[1.0,2.0],[3.0,4.0]]])

corr2d_multi_in(X,K)
```

```
tensor([[ 56.,  72.],
        [104., 120.]])
```

7.4.2. Multiple Output Channels (Discussion)

- In deeper channel network, each channel responds to different set of features

- Channels are optimized to be jointly useful (some direction in channel space corresponds to detecting edges)
- Shape of multiple channel output: $c_o * c_i * k_h * k_w$

```
def corr2d_multi_in_out(X,K):
  return torch.stack([corr2d_multi_in(X,k) for k in K], 0)
```

```
K = torch.stack((K, K+1, K+2), 0)
K.shape
```

```
torch.Size([3, 2, 2, 2])
```

```
corr2d_multi_in_out(X,K)
```

```
tensor([[[ 56.,  72.],
         [104., 120.]],

        [[ 76., 100.],
         [148., 172.]],

        [[ 96., 128.],
         [192., 224.]]])
```

7.3.1. 1x1 Convolutional Layer (discussion)

- The only computation of the 1x1 convolution happens on the channel dimension
-

```
def corr2d_multi_in_out_1x1(X,K):
  c_i, h, w = X.shape
  c_o = K.shape[0]
  X = X.reshape((c_i, h*w))
  K = K.reshape((c_o, c_i))
  Y = torch.matmul(K,X)
  return Y.reshape((c_o, h, w))
```

```
X = torch.normal(0,1, (3,3,3))
K = torch.normal(0,1, (2,3,1,1))
Y1 = corr2d_multi_in_out_1x1(X,K)
Y2 = corr2d_multi_in_out(X,K)
assert float(torch.abs(Y1-Y2).sum()) < 1e-6
```

7.5. Pooling

7.5.1. Maximum & Average Pooling (Discussion)

- pooling: technique used to reduce spatial dimentions, which helps to decrease computation
- a fixed-shape window that is slid over all regions in the input according to its stride, computing a single output for each location traversed by the fixed-shape window
- but there is no kernel
- calculates either the max or avg. value of the elements in the pooling window

```
def pool2d(X, pool_size, mode='max'):
  p_h, p_w = pool_size
  Y = torch.zeros((X.shape[0] - p_h + 1, X.shape[1] - p_w + 1))
  for i in range (Y.shape[0]):
    for j in range (Y.shape[1]):
      if mode == 'max':
        Y[i,j] = X[i: i+p_h, j: j+p_w].max()
      elif mode == 'avg':
        Y[i,j] = X[i: i+p_h, j: j+p_w].mean()
  return Y
```

```
X = torch.tensor([[0.0, 1.0, 2.0], [3.0, 4.0, 5.0], [6.0, 7.0,8.0]])

pool2d(X, (2,2))
```

```
tensor([[4., 5.],
        [7., 8.]])
```

```
pool2d(X, (2,2), 'avg')
```

```
tensor([[2., 3.],
        [5., 6.]])
```

7.5.2. Padding and Stride (Discussion)

- We can demonstrate the use of padding and stride in pooling layers via built-in 2D max-pooling layer from DL framework

```
X = torch.arange(16, dtype = torch.float32).reshape((1,1,4,4))
X
```

```
tensor([[[[ 0.,  1.,  2.,  3.],
          [ 4.,  5.,  6.,  7.],
          [ 8.,  9., 10., 11.],
          [12., 13., 14., 15.]]]])
```

```
pool2d = nn.MaxPool2d(3)
pool2d(X)
```

```
tensor([[[[10.]]]])
```

```
pool2d = nn.MaxPool2d(3, padding=1, stride=2)
pool2d(X)
```

```
tensor([[[[ 5.,  7.],
          [13., 15.]]]])
```

```
pool2d = nn.MaxPool2d((2,3), stride=(2,3), padding=(0,1))
pool2d(X)
```

```
tensor([[[[ 5.,  7.],
          [13., 15.]]]])
```

7.5.3. Multiple Channels

```
X = torch.cat((X, X+1), 1)
X
```

```
tensor([[[[ 0.,  1.,  2.,  3.],
          [ 4.,  5.,  6.,  7.],
          [ 8.,  9., 10., 11.],
          [12., 13., 14., 15.]],

         [[ 1.,  2.,  3.,  4.],
          [ 5.,  6.,  7.,  8.],
          [ 9., 10., 11., 12.],
          [13., 14., 15., 16.]]]])
```

```
pool2d = nn.MaxPool2d(3, padding=1, stride=2)
pool2d(X)
```

```
tensor([[[[ 5.,  7.],
          [13., 15.]],

         [[ 6.,  8.],
          [14., 16.]]]])
```

7.6. Convolutional Neural Networks (LeNet)

```
import torch
from torch import nn
from d2l import torch as d2l
```

7.6.1. LeNet

- 2 parts in LeNet: (i) a convolutional encoder consisting of 2 convolutional layers (ii) a dense block consisting of 3 fully connected layers (120, 84, 10 outputs)

- To pass output from convolutional block to the dense block, each example int he minibatch should be flattened

```
def init_cnn(module):
  if type(module) == nn.Linear or type(module) == nn.Conv2d:
    nn.init.xavier_uniform_(module.weight)

class LeNet(d2l.Classifier):
  def __init__(self, lr=0.1, num_classes=10):
    super().__init__()
    self.save_hyperparameters()
    self.net = nn.Sequential(
        nn.LazyConv2d(6, kernel_size=5, padding=2), nn.Sigmoid(),
        nn.AvgPool2d(kernel_size=2, stride=2),
        nn.LazyConv2d(16, kernel_size=5), nn.Sigmoid(),
        nn.AvgPool2d(kernel_size=2, stride=2),
        nn.Flatten(),
        nn.LazyLinear(120), nn.Sigmoid(),
        nn.LazyLinear(84), nn.Sigmoid(),
        nn.LazyLinear(num_classes))

```

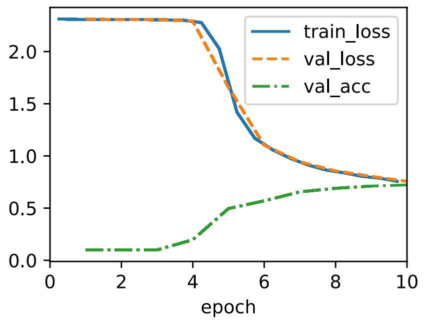
```
@d2l.add_to_class(d2l.Classifier)
def layer_summary(self, X_shape):
  X = torch.randn(*X_shape)
  for layer in self.net:
    X = layer(X)
    print(layer.__class__.__name__, 'output shape:\t', X.shape)

model = LeNet()
model.layer_summary((1,1,28,28))
```

```
Conv2d output shape:     torch.Size([1, 6, 28, 28])
Sigmoid output shape:    torch.Size([1, 6, 28, 28])
AvgPool2d output shape:  torch.Size([1, 6, 14, 14])
Conv2d output shape:     torch.Size([1, 16, 10, 10])
Sigmoid output shape:    torch.Size([1, 16, 10, 10])
AvgPool2d output shape:  torch.Size([1, 16, 5, 5])
Flatten output shape:    torch.Size([1, 400])
Linear output shape:     torch.Size([1, 120])
Sigmoid output shape:    torch.Size([1, 120])
Linear output shape:     torch.Size([1, 84])
Sigmoid output shape:    torch.Size([1, 84])
Linear output shape:     torch.Size([1, 10])
```

7.6.2. Training

```
trainer = d2l.Trainer(max_epochs = 10, num_gpus = 1)
data = d2l.FashionMNIST(batch_size=128)
model = LeNet(lr=0.1)
model.apply_init([next(iter(data.get_dataloader(True)))[0]], init_cnn)
trainer.fit(model, data)
```



Chp8. Modern Convolutional Neural Networks

8.2 Networks Using Blocks (VGG)

```
import torch
from torch import nn
```

```
from d2l import torch as d2l
```

8.2.1. VGG Blocks (Discussion)

- Problem of basic building block of CNNs is tat the spatial resolution decreases quite rapidly
- VGG block: consists of a sequence of convolutions with 3x2 kernels with padding of 1, and 2x2 max-pooling layer with stride of 2

```
def vgg_block(num_convs, out_channels):
  layers = []
  for _ in range(num_convs):
    layers.append(nn.LazyConv2d(out_channels, kernel_size=3, padding=1))
    layers.append(nn.ReLU())
  layers.append(nn.MaxPool2d(kernel_size=2, stride=2))
  return nn.Sequential(*layers)
```

8.2.2. VGG Network (Discussion)

- VGG Network is divided into 2 parts: (i) consists mostly of convolutional and pooling layers (ii) consists of fully connected layers
- We need to build a specific network we simply iterate over arch to compose the blocks

```
class VGG(d2l.Classifier):
  def __init__(self, arch, lr=0.1, num_classes=10):
    super().__init__()
    self.save_hyperparameters()
    conv_blks = []
    for (num_convs, out_channels) in arch:
      conv_blks.append(vgg_block(num_convs, out_channels))
    self.net = nn.Sequential(
        *conv_blks, nn.Flatten(),
        nn.LazyLinear(4096), nn.ReLU(), nn.Dropout(0.5),
        nn.LazyLinear(4096), nn.ReLU(), nn.Dropout(0.5),
        nn.LazyLinear(num_classes))
    self.net.apply(d2l.init_cnn)
```

```
VGG(arch=((1, 64), (1, 128), (2, 256), (2, 512), (2, 512))).layer_summary((1,1,224,224))
```

```
Sequential output shape:         torch.Size([1, 64, 112, 112])
Sequential output shape:         torch.Size([1, 128, 56, 56])
Sequential output shape:         torch.Size([1, 256, 28, 28])
Sequential output shape:         torch.Size([1, 512, 14, 14])
Sequential output shape:         torch.Size([1, 512, 7, 7])
Flatten output shape:    torch.Size([1, 25088])
Linear output shape:     torch.Size([1, 4096])
ReLU output shape:       torch.Size([1, 4096])
Dropout output shape:    torch.Size([1, 4096])
Linear output shape:     torch.Size([1, 4096])
ReLU output shape:       torch.Size([1, 4096])
Dropout output shape:    torch.Size([1, 4096])
Linear output shape:     torch.Size([1, 10])
```

8.2.3. Training

```
model = VGG(arch=((1,16), (1,32), (2, 64), (2, 128)), lr=0.01)
trainerr = d2l.Trainer(max_epochs=10, num_gpus=1)
data = d2l.FashionMNIST(batch_size=128, resize=(224,224))
model.apply_init([next(iter(data.get_dataloader(True)))[0]], d2l.init_cnn
trainer.fit(model, data)
```

8.6. Residual Networks and ResNeXt

8.6.1 Discussion

- Say, F is the class of functions that a specific network architecutre can reach
- Given a data set with features X and labels y, we can find f^*_F following optimization problem:

$$f^*_F \stackrel{\text{def}}{=} \arg\min_f L(\mathbf{X}, \mathbf{y}, f) \text{ subject to } f \in F$$

- Only if larger function classes contain the smaller ones -> guarantee that increasing them strictly increases the expressive power of the network

8.6.2 Discussion

- With residual blocks, inputs can forward propagate faster via residual connections across layers
- In the example, the residual block can be thought of as a special case of the multi-branch Inception block (2 branches one of which is the identity mapping)

```
import torch
from torch import nn
from torch.nn import functional as F
from d2l import torch as d2l
```

```
class Residual(nn.Module):
  def __init__(self, num_channels, use_1x1conv=False, strides=1):
    super().__init__()
    self.conv1 = nn.LazyConv2d(num_channels, kernel_size=3, padding=1, stride=strides)
    self.conv2 = nn.LazyConv2d(num_channels, kernel_size=3, padding=1)
    if use_1x1conv:
      self.conv3 = nn.LazyConv2d(num_channels, kernel_size=1, stride=strides)
    else:
      self.conv3 = None
    self.bn1 = nn.BatchNorm2d(num_channels)
    self.bn2 = nn.BatchNorm2d(num_channels)

  def forward(self, X):
    Y = F.relu(self.bn1(self.conv1(X)))
    Y = self.bn2(self.conv2(Y))
    if self.conv3:
      X = self.conv3(X)
    Y += X
    return F.relu(Y)
```

```
blk = Residual(3)
X = torch.randn(4,3,6,6)
blk(X).shape
```

```
torch.Size([4, 3, 6, 6])
```

```
blk = Residual(6, use_1x1conv=True, strides=2)
blk(X).shape
```

```
torch.Size([4, 6, 3, 3])
```

8.6.3 ResNet

```
class ResNet(d2l.Classifier):
    def b1(self):
        return nn.Sequential(
            nn.LazyConv2d(64, kernel_size=7, stride=2, padding=3),
            nn.LazyBatchNorm2d(), nn.ReLU(),
```