$28 \times 28 \xrightarrow{\text{Flatten}} 900$ | W

300×300
90K

Prob with Linear layer

$W \times x$
$5 \times 900 \quad 900 \times 1$
90K 90K

Number of weights required α input dimensions

Convolution layers → which can we use Conv layers
↳ shares the weights

Image-based problems
shift invariant

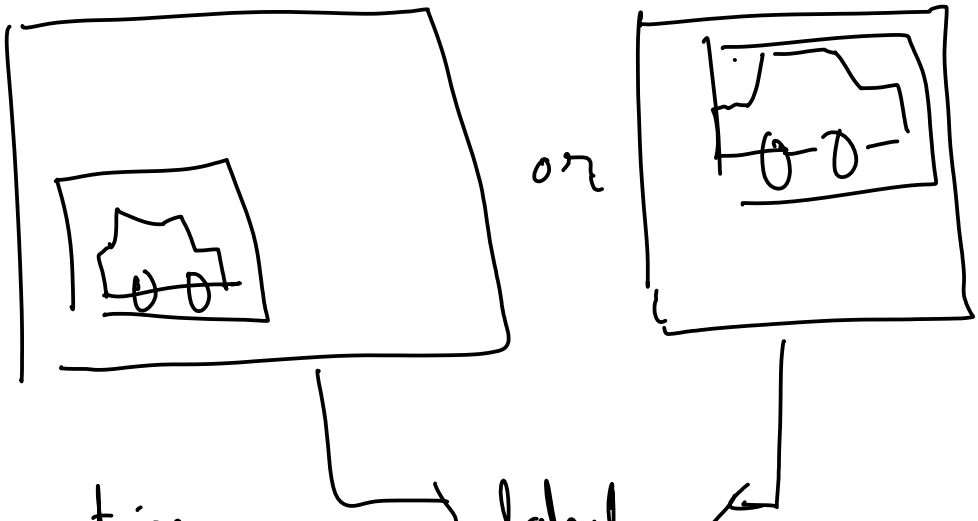


Image - classification → label = car

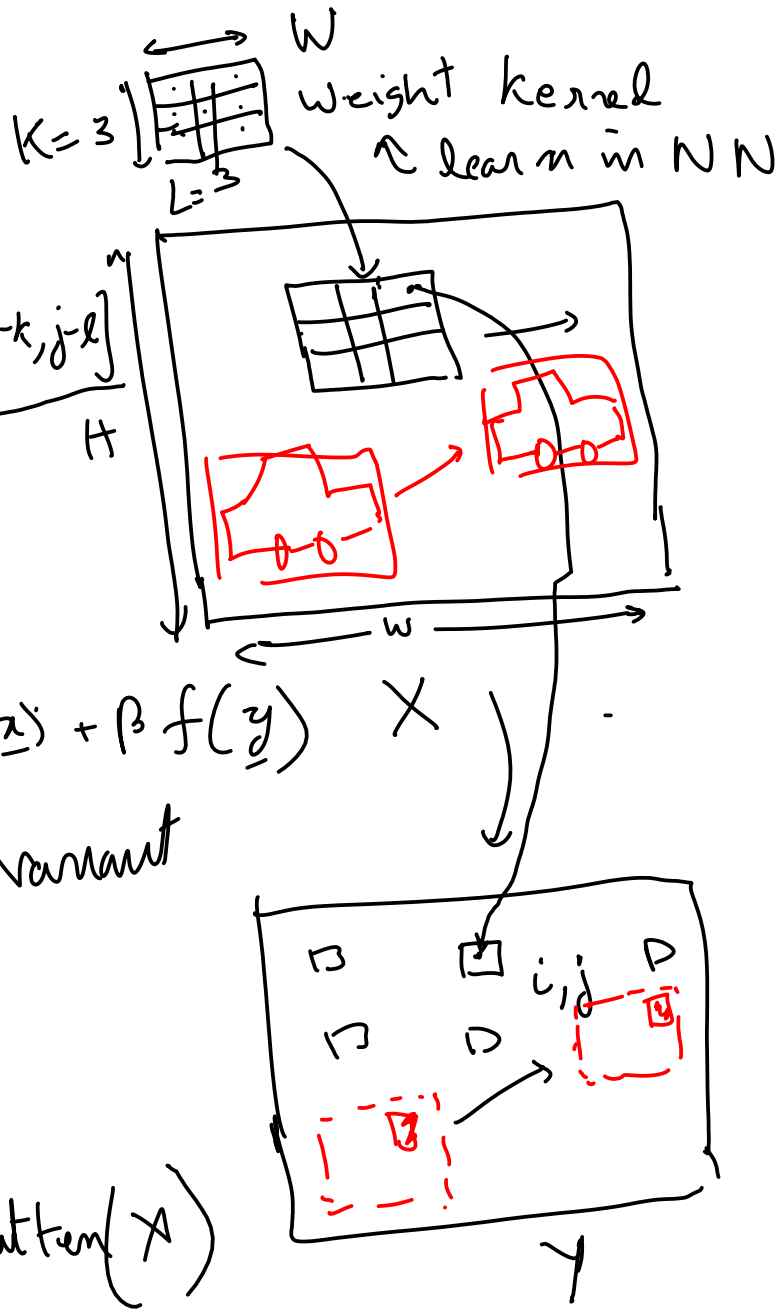
Convolution operation

$$(k \circledast f)(y) = \int_t k(t) f(y-t)\,dt$$

$$(k \circledast f)(y) = \sum_t k(t) f(y-t)$$

$k(t)$: weight

Conv 2D



$$Y[i,j] = \sum_{k=0}^{K-1} \sum_{l=0}^{L-1} W[k,l]\, X[i-k, j-l]$$

Observations

✓ ① Conv VS Linear

$$f(\alpha x + \beta y) = \alpha f(x) + \beta f(y) \quad X$$

② Conv ∀ shift invariant

$$\text{flatten}(Y) = W_{\text{Linear}} \, \text{flatten}(X)$$

You can write Conv layer as a Linear Layer

Conv $\subseteq$ Linear layer

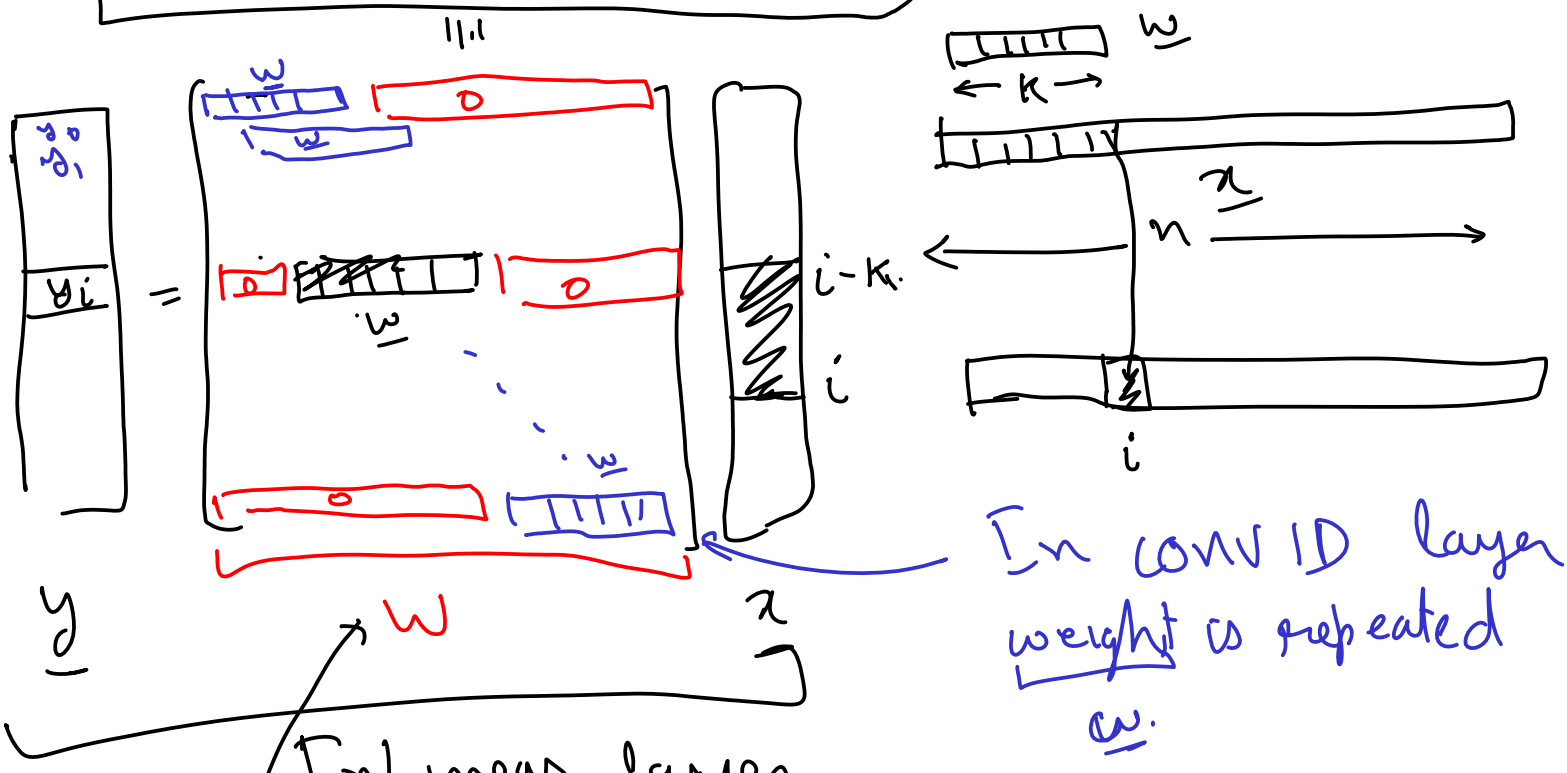
Conv 1D

$$\underline{y}[i] = \sum_{k=0}^{K-1} \underline{w}[k]\, \underline{x}[i-k]$$

$k < n$

$\underline{y} \in \mathbb{R}^{n+k-1}$

$\underline{x} \in \mathbb{R}^{n}$



In conv 1D layer weight is repeated ov.

In Linear layer

Entire W is learnable with no repitition

In [1]:
```
# Adapted from: Chapter 7 and 8 of Deep Learning with Pytorch by Eli Stevens
try:
    import torch as t
    import torch.nn as tnn
except ImportError:
    print("Colab users: pytorch comes preinstalled. Select Change Ru")
    print("Local users: Please install pytorch for your hardware using instr
    print("ACG users: Please follow instructions here: https://vikasdhiman.i

    raise

if t.cuda.is_available():
    DEVICE="cuda"
elif t.mps.is_available():
    DEVICE="mps"
else:
    DEVICE="cpu"

DTYPE = t.get_default_dtype()
```

In [2]:
```
## Doing it the Pytorch way without using our custom feature extraction

import torch
import torch.nn
import torch.optim
import torchvision
from torchvision.transforms import ToTensor, Compose, Normalize
from torch.utils.data import DataLoader

torch.manual_seed(17)
DATASET_MEAN = [0.4914, 0.4822, 0.4465]
DATASET_STD = [0.2470, 0.2435, 0.2616]
# Getting the dataset, the Pytorch way
all_training_data = torchvision.datasets.CIFAR10(
    root="data",
    train=True,
    download=True,
    transform=Compose([ToTensor(),
                       Normalize(DATASET_MEAN, # dataset mean
                                 DATASET_STD)]) # dataset std
)

test_data = torchvision.datasets.CIFAR10(
    root="data",
    train=False,
    download=True,
    transform=Compose([ToTensor(),
                       Normalize(DATASET_MEAN, # dataset mean
                                 DATASET_STD)]) # dataset std
)
```

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

In [3]:
```
training_data, validation_data = torch.utils.data.random_split(all_training_
```

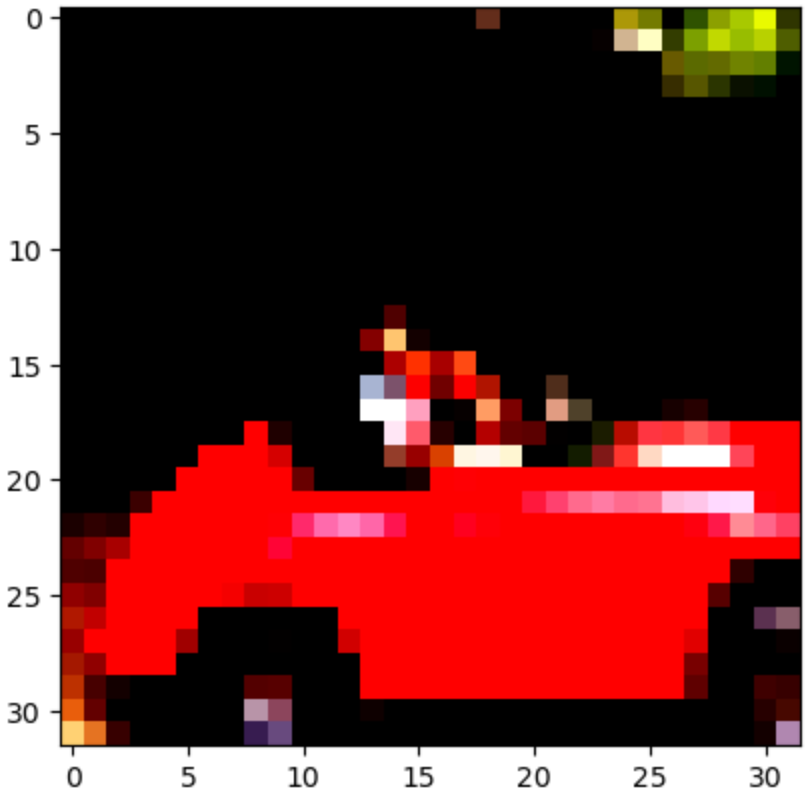
In [4]:
```
img, label = all_training_data[99]
img.shape, label
```

Out[4]:
```
(torch.Size([3, 32, 32]), 1)
```

In [5]:
```
import matplotlib.pyplot as plt
plt.imshow(img.permute(1, 2, 0))
```

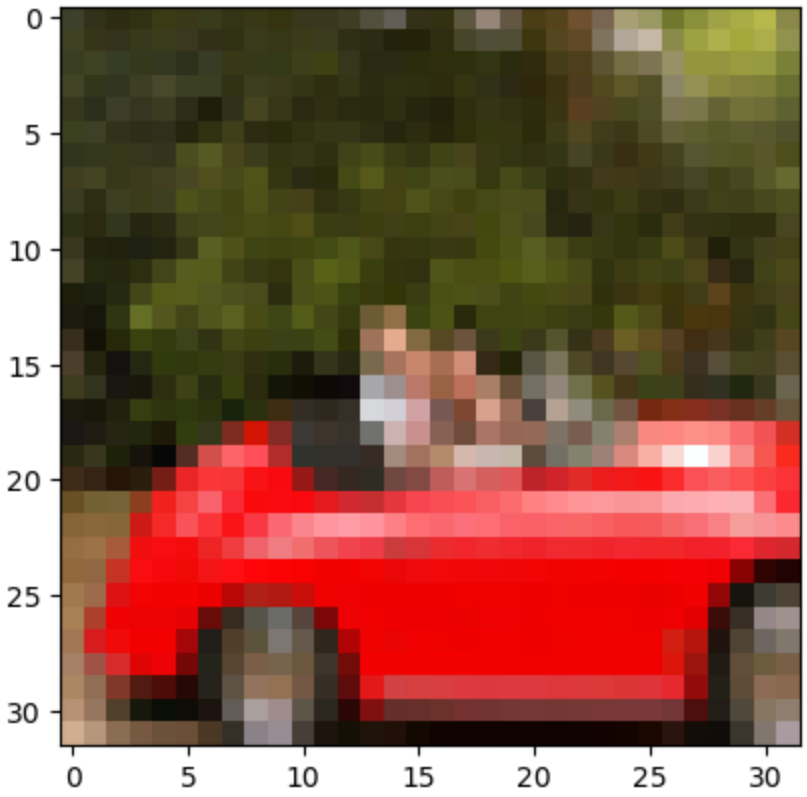
```
Clipping input data to the valid range for imshow with RGB data ([0..1] for
floats or [0..255] for integers).
```

Out[5]:
```
<matplotlib.image.AxesImage at 0x7efdecbcb5b0>
```



In [6]:
```
plt.imshow((img.permute(1, 2, 0) *  torch.Tensor(DATASET_STD)
            +  torch.Tensor(DATASET_MEAN)))
```

Out[6]:
```
<matplotlib.image.AxesImage at 0x7efdecb04940>
```



In [7]:
```
imgs = torch.stack([img_t for img_t, _ in all_training_data], dim=3)
imgs.reshape(3, -1).mean(dim=-1), imgs.reshape(3, -1).std(dim=-1)
```

Out[7]:
```
(tensor([-1.2762e-06, -1.7074e-04,  1.1819e-04]),
 tensor([1.0001, 0.9999, 1.0000]))
```

In [8]:
```
import pickle
cifar_meta = pickle.load(open("data/cifar-10-batches-py/batches.meta", "rb")
class_names = [c.decode('utf-8') for c in cifar_meta[b'label_names']]
class_names
```

Out[8]:
```
['airplane',
 'automobile',
 'bird',
 'cat',
 'deer',
 'dog',
 'frog',
 'horse',
 'ship',
 'truck']
```

In [9]:
```
# Hyper parameters
learning_rate = 1e-3 # controls how fast the gradient descent goes
batch_size = 64
epochs = 5
momentum = 0.9

training_dataloader = DataLoader(training_data, shuffle=True, batch_size=bat
validation_dataloader = DataLoader(validation_data,  batch_size=batch_size)
test_dataloader = DataLoader(test_data,  batch_size=batch_size)
```

```
X, y = next(iter(training_dataloader))
X.shape
```

Out[9]:
```
torch.Size([64, 3, 32, 32])
```

In [10]:
```
!pip install tensorboard
```

```
Requirement already satisfied: tensorboard in /home/vdhiman/.local/minicond
a3/envs/ece490/lib/python3.10/site-packages (2.12.0)
Requirement already satisfied: google-auth-oauthlib<0.5,>=0.4.1 in /home/vd
himan/.local/miniconda3/envs/ece490/lib/python3.10/site-packages (from tens
orboard) (0.4.6)
Requirement already satisfied: grpcio>=1.48.2 in /home/vdhiman/.local/minic
onda3/envs/ece490/lib/python3.10/site-packages (from tensorboard) (1.53.0)
Requirement already satisfied: tensorboard-data-server<0.8.0,>=0.7.0 in /ho
me/vdhiman/.local/miniconda3/envs/ece490/lib/python3.10/site-packages (from
tensorboard) (0.7.0)
Requirement already satisfied: requests<3,>=2.21.0 in /home/vdhiman/.local/
miniconda3/envs/ece490/lib/python3.10/site-packages (from tensorboard) (2.2
8.1)
Requirement already satisfied: markdown>=2.6.8 in /home/vdhiman/.local/mini
conda3/envs/ece490/lib/python3.10/site-packages (from tensorboard) (3.4.3)
Requirement already satisfied: tensorboard-plugin-wit>=1.6.0 in /home/vdhim
an/.local/miniconda3/envs/ece490/lib/python3.10/site-packages (from tensorb
oard) (1.8.1)
Requirement already satisfied: google-auth<3,>=1.6.3 in /home/vdhiman/.loca
l/miniconda3/envs/ece490/lib/python3.10/site-packages (from tensorboard)
(2.17.0)
Requirement already satisfied: wheel>=0.26 in /home/vdhiman/.local/minicond
a3/envs/ece490/lib/python3.10/site-packages (from tensorboard) (0.37.1)
Requirement already satisfied: setuptools>=41.0.0 in /home/vdhiman/.local/m
iniconda3/envs/ece490/lib/python3.10/site-packages (from tensorboard) (65.
6.3)
Requirement already satisfied: werkzeug>=1.0.1 in /home/vdhiman/.local/mini
conda3/envs/ece490/lib/python3.10/site-packages (from tensorboard) (2.2.3)
Requirement already satisfied: numpy>=1.12.0 in /home/vdhiman/.local/minico
nda3/envs/ece490/lib/python3.10/site-packages (from tensorboard) (1.23.5)
Requirement already satisfied: protobuf>=3.19.6 in /home/vdhiman/.local/min
iconda3/envs/ece490/lib/python3.10/site-packages (from tensorboard) (4.22.
1)
Requirement already satisfied: absl-py>=0.4 in /home/vdhiman/.local/minicon
da3/envs/ece490/lib/python3.10/site-packages (from tensorboard) (1.4.0)
Requirement already satisfied: rsa<5,>=3.1.4 in /home/vdhiman/.local/minico
nda3/envs/ece490/lib/python3.10/site-packages (from google-auth<3,>=1.6.3->
tensorboard) (4.9)
Requirement already satisfied: cachetools<6.0,>=2.0.0 in /home/vdhiman/.loc
al/miniconda3/envs/ece490/lib/python3.10/site-packages (from google-auth<3,
>=1.6.3->tensorboard) (5.3.0)
Requirement already satisfied: pyasn1-modules>=0.2.1 in /home/vdhiman/.loca
l/miniconda3/envs/ece490/lib/python3.10/site-packages (from google-auth<3,>
=1.6.3->tensorboard) (0.2.8)
Requirement already satisfied: six>=1.9.0 in /home/vdhiman/.local/miniconda
3/envs/ece490/lib/python3.10/site-packages (from google-auth<3,>=1.6.3->ten
sorboard) (1.16.0)
Requirement already satisfied: requests-oauthlib>=0.7.0 in /home/vdhiman/.l
ocal/miniconda3/envs/ece490/lib/python3.10/site-packages (from google-auth-
oauthlib<0.5,>=0.4.1->tensorboard) (1.3.1)
Requirement already satisfied: certifi>=2017.4.17 in /home/vdhiman/.local/m
iniconda3/envs/ece490/lib/python3.10/site-packages (from requests<3,>=2.21.
0->tensorboard) (2022.12.7)
Requirement already satisfied: urllib3<1.27,>=1.21.1 in /home/vdhiman/.loca
l/miniconda3/envs/ece490/lib/python3.10/site-packages (from requests<3,>=2.
21.0->tensorboard) (1.26.14)
```

```
Requirement already satisfied: charset-normalizer<3,>=2 in /home/vdhiman/.l
ocal/miniconda3/envs/ece490/lib/python3.10/site-packages (from requests<3,>
=2.21.0->tensorboard) (2.0.4)
Requirement already satisfied: idna<4,>=2.5 in /home/vdhiman/.local/minicon
da3/envs/ece490/lib/python3.10/site-packages (from requests<3,>=2.21.0->ten
sorboard) (3.4)
Requirement already satisfied: MarkupSafe>=2.1.1 in /home/vdhiman/.local/mi
niconda3/envs/ece490/lib/python3.10/site-packages (from werkzeug>=1.0.1->te
nsorboard) (2.1.1)
Requirement already satisfied: pyasn1<0.5.0,>=0.4.6 in /home/vdhiman/.loca
l/miniconda3/envs/ece490/lib/python3.10/site-packages (from pyasn1-modules>
=0.2.1->google-auth<3,>=1.6.3->tensorboard) (0.4.8)
Requirement already satisfied: oauthlib>=3.0.0 in /home/vdhiman/.local/mini
conda3/envs/ece490/lib/python3.10/site-packages (from requests-oauthlib>=0.
7.0->google-auth-oauthlib<0.5,>=0.4.1->tensorboard) (3.2.2)
```

In [17]:
```
%tensorboard --logdir=runs
```

```
Reusing TensorBoard on port 6006 (pid 543069), started 0:05:49 ago. (Use '!
kill 543069' to kill it.)
```

In [22]:

```
from torch.utils.tensorboard import SummaryWriter
import os
writer = SummaryWriter()

loss = torch.nn.CrossEntropyLoss()
# TODO:
# Define model = ?
```

```
model = tnn.Sequential(
    torch.nn.Flatten(),
    tnn.Linear(3*32*32, 100),
    tnn.ReLU(),
    tnn.Linear(100, 10))


# Define optimizer
optimizer = torch.optim.SGD(model.parameters(), lr=learning_rate, momentum=m

def loss_and_accuracy(model, loss, validation_dataloader, device=DEVICE):
        # Validation loop
        validation_size = len(validation_dataloader.dataset)
        num_batches = len(validation_dataloader)
        test_loss, correct = 0, 0

        with torch.no_grad():
            model.eval() # Put model in eval mode, affects layers like dropo
            for X, y in validation_dataloader:
                X = X.to(device)
                y = y.to(device)
                pred = model(X)
                test_loss += loss(pred, y)
                correct += (pred.argmax(dim=-1) == y).type(DTYPE).sum()

        test_loss /= num_batches
        correct /= validation_size
        return test_loss, correct

def train(model, loss, training_dataloader, validation_dataloader, device=DE
    model.to(device)
    t0 = 0
    if os.path.exists("runs/model_ckpt.pt"):
        checkpoint = torch.load("runs/model_ckpt.pt")
        model.load_state_dict(checkpoint['model_state_dict'])
        optimizer.load_state_dict(checkpoint['optimizer_state_dict'])
        t0 = checkpoint['epoch']

    for t in range(t0, epochs):
        # Train loop
        training_size = len(training_dataloader.dataset)
        nbatches = len(training_dataloader)
        model.train() # Put model in train mode, affects layers like dropout
        for batch, (X, y) in enumerate(training_dataloader):
            X = X.to(device)
            y = y.to(device)
            # Compute prediction and loss
            pred = model(X)
            loss_t = loss(pred, y)

            # Backpropagation
            optimizer.zero_grad()
            loss_t.backward()
            optimizer.step()

            if batch % 100 == 0:
```

```
                writer.add_scalar("Train/loss_batch", loss_t,  t*nbatches +
                loss_t, current = loss_t.item(), (batch + 1) * len(X)
                print(f"loss: {loss_t:>7f}  [{current:>5d}/{training_size:>5

        writer.add_scalar("Train/loss", loss_t, t)
        valid_loss, correct = loss_and_accuracy(model, loss, validation_data
        writer.add_scalar("Valid/loss", valid_loss, t)
        writer.add_scalar("Valid/accuracy", correct, t)
        print(f"Validation Error: \n Accuracy: {(100*correct):>0.1f}%, Avg l
        if t % 3 == 0:
            torch.save({
                'epoch': t,
                'model_state_dict': model.state_dict(),
                'optimizer_state_dict': optimizer.state_dict()
                }, "runs/model_ckpt.pt")
    return model

trained_model = train(model, loss, training_dataloader, validation_dataloade

test_loss, correct = loss_and_accuracy(model, loss, test_dataloader)
print(f"Test Error: \n Accuracy: {(100*correct):>0.1f}%, Avg loss: {test_los
```

```
Validation Error: 4864/45000]
 Accuracy: 48.4%, Avg loss: 1.453683

Validation Error: 4864/45000]
 Accuracy: 49.2%, Avg loss: 1.440753

Test Error:
 Accuracy: 50.3%, Avg loss: 1.427571
```

Limits of fully connected layers

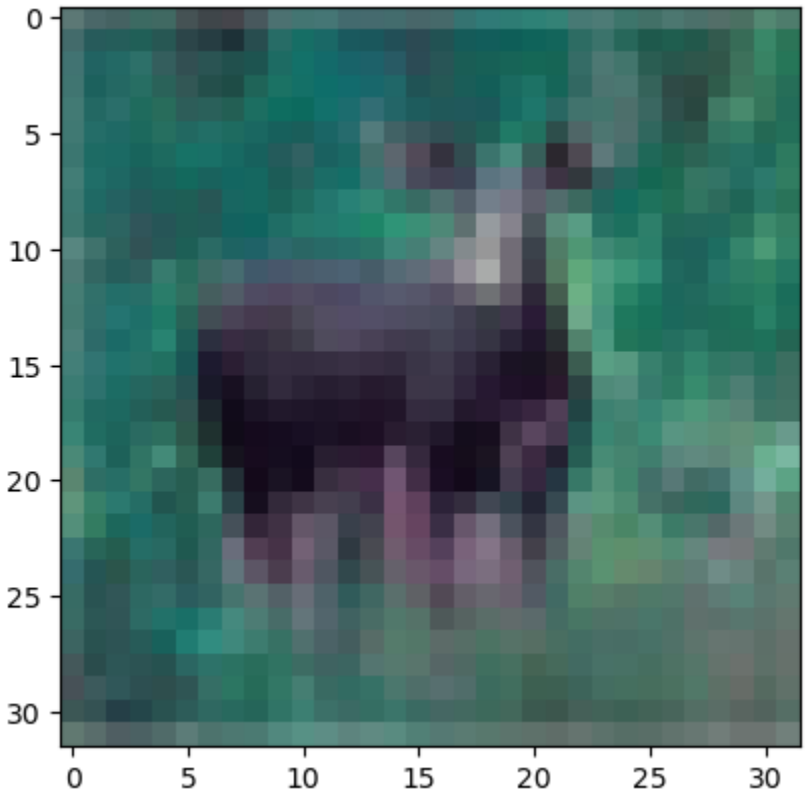
Convolutions bring translation invariance

In [32]:
```
conv = torch.nn.Conv2d(3, 1, kernel_size=3)
conv
```

Out[32]:
```
Conv2d(3, 1, kernel_size=(3, 3), stride=(1, 1))
```

In [33]:
```
img, label = training_data[99]
plt.imshow(img.permute(1, 2, 0) * t.Tensor(DATASET_STD) + t.Tensor(DATASET_M
```

Out[33]:
```
<matplotlib.image.AxesImage at 0x7efd51214ee0>
```



Learning with Convolutions

Maxpooling

In [ ]: