Лабораторная работа № 3

Многослойные сети. Алгоритм обратного распространения ошибки

Цель работы: исследование свойств многослойной нейронной сети прямого распространения и алгоритмов ее обучения, применение сети в задачах классификации и аппроксимации функции

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```python
import numpy as np

import torch
import torch.nn as nn
from torch.utils.data import TensorDataset, DataLoader

import matplotlib.pyplot as plt

from sklearn.model_selection import train_test_split
```

Применение многослойной нейронной сети в задачах классификации

Функция, которая генерирует координаты точек эллипса по параметрическим уравнениям

```python
def ellipse(t, a, b, x0, y0):
    x = x0 + a * np.cos(t)
    y = y0 + b * np.sin(t)
    return x, y

def parabola(t, p, x0, y0):
    x = x0 + p * t**2
    y = y0 + t
    return x, y
```

Функция, выполняющая поворот точек вокруг начала координат

```python
def rotate(x, y, alpha):
    xr = x * np.cos(alpha) - y * np.sin(alpha)
    yr = x * np.sin(alpha) + y * np.cos(alpha)
    return xr, yr
```

Генерирация равномерно распределенных значений от 0 до 2π включительно с общим количеством точек равным 200

```python
t_for_ellipse = np.linspace(0, 2 * np.pi, 200)
t_for_parabola = np.linspace(-5, 5, 200)
```

Классы, выраженные эллипсами и параболой

```python
# Класс 1
x1, y1 = ellipse(t_for_ellipse, a=0.4, b=0.15, x0=0.1, y0=-0.15)
x1, y1 = rotate(x1, y1, np.pi / 6.)

# Класс 2
x2, y2 = ellipse(t_for_ellipse, a=0.7, b=0.5, x0=0., y0=0.)
x2, y2 = rotate(x2, y2, -np.pi / 3.)

# Класс 3
x3, y3 = parabola(t_for_parabola, p=1, x0=-0.8, y0=0.)
x3, y3 = rotate(x3, y3, np.pi / 2.)
```

Создание списков points для каждого класса. Далее, создаются списки классов classes1, classes2, classes3 в формате one-hot encoding для каждого класса. Наконец, переменные X и Y объединяют все точки и соответствующие им классы для последующего использования в обучении многослойной нейронной сети.

```python
points1 = [[x, y] for x, y in zip(x1, y1)]
points2 = [[x, y] for x, y in zip(x2, y2)]
points3 = [[x, y] for x, y in zip(x3, y3)]

classes1 = [[1., 0., 0.] for _ in range(len(points1))]
classes2 = [[0., 1., 0.] for _ in range(len(points2))]
classes3 = [[0., 0., 1.] for _ in range(len(points3))]

X = points1 + points2 + points3
Y = classes1 + classes2 + classes3
```

Разделение данных на обучающий (x_train, y_train) и тестовый (x_test, y_test) наборы. 20% данных будут использоваться для тестирования, а 80% - для обучения. Параметр random_state=42 фиксирует случайное разбиение, обеспечивая воспроизводимость результатов.

```python
x_train, x_test, y_train, y_test = train_test_split(X, Y,
test_size=0.2, random_state=42)
```

Преобразование в тензоры

```python
x_train = torch.FloatTensor(np.array(x_train))
y_train = torch.FloatTensor(np.array(y_train))
```

```
x_test = torch.FloatTensor(np.array(x_test))
y_test = torch.FloatTensor(np.array(y_test))
```

Через train_loader будем загружать на обучение батчи размером 10% от обучающего датасета.

```
train_dataset = TensorDataset(x_train, y_train)
test_dataset = TensorDataset(x_test, y_test)

batch_size = int(len(train_dataset) * 0.1)
train_loader = DataLoader(train_dataset, batch_size)
```

Создание двухслойной сети. Сеть состоит из двух полносвязных слоев, применяющих нелинейные функции активации tanh и sigmoid. tanh в скрытом слое помогает избежать проблемы затухающих градиентов, а sigmoid в выходном слое сжимает значения в нужный диапазон для предсказания цветов.

```
class TwoLayerNet(nn.Module):
    def __init__(self, in_features: int, hidden_layer: int,
out_features: int):
        super().__init__()
        self.fc1 = nn.Linear(in_features, hidden_layer)
        self.fc2 = nn.Linear(hidden_layer, out_features)

    def forward(self, x):
        x = self.fc1(x)
        x = torch.tanh(x)
        x = self.fc2(x)
        x = torch.sigmoid(x)
        return x
```

Сеть настроена на прогнозирование трех значений в диапазоне [0, 1], что может быть интерпретировано как цветовая компонента RGB.

```
two_layer_net = TwoLayerNet(2, 100, 3)
loss_function = nn.MSELoss()
optimizer = torch.optim.Adam(two_layer_net.parameters())
```

Внутри цикла по эпохам, для каждого батча, модель обновляется, вычисляется значение функции потерь и производится оптимизация параметров.

```
def fit(model, train_loader, criterion, optimizer, epochs):
    losses = []

    running_loss = 0.0
    processed_data = 0

    log_template = "\nEpoch {ep:03d} train_loss: {t_loss:0.4f}"
```

```python
    for epoch in range(epochs):
        for inputs, labels in train_loader:
            optimizer.zero_grad()
            outp = model(inputs)

            loss = criterion(outp, labels)

            loss.backward()
            optimizer.step()

            running_loss += loss.item() * inputs.size(0)
            processed_data += inputs.size(0)

        train_loss = running_loss / processed_data
        losses.append(train_loss)
        print(log_template.format(ep=epoch+1, t_loss=loss))
    return losses
```

Выполняет предсказание с использованием модели, обученной на тестовых данных.

```python
def predict(model, x_test):
    with torch.no_grad():
        model.eval()
        outp = model(x_test)
    return outp
```

Процесс обучения, который включает 2500 эпох.

```python
losses = fit(two_layer_net, train_loader, loss_function, optimizer,
2500)


Epoch 001 train_loss: 0.2205

Epoch 002 train_loss: 0.2000

Epoch 003 train_loss: 0.1889

Epoch 004 train_loss: 0.1827

Epoch 005 train_loss: 0.1790

Epoch 006 train_loss: 0.1766

Epoch 007 train_loss: 0.1749

Epoch 008 train_loss: 0.1736

Epoch 009 train_loss: 0.1726
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Epoch 010 train_loss: 0.1718

Epoch 011 train_loss: 0.1712

Epoch 012 train_loss: 0.1706

Epoch 013 train_loss: 0.1701

Epoch 014 train_loss: 0.1696

Epoch 015 train_loss: 0.1692

Epoch 016 train_loss: 0.1688

Epoch 017 train_loss: 0.1684

Epoch 018 train_loss: 0.1680

Epoch 019 train_loss: 0.1677

Epoch 020 train_loss: 0.1674

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Epoch 022 train_loss: 0.1668

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Epoch 1109 train_loss: 0.0358
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Epoch 1114 train_loss: 0.0357
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Epoch 1120 train_loss: 0.0356
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Epoch 1122 train_loss: 0.0355
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Epoch 2500 train_loss: 0.0230
```

График функции потерь (ошибка - MSE)

```python
plt.plot(losses, color='red', label='Training Loss')
plt.legend()
plt.xlabel('Epochs')
plt.ylabel('Loss')
plt.title('Training Loss Over Epochs')
plt.show()
```

Training Loss Over Epochs

Формируется сетка точек для области [-1, 1] x [-1, 1] с использованием np.linspace, и каждая точка представляется парой координат x и y. Затем эти точки преобразуются в тензор модель используется для предсказания цветовых компонент RGB для каждой точки. Результаты предсказаний сохраняются в переменной predicted_RGB, которая изменяется в форму (200, 200, 3) для удобства последующего использования.

```python
x_test = [[x, y] for x in np.linspace(-1, 1, 200) for y in
np.linspace(-1, 1, 200)]

x_test = torch.FloatTensor(np.array(x_test))

predicted_RGB = predict(two_layer_net, x_test)
predicted_RGB = predicted_RGB.reshape((200, 200, 3))
```

Визуализация приведенных выше классов.

```python
plt.plot(x1, y1)
plt.plot(x2, y2)
plt.plot(x3, y3)

plt.grid(True, which='both')
plt.axhline(y=0, color='k')
plt.axvline(x=0, color='k')
```

```
plt.axis('equal')
plt.xlim(-2, 2)
plt.ylim(-2, 2)
plt.show()
```
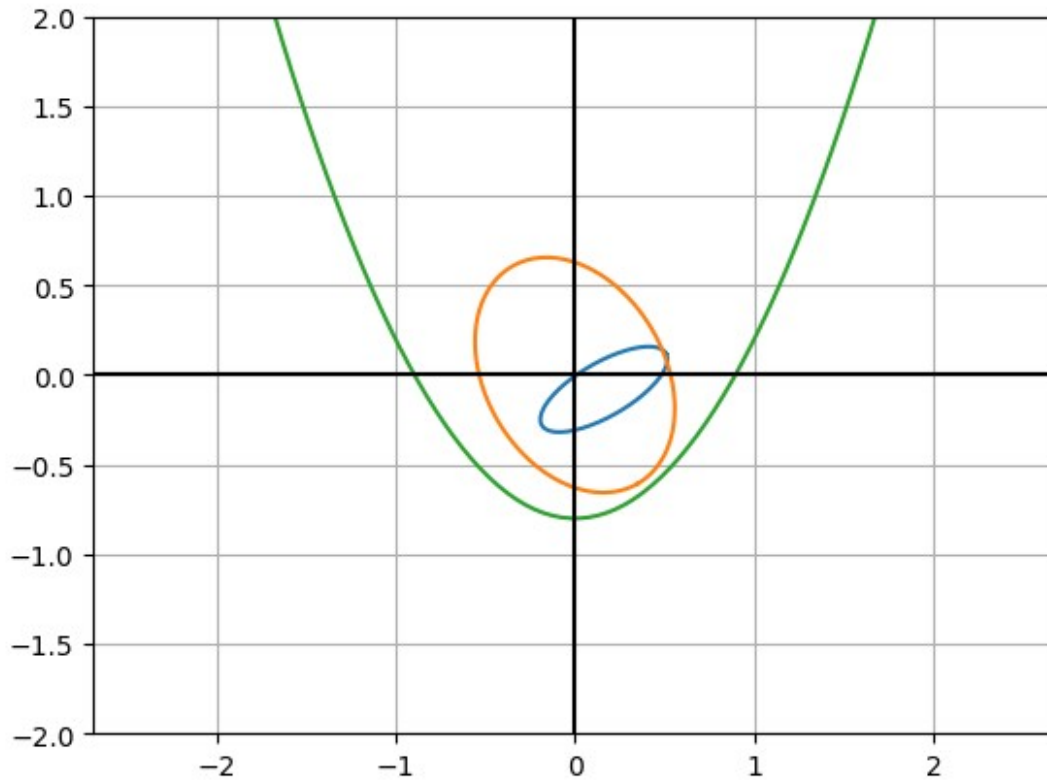

Разделение области на классы, которые линейно неразделимы

```
rotated_image = np.rot90(predicted_RGB)
flipped_image = np.fliplr(rotated_image)
plt.imshow(flipped_image)
```

```
<matplotlib.image.AxesImage at 0x1f17fd9a0b0>
```
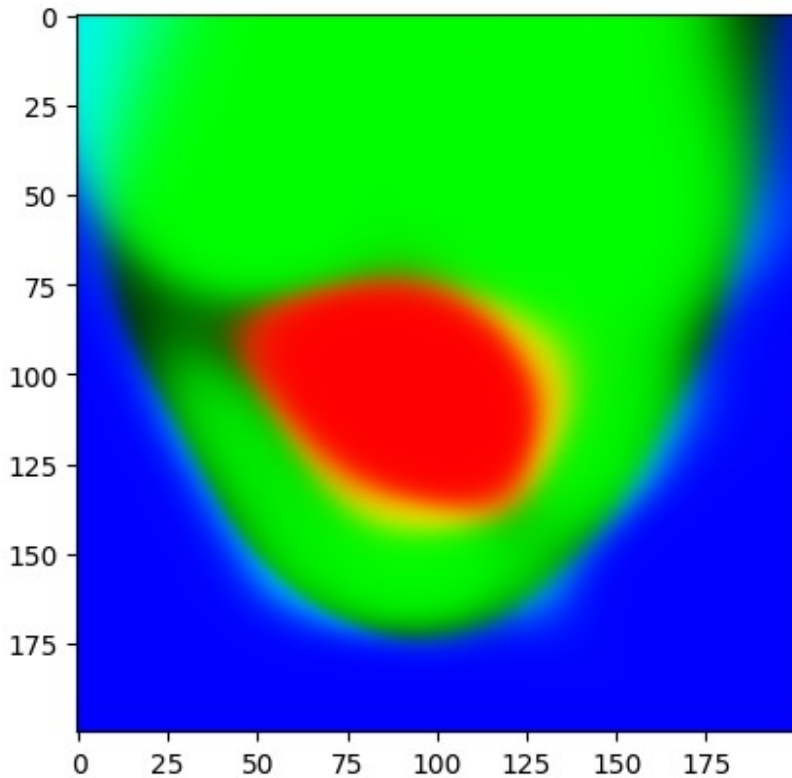
Применение многослойной нейронной сети в задачах аппроксимации функций

Функция для аппроксимации

```python
def function(t):
    return np.cos(-5 * t**2 + 10 * t - 5)
```

Создадим два набора точек - один разряженный, другой - эталонный

```python
t1 = np.linspace(0, 2.5, 150)
f1 = function(t1)

t2 = np.linspace(0, 2.5, 2000)
f2 = function(t2)
```

Преобразуем данные для обучения и тестированияв тензоры. Изменяем форму данных, чтобы соответствовать ожидаемому формату для использования в многослойной нейронной сети. Создается датасет для обучения, который будет использоваться при обучении сети.

```python
x_train2 = torch.FloatTensor(t1)
y_train2 = torch.FloatTensor(f1)
```

```
x_train2 = x_train2.view(-1, 1)
y_train2 = y_train2.view(-1, 1)
train_dataset2 = TensorDataset(x_train2, y_train2)

x_test2 = torch.FloatTensor(t2)
x_test2 = x_test2.view(-1, 1)
```

В данном классе трехслойной нейросети использование tanh в скрытых слоях предоставляет сети возможность работать со сложными, нелинейными зависимостями, что важно для успешной аппроксимации разряженной функции.

```
class TripleLayerNetwork (nn.Module):
    def __init__(self, in_features: int, hidden_layer: list,
out_features: int):
        super().__init__()
        assert len(hidden_layer) == 2
        self.fc1 = nn.Linear(in_features, hidden_layer[0])
        self.fc2 = nn.Linear(hidden_layer[0], hidden_layer[1])
        self.fc3 = nn.Linear(hidden_layer[1], out_features)

    def forward(self, x):
        x = self.fc1(x)
        x = torch.tanh(x)
        x = self.fc2(x)
        x = torch.tanh(x)
        x = self.fc3(x)
        return x
```

Экземпляр модели будет с одним входным признаком, двумя скрытыми слоями (40 и 12 нейронов соответственно) и одним выходным признаком.

```
three_layer_net = TripleLayerNetwork (1, [40, 12], 1)
loss_function = nn.MSELoss()
optimizer = torch.optim.Adam(three_layer_net.parameters())

batch_size = 10
train_loader2 = DataLoader(train_dataset2, batch_size)

losses2 = fit(three_layer_net, train_loader2, loss_function,
optimizer, 2500)


Epoch 001 train_loss: 1.0338

Epoch 002 train_loss: 0.9568

Epoch 003 train_loss: 0.8739

Epoch 004 train_loss: 0.8205
```

```
Epoch 005 train_loss: 0.7886

Epoch 006 train_loss: 0.7669

Epoch 007 train_loss: 0.7491

Epoch 008 train_loss: 0.7331

Epoch 009 train_loss: 0.7187

Epoch 010 train_loss: 0.7057

Epoch 011 train_loss: 0.6941

Epoch 012 train_loss: 0.6836

Epoch 013 train_loss: 0.6739

Epoch 014 train_loss: 0.6650

Epoch 015 train_loss: 0.6566

Epoch 016 train_loss: 0.6486

Epoch 017 train_loss: 0.6409

Epoch 018 train_loss: 0.6334

Epoch 019 train_loss: 0.6261

Epoch 020 train_loss: 0.6189

Epoch 021 train_loss: 0.6118

Epoch 022 train_loss: 0.6048

Epoch 023 train_loss: 0.5977

Epoch 024 train_loss: 0.5907

Epoch 025 train_loss: 0.5836

Epoch 026 train_loss: 0.5765

Epoch 027 train_loss: 0.5694

Epoch 028 train_loss: 0.5623

Epoch 029 train_loss: 0.5551

Epoch 030 train_loss: 0.5480
```

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Epoch 031 train_loss: 0.5408

Epoch 032 train_loss: 0.5336

Epoch 033 train_loss: 0.5264

Epoch 034 train_loss: 0.5193

Epoch 035 train_loss: 0.5121

Epoch 036 train_loss: 0.5051

Epoch 037 train_loss: 0.4980

Epoch 038 train_loss: 0.4911

Epoch 039 train_loss: 0.4842

Epoch 040 train_loss: 0.4773

Epoch 041 train_loss: 0.4706

Epoch 042 train_loss: 0.4640

Epoch 043 train_loss: 0.4575

Epoch 044 train_loss: 0.4511

Epoch 045 train_loss: 0.4448

Epoch 046 train_loss: 0.4387

Epoch 047 train_loss: 0.4326

Epoch 048 train_loss: 0.4268

Epoch 049 train_loss: 0.4210

Epoch 050 train_loss: 0.4154

Epoch 051 train_loss: 0.4099

Epoch 052 train_loss: 0.4046

Epoch 053 train_loss: 0.3994

Epoch 054 train_loss: 0.3944

Epoch 055 train_loss: 0.3895

Epoch 056 train_loss: 0.3847
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Epoch 057 train_loss: 0.3801

Epoch 058 train_loss: 0.3757

Epoch 059 train_loss: 0.3713

Epoch 060 train_loss: 0.3671

Epoch 061 train_loss: 0.3631

Epoch 062 train_loss: 0.3591

Epoch 063 train_loss: 0.3553

Epoch 064 train_loss: 0.3517

Epoch 065 train_loss: 0.3481

Epoch 066 train_loss: 0.3447

Epoch 067 train_loss: 0.3413

Epoch 068 train_loss: 0.3381

Epoch 069 train_loss: 0.3350

Epoch 070 train_loss: 0.3320

Epoch 071 train_loss: 0.3291

Epoch 072 train_loss: 0.3263

Epoch 073 train_loss: 0.3236

Epoch 074 train_loss: 0.3210

Epoch 075 train_loss: 0.3185

Epoch 076 train_loss: 0.3161

Epoch 077 train_loss: 0.3137

Epoch 078 train_loss: 0.3114

Epoch 079 train_loss: 0.3093

Epoch 080 train_loss: 0.3072

Epoch 081 train_loss: 0.3051

Epoch 082 train_loss: 0.3032
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Epoch 083 train_loss: 0.3013

Epoch 084 train_loss: 0.2995

Epoch 085 train_loss: 0.2977

Epoch 086 train_loss: 0.2960

Epoch 087 train_loss: 0.2944

Epoch 088 train_loss: 0.2929

Epoch 089 train_loss: 0.2914

Epoch 090 train_loss: 0.2899

Epoch 091 train_loss: 0.2885

Epoch 092 train_loss: 0.2872

Epoch 093 train_loss: 0.2859

Epoch 094 train_loss: 0.2846

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Epoch 096 train_loss: 0.2823

Epoch 097 train_loss: 0.2812

Epoch 098 train_loss: 0.2802

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Epoch 100 train_loss: 0.2782

Epoch 101 train_loss: 0.2772

Epoch 102 train_loss: 0.2763

Epoch 103 train_loss: 0.2755

Epoch 104 train_loss: 0.2747

Epoch 105 train_loss: 0.2739

Epoch 106 train_loss: 0.2731

Epoch 107 train_loss: 0.2724

Epoch 108 train_loss: 0.2717
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Epoch 109 train_loss: 0.2710

Epoch 110 train_loss: 0.2704

Epoch 111 train_loss: 0.2698

Epoch 112 train_loss: 0.2692

Epoch 113 train_loss: 0.2687

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Epoch 122 train_loss: 0.2647

Epoch 123 train_loss: 0.2644

Epoch 124 train_loss: 0.2641

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Epoch 758 train_loss: 0.4080
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Epoch 784 train_loss: 0.4198
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Epoch 810 train_loss: 0.4322
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Epoch 914 train_loss: 0.4815
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Epoch 992 train_loss: 0.5106
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Epoch 1018 train_loss: 0.5166
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Epoch 1105 train_loss: 0.5212

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Epoch 1116 train_loss: 0.5198

Epoch 1117 train_loss: 0.5196

Epoch 1118 train_loss: 0.5194

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Epoch 1121 train_loss: 0.5188

Epoch 1122 train_loss: 0.5186
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Epoch 1148 train_loss: 0.5104
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Epoch 1174 train_loss: 0.4987
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Epoch 1189 train_loss: 0.4903

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Epoch 1233 train_loss: 0.4600
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Epoch 1252 train_loss: 0.4432
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Epoch 1278 train_loss: 0.4165
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Epoch 1297 train_loss: 0.3948

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Epoch 1303 train_loss: 0.3881

Epoch 1304 train_loss: 0.3877
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Epoch 1355 train_loss: 0.3360

Epoch 1356 train_loss: 0.3360
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Epoch 1382 train_loss: 0.3180
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Epoch 1882 train_loss: 0.2211

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Epoch 1902 train_loss: 0.2195
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Epoch 1910 train_loss: 0.2189
Epoch 1911 train_loss: 0.2125
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Epoch 1913 train_loss: 0.2123
Epoch 1914 train_loss: 0.2186
Epoch 1915 train_loss: 0.2122
Epoch 1916 train_loss: 0.2184
Epoch 1917 train_loss: 0.2121
Epoch 1918 train_loss: 0.2183
Epoch 1919 train_loss: 0.2120
Epoch 1920 train_loss: 0.2181
Epoch 1921 train_loss: 0.2118
Epoch 1922 train_loss: 0.2180
Epoch 1923 train_loss: 0.2117
Epoch 1924 train_loss: 0.2178
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Epoch 1926 train_loss: 0.2177
Epoch 1927 train_loss: 0.2115
Epoch 1928 train_loss: 0.2176
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Epoch 1950 train_loss: 0.2161

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Epoch 1953 train_loss: 0.2100

Epoch 1954 train_loss: 0.2158
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Epoch 2481 train_loss: 0.1966

Epoch 2482 train_loss: 0.1997

Epoch 2483 train_loss: 0.1966

Epoch 2484 train_loss: 0.1996

Epoch 2485 train_loss: 0.1966

Epoch 2486 train_loss: 0.1996

Epoch 2487 train_loss: 0.1965

Epoch 2488 train_loss: 0.1996

Epoch 2489 train_loss: 0.1965

Epoch 2490 train_loss: 0.1995

Epoch 2491 train_loss: 0.1965

Epoch 2492 train_loss: 0.1995

Epoch 2493 train_loss: 0.1964

Epoch 2494 train_loss: 0.1994

Epoch 2495 train_loss: 0.1964

Epoch 2496 train_loss: 0.1994

Epoch 2497 train_loss: 0.1964

Epoch 2498 train_loss: 0.1994

Epoch 2499 train_loss: 0.1964

Epoch 2500 train_loss: 0.1993
```

График функции потерь (ошибка - MSE)

```python
plt.plot(losses2, color='red', label='Training Loss')
plt.legend()
plt.xlabel('Epochs')
plt.ylabel('Loss')
plt.title('Training Loss Over Epochs')
plt.show()
```
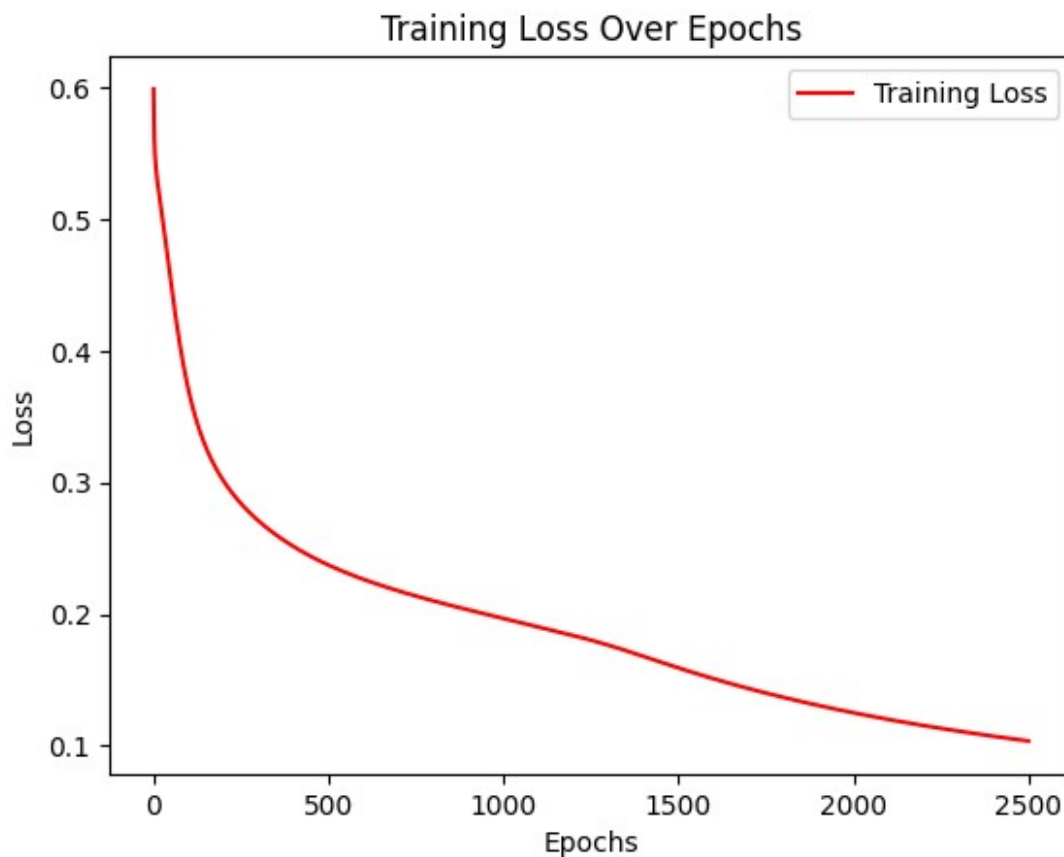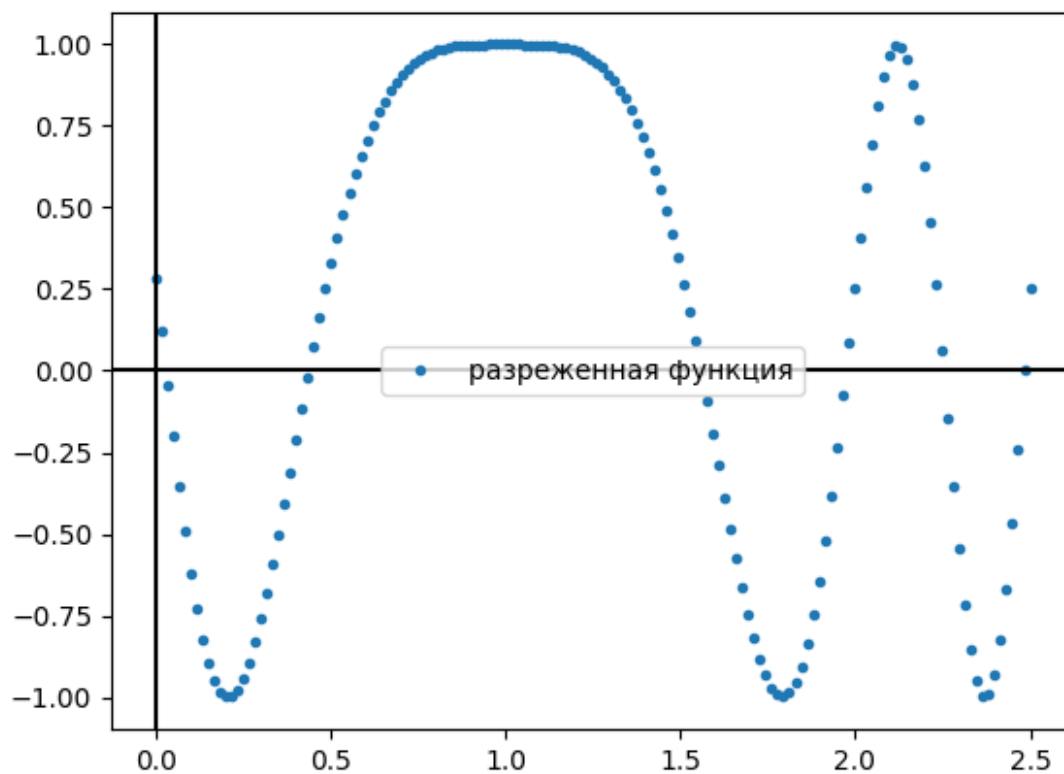

Получение предсказанных значений для тестового набора данных

```python
f2_pred = predict(three_layer_net, x_test2)
```

Сравнение разреженного варианта, приближения и истинной функции

```python
plt.plot(t1, f1, '.', label='разреженная функция')

plt.axhline(y=0, color='k')
plt.axvline(x=0, color='k')

plt.legend()
plt.show()
```
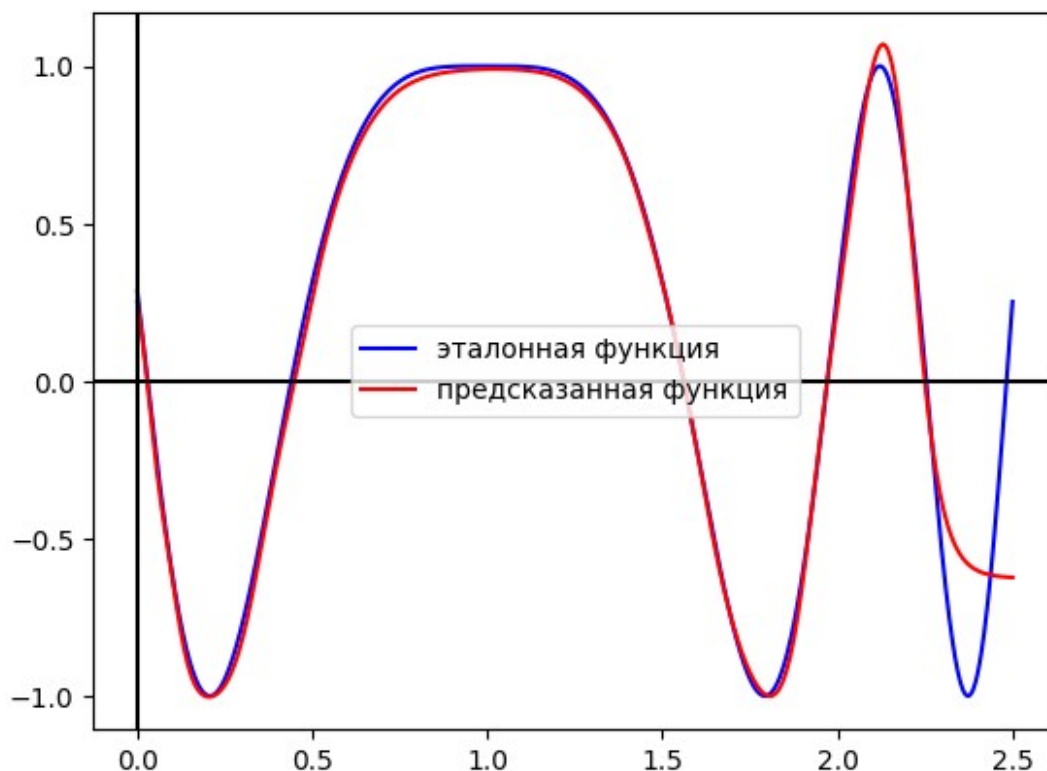
```python
plt.plot(t2, f2, color="blue", label='эталонная функция')
plt.plot(t2, f2_pred, color="red", label='предсказанная функция')

plt.axhline(y=0, color='k')
plt.axvline(x=0, color='k')

plt.legend()
plt.show()
```

Выводы: В ходе выполнения лабораторной работы были разработаны и обучены две многослойные нейронные сети с использованием алгоритма обратного распространения ошибки. Первая сеть применялась в задаче классификации для разделения линейно неразделимых данных, вторая же использовалась для аппроксимации функции.

Обе сети продемонстрировали хорошие результаты после обучения, хотя требовалось до 2500 эпох для достижения стабильных результатов. Важно отметить, что многослойные нейронные сети обладают способностью изучать сложные зависимости в данных, что делает их мощным инструментом для разнообразных задач машинного обучения.