

Deep Learning

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1 Introduction

2 A Brief Overview of Tensors

You are likely familiar with scalars, vectors, and matrices. These can be thought of as analagous data structures in zero, one, and two-dimensions, respectively. When generalizing to N dimensions, we refer to these collectively as tensors. A scalar is a zero-order tensor, a vector is a first-order tensor, and a matrix is a second-order tensor. A third-order tensor can be visualized as a stack of matrices. A fourth-order tensor would then be a vector of third order tensors. A fifth-order tensor is a matrix of third-order tensors... and so on.

2.1 Tensor Products

Tensor additon and subtraction are self-explanatory if matrix addition and subtraction are understood. The same cannot be said for tensor products. Below is an overview of tensor products necessary for the decompositions that will be presented in the next section.

2.1.1 Outer Product \circ

A tensor $T^{(N)}$ can be expressed as a product of N vectors. This is called the outer product (denoted \circ).

$$T^{(N)} = u_1 \circ u_2 \circ \dots \circ u_N \quad (1)$$

2.1.2 Kronecker Product \otimes

The Konecker product of two matrices A and B , their Kronecker product is a matrix of the products of each element in A and the entire matrix B .

$$A \otimes B = \begin{bmatrix} a_{11}B & a_{12}B & \dots & a_{1n}B \\ a_{21}B & a_{22}B & \dots & a_{2n}B \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1}B & am2B & \dots & a_{mn}B \end{bmatrix} \quad (2)$$

2.1.3 Khatri-Rao Product \odot

The Khatri-Rao product of two matrices A and B , each with the same number of columns, is a matrix composed of the Kronecker products of the columns in matrix A and the columns in matrix B with the same indices.

$$A^{:\times n} \odot B^{:\times n} = [a_{:,1} \otimes b_{:,1} \quad a_{:,2} \otimes b_{:,2} \quad \dots \quad a_{:,n} \otimes b_{:,n}] \quad (3)$$

2.1.4 Hadamard Product $*$

The Hadamard product of two matrices A and B of the same dimensions is a matrix formed of the products of the elements in A and B with the same indices.

$$A^{m \times n} * B^{m \times n} = \begin{bmatrix} a_{11}b_{11} & a_{12}b_{12} & \dots & a_{1n}b_{1n} \\ a_{21}b_{21} & a_{22}b_{22} & \dots & a_{2n}b_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1}b_{m1} & a_{m2}b_{m2} & \dots & a_{mn}b_{mn} \end{bmatrix} \quad (4)$$

2.2 Tensor Decompositions

2.2.1 CP Decomposition

The canonical polyadic, or CP Decomposition, decomposes a tensor into vectors.

$$T = \sum_{r=1}^R u_r^{(1)} \circ u_r^{(2)} \circ \dots \circ u_r^{(R)} \quad (5)$$

2.2.2 Tucker Decomposition

The Tucker decomposition decomposes a tensor into a core tensor and factored matrices.

$$T = C \prod_{n=1}^N A^n \quad (6)$$

where C is the core tensor.

2.2.3 Tensor Train

The tensor train decomposition decomposes a tensor into a product of third-order tensors. It is used when a tensor is too large for the CP decomposition to be practical.

3 Selecting A Network Architecture

4 Convolutional Neural Networks

4.1 What Is Convolution?

Many young people who are active on social media use filters on their pictures before posting them. These filters apply different effects to the photo, such as blurring, making the image black and white, or adding cartoon-like effects. When you apply a filter to a photo, you are using convolution. Convolution is an operation that takes the aggregation of the element-wise product of a tensor of input data and a (typically smaller) tensor, called a kernel. This produces a feature map. In the context of image processing, the original image is the input data, the filter is the kernel, and the filtered image is the feature map.

This is an example of discrete convolution, which is the case that we will be primarily concerned with.

In one dimension, discrete convolution is denoted

$$\underbrace{s(i)}_{\text{feature map}} = (x * y)(i) = \sum_m \underbrace{x(m)}_{\text{input data}} \underbrace{y(i-m)}_{\text{kernel}} \quad (7)$$

One of the most common applications of CNNs is in digital image processing. In the case of a black and white image, the input data is a two-dimensional tensor. Discrete convolution in two dimensions can be performed as follows [1].

$$s(i, j) = (x * y)(i, j) = \sum_m \sum_n x(i, j) y(i - m, j - n) \quad (8)$$

Since convolution is commutative, equation 9 also holds.

$$s(i, j) = (y * x)(i, j) = \sum_m \sum_n x(i - m, j - n) y(i, j) \quad (9)$$

Two-dimensional discrete convolution is equivalent to reversing the row and column indices of the kernel, performing element-wise multiplication, and taking the sum of the products. In the context of deep learning, the term “convolution” often refers to a similar operation called cross-correlation (equation). This is equivalent to convolution without the reversing of the matrix indices [1].

$$s(i, j) = (y * x)(i, j) = \sum_m \sum_n x(i + m, j + n) y(i, j) \quad (10)$$

4.2 How Convolution is Used in Deep Neural Networks

Since one kernel can only extract one feature, each convolutional layer in a network uses multiple kernels. CNNs can be very computationally expensive to train, so we often skip over positions in the kernels to reduce training time. The width of the kernel and the size of the output can also be controlled by zero padding the input. Without zero padding, the output of each later would continue to shrink. The number of rows/columns per convolution is referred to as the stride of the convolution operation [1].

4.3 The Convolutional Layer

The convolutional layers used in a CNN have three steps [1].

1. Several parallel convolutions yield a set of linear activations.
2. Each linear activation function is run through a non-linear activation function, such as ReLU. This introduces non-linearity and gives the network more flexibility.
3. A pooling function replaces the output at a given location with a summary statistic of nearby outputs. One common pooling function is the max pooling function, which provides the maximum output within a rectangular neighbourhood. Pooling is useful when we only care about whether a feature is present and not its specific location. It is also helpful when processing different-sized inputs.

The output of each layer is then used as input to the next layer.

4.4 Image Classification Example

In this example, we will use convolutional neural networks to perform image classification on the Rock Paper Scissors dataset.

```
import tensorflow as tf
from tensorflow.keras import layers, models, Input
from tensorflow.keras.callbacks import EarlyStopping
import tensorflow_datasets as tfds
import matplotlib.pyplot as plt
import numpy as np

tf.keras.utils.set_random_seed(42) # Set random seed for reproducibility
```

The dataset is only partitioned into training and test sets, so we set aside 30% of the training set as a validation set.

```
(ds_train, ds_val, ds_test) = tfds.load(
    'rock_paper_scissors',
    split=['train[:70%]', 'train[70%:]', 'test'],
    shuffle_files=True,
    as_supervised=True
)
```

Next, we normalize by dividing by 255 and resize the images to 128x128. We also shuffle the training data to ensure that the model doesn't learn its order, and batch the training, validation, and test data.

```
def preprocess(image, label):
    image = tf.cast(image, tf.float32) / 255.0 # Normalize images
    image = tf.image.resize(image, [128, 128]) # Resize images
    return image, label
```

```

BATCH_SIZE = 32
SHUFFLE_BUFFER_SIZE = 1000

ds_train = ds_train.map(preprocess).shuffle(SHUFFLE_BUFFER_SIZE).batch(BATCH_SIZE)
    # shuffle so the model doesn't learn the order of the training data
ds_val = ds_val.map(preprocess).batch(BATCH_SIZE)
ds_test = ds_test.map(preprocess).batch(BATCH_SIZE)

```

We start with a simple network with one convolutional layer with 16 filters and a 3x3 kernel.

```

input_shape = (128, 128, 3)

model = models.Sequential([
    layers.Input(shape=input_shape),
    layers.Conv2D(16, (3, 3), activation='relu'), # Convolution step
    layers.MaxPooling2D((2, 2)), # Pooling step
    layers.Flatten(), # Flattening for classification
    layers.Dense(128, activation='relu'), # Dense layer before final
    classification layer
    layers.Dense(3) # 3 classes
])

model.compile(optimizer='adam',
              loss=tf.keras.losses.SparseCategoricalCrossentropy(from_logits=True)
              ,
              metrics=['accuracy']
              )

```

Before fitting our model, we add an early stop mechanism to prevent overfitting.

```

early_stop = EarlyStopping(
    monitor='val_loss',
    min_delta=0.001,
    patience=3,
    verbose=1,
    mode='auto',
    restore_best_weights=True
)

history = model.fit(ds_train, epochs=10, validation_data=(ds_val), callbacks=[
    early_stop])

Epoch 1/10
56/56 [=====] - 10s 85ms/step - loss: 1.0240 - accuracy:
0.7137 - val_loss: 0.2209 - val_accuracy: 0.9563
Epoch 2/10
56/56 [=====] - 5s 61ms/step - loss: 0.0743 - accuracy:
0.9881 - val_loss: 0.0240 - val_accuracy: 0.9947
Epoch 3/10
56/56 [=====] - 4s 37ms/step - loss: 0.0131 - accuracy:
0.9989 - val_loss: 0.0148 - val_accuracy: 0.9947
Epoch 4/10
56/56 [=====] - 4s 37ms/step - loss: 0.0045 - accuracy:
1.0000 - val_loss: 0.0062 - val_accuracy: 0.9987
Epoch 5/10
56/56 [=====] - 5s 58ms/step - loss: 0.0020 - accuracy:
1.0000 - val_loss: 0.0042 - val_accuracy: 1.0000
Epoch 6/10
56/56 [=====] - 4s 38ms/step - loss: 0.0013 - accuracy:
1.0000 - val_loss: 0.0039 - val_accuracy: 1.0000
Epoch 7/10

```

```

56/56 [=====] - 4s 38ms/step - loss: 0.0010 - accuracy:
1.0000 - val_loss: 0.0041 - val_accuracy: 0.9987
Epoch 8/10
53/56 [=====>..] - ETA: 0s - loss: 8.3814e-04 - accuracy:
1.0000Restoring model weights from the end of the best epoch: 5.
56/56 [=====] - 5s 59ms/step - loss: 8.2481e-04 -
accuracy: 1.0000 - val_loss: 0.0032 - val_accuracy: 0.9987
Epoch 8: early stopping

```

Training accuracy of 100% and validation accuracy of over 99%? If something seems too good to be true, it probably is. Let's evaluate on the test data.

```
model.evaluate(ds_test)
```

```

12/12 [=====] - 1s 104ms/step - loss: 1.3345 - accuracy:
0.7151
[1.3345420360565186, 0.7150537371635437]

```

As expected, no such luck. What happens when we add another convolutional layer?

```

model = models.Sequential([
    layers.Input(shape=input_shape),
    layers.Conv2D(16, (3, 3), activation='relu'), # First convolution step
    layers.MaxPooling2D((2, 2)), # First pooling step
    layers.Conv2D(32, (3, 3), activation='relu'), # Second convolution step
    layers.MaxPooling2D((2, 2)), # Second pooling step
    layers.Flatten(), # Flattening for classification
    layers.Dense(128, activation='relu'), # Dense layer before final
    classification layer
    layers.Dense(3) # 3 classes
])

model.compile(optimizer='adam',
              loss=tf.keras.losses.SparseCategoricalCrossentropy(from_logits=True),
              metrics=['accuracy'])

history = model.fit(ds_train, epochs=10, validation_data=(ds_val), callbacks=[
    early_stop])

Epoch 1/10
56/56 [=====] - 6s 43ms/step - loss: 1.4043 - accuracy:
0.5890 - val_loss: 0.4816 - val_accuracy: 0.9206
Epoch 2/10
56/56 [=====] - 5s 54ms/step - loss: 0.2150 - accuracy:
0.9552 - val_loss: 0.0609 - val_accuracy: 0.9881
Epoch 3/10
56/56 [=====] - 4s 38ms/step - loss: 0.0441 - accuracy:
0.9909 - val_loss: 0.0182 - val_accuracy: 0.9987
Epoch 4/10
56/56 [=====] - 4s 39ms/step - loss: 0.0143 - accuracy:
0.9977 - val_loss: 0.0076 - val_accuracy: 0.9987
Epoch 5/10
56/56 [=====] - 5s 60ms/step - loss: 0.0053 - accuracy:
0.9994 - val_loss: 0.0030 - val_accuracy: 1.0000
Epoch 6/10
56/56 [=====] - 4s 41ms/step - loss: 0.0022 - accuracy:
1.0000 - val_loss: 0.0019 - val_accuracy: 1.0000
Epoch 7/10
56/56 [=====] - 4s 39ms/step - loss: 0.0016 - accuracy:
1.0000 - val_loss: 0.0013 - val_accuracy: 1.0000

```

```

Epoch 8/10
56/56 [=====] - 5s 60ms/step - loss: 9.5238e-04 -
accuracy: 1.0000 - val_loss: 0.0011 - val_accuracy: 1.0000
Epoch 9/10
56/56 [=====] - 4s 38ms/step - loss: 6.9435e-04 -
accuracy: 1.0000 - val_loss: 8.4804e-04 - val_accuracy: 1.0000
Epoch 10/10
56/56 [=====] - 4s 38ms/step - loss: 5.3139e-04 -
accuracy: 1.0000 - val_loss: 7.7833e-04 - val_accuracy: 1.0000

```

```
\lstinputlisting[firstline=100,lastline=100]{dl-scripts/cnn-ex1-colab.py}
```

```
\begin{lstlisting}[style=output]
```

```

12/12 [=====] - 0s 16ms/step - loss: 1.0663 - accuracy:
0.7634
[1.0662583112716675, 0.7634408473968506]

```

An improvement, but still not amazing. Would a third convolutional layer help?

```

model = models.Sequential([
    layers.Input(shape=input_shape),
    layers.Conv2D(16, (3, 3), activation='relu'), # First convolution step
    layers.MaxPooling2D((2, 2)), # First pooling step
    layers.Conv2D(32, (3, 3), activation='relu'), # Second convolution step
    layers.MaxPooling2D((2, 2)), # Second pooling step
    layers.Conv2D(64, (3, 3), activation='relu'), # Third convolution step
    layers.MaxPooling2D((2, 2)), # Third pooling step
    layers.Flatten(), # Flattening for classification
    layers.Dense(128, activation='relu'), # Dense layer before final
    classification layer
    layers.Dense(3) # 3 classes
])

model.compile(optimizer='adam',
              loss=tf.keras.losses.SparseCategoricalCrossentropy(from_logits=True),
              metrics=['accuracy'])

history = model.fit(ds_train, epochs=10, validation_data=(ds_val), callbacks=[
    early_stop])

```

```

Epoch 1/10
56/56 [=====] - 7s 44ms/step - loss: 0.6999 - accuracy:
0.7035 - val_loss: 0.1999 - val_accuracy: 0.9101
Epoch 2/10
56/56 [=====] - 4s 39ms/step - loss: 0.0600 - accuracy:
0.9864 - val_loss: 0.0188 - val_accuracy: 0.9934
Epoch 3/10
56/56 [=====] - 5s 53ms/step - loss: 0.0240 - accuracy:
0.9949 - val_loss: 0.0071 - val_accuracy: 1.0000
Epoch 4/10
56/56 [=====] - 4s 39ms/step - loss: 0.0022 - accuracy:
1.0000 - val_loss: 0.0011 - val_accuracy: 1.0000
Epoch 5/10
56/56 [=====] - 4s 41ms/step - loss: 7.2477e-04 -
accuracy: 1.0000 - val_loss: 7.4349e-04 - val_accuracy: 1.0000
Epoch 6/10
56/56 [=====] - 5s 63ms/step - loss: 4.0359e-04 -
accuracy: 1.0000 - val_loss: 3.2628e-04 - val_accuracy: 1.0000
Epoch 7/10

```



```

52/56 [=====>...] - ETA: 0s - loss: 2.2042e-04 - accuracy:
1.0000Restoring model weights from the end of the best epoch: 4.
56/56 [=====] - 4s 39ms/step - loss: 2.1410e-04 -
accuracy: 1.0000 - val_loss: 3.2290e-04 - val_accuracy: 1.0000
Epoch 7: early stopping

```

```
model.evaluate(ds_test)
```

```

12/12 [=====] - 0s 10ms/step - loss: 1.1395 - accuracy:
0.7930
[1.1395031213760376, 0.7930107712745667]

```

A slight improvement. What about a fourth layer?

```

model = models.Sequential([
    layers.Input(shape=input_shape),
    layers.Conv2D(16, (3, 3), activation='relu'), # First convolution step
    layers.MaxPooling2D((2, 2)), # First pooling step
    layers.Conv2D(32, (3, 3), activation='relu'), # Second convolution step
    layers.MaxPooling2D((2, 2)), # Second pooling step
    layers.Conv2D(64, (3, 3), activation='relu'), # Third convolution step
    layers.MaxPooling2D((2, 2)), # Third pooling step
    layers.Conv2D(128, (3, 3), activation='relu'), # Fourth convolution step
    layers.MaxPooling2D((2, 2)), # Fourth pooling step
    layers.Flatten(), # Flattening for classification
    layers.Dense(128, activation='relu'), # Dense layer before final
    classification layer
    layers.Dense(3) # 3 classes
])

model.compile(optimizer='adam',
              loss=tf.keras.losses.SparseCategoricalCrossentropy(from_logits=True),
              metrics=['accuracy'])

history = model.fit(ds_train, epochs=10, validation_data=(ds_val), callbacks=[
    early_stop])

```

```

Epoch 1/10
56/56 [=====] - 6s 46ms/step - loss: 0.7071 - accuracy:
0.6604 - val_loss: 0.1421 - val_accuracy: 0.9563
Epoch 2/10
56/56 [=====] - 5s 40ms/step - loss: 0.0583 - accuracy:
0.9853 - val_loss: 0.0080 - val_accuracy: 0.9987
Epoch 3/10
56/56 [=====] - 4s 39ms/step - loss: 0.0057 - accuracy:
0.9983 - val_loss: 0.0020 - val_accuracy: 1.0000
Epoch 4/10
56/56 [=====] - 4s 48ms/step - loss: 0.0026 - accuracy:
0.9989 - val_loss: 0.0017 - val_accuracy: 1.0000
Epoch 5/10
56/56 [=====] - 5s 40ms/step - loss: 0.0038 - accuracy:
0.9994 - val_loss: 0.0136 - val_accuracy: 0.9921
Epoch 6/10
56/56 [=====] - 4s 41ms/step - loss: 0.0018 - accuracy:
0.9994 - val_loss: 2.4979e-04 - val_accuracy: 1.0000
Epoch 7/10
56/56 [=====] - 4s 43ms/step - loss: 1.2425e-04 -
accuracy: 1.0000 - val_loss: 1.3199e-04 - val_accuracy: 1.0000
Epoch 8/10

```

```

56/56 [=====] - 5s 39ms/step - loss: 9.3137e-05 -
    accuracy: 1.0000 - val_loss: 9.6794e-05 - val_accuracy: 1.0000
Epoch 9/10
54/56 [=====>..] - ETA: 0s - loss: 7.5662e-05 - accuracy:
    1.0000Restoring model weights from the end of the best epoch: 6.
56/56 [=====] - 4s 39ms/step - loss: 7.4308e-05 -
    accuracy: 1.0000 - val_loss: 7.7891e-05 - val_accuracy: 1.0000
Epoch 9: early stopping

```

```
model.evaluate(ds_test)
```

```

12/12 [=====] - 0s 10ms/step - loss: 0.1825 - accuracy:
    0.9409
[0.1824917197227478, 0.9408602118492126]

```

Now that we have reached the accuracy threshold, let's plot the learning curves.

```

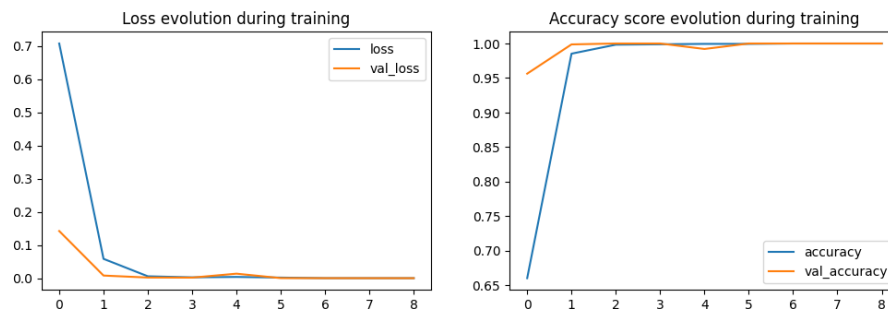
def plot_learning_curves(history):
    plt.figure(figsize=(12, 8))

    plt.subplot(2, 2, 1)
    plt.plot(history.history['loss'], label='loss')
    plt.plot(history.history['val_loss'], label='val_loss')
    plt.title('Loss evolution during training')
    plt.legend()

    plt.subplot(2, 2, 2)
    plt.plot(history.history['accuracy'], label='accuracy')
    plt.plot(history.history['val_accuracy'], label='val_accuracy')
    plt.title('Accuracy score evolution during training')
    plt.legend();

plot_learning_curves(history)

```



```

# Make predictions on the test set
test_images, test_labels = [], []
for images, labels in ds_test:
    test_images.append(images.numpy())
    test_labels.append(labels.numpy())
test_images = np.concatenate(test_images)
test_labels = np.concatenate(test_labels)

predictions = model.predict(test_images)
predicted_labels = np.argmax(predictions, axis=1)

# Identify correct and incorrect predictions
correct_predictions = predicted_labels == test_labels

```

```

incorrect_predictions = predicted_labels != test_labels

# Get indices for correct and incorrect predictions
correct_indices = np.where(correct_predictions)[0]
incorrect_indices = np.where(incorrect_predictions)[0]

# Function to plot images with their predictions and true labels
def plot_predictions(images, true_labels, predicted_labels, indices, title):
    plt.figure(figsize=(10, 10))
    for i, index in enumerate(indices[:25]): # Plot the first 25 images
        plt.subplot(5, 5, i + 1)
        plt.imshow(images[index])
        plt.title(f"True: {true_labels[index]}, Pred: {predicted_labels[index]}")
        plt.axis('off')
    plt.suptitle(title)
    plt.show()

# Plot correct predictions
plot_predictions(test_images, test_labels, predicted_labels, correct_indices,
                title="Correct Predictions")

# Plot incorrect predictions
plot_predictions(test_images, test_labels, predicted_labels, incorrect_indices,
                title="Incorrect Predictions")

```



Look at the images that were classified incorrectly. It seems that the model's most significant weakness is misclassifying scissors as paper. Do you notice anything about these scissor images compared to the scissor and paper images in the correct predictions? How could the model potentially be improved?

Incorrect Predictions



5 Recurrent Neural Networks

6 Generative Models

6.1 Generative Adversarial Neural Networks

6.2 Variational Autoencoders

6.3 Quantization