

Things to include in the report

1. Create SGD regression

Test for different learning rates, mini batches, epochs, adaptive learning rate?

Compare with OLS and Ridge on Franke function

For ridge study results as function of the hyper-parameters  $\lambda$  and learning rate (heat map)

2. Create NN

Discuss initializing weights and biases, cost functions, activation functions and all that stuff. What to do on the output layer regarding activation function.

Compare NN regression on Franke function vs. OLS and Ridge ( $\lambda$  and  $\eta$  heat map)

Compare to SKLearn/Tensorflow

3. Try out different activation functions (Sigmoid, Relu and Leaky relu)

4. Classification (costfunction = logistic)

Test logic gates classification

Breast cancer data: Important to scale here. Discuss also methods/whether to reduce dimensions. Measure performance with accuracy. Again: optimize for hyper-parameters and various activation functions perhaps.

5. Write logistic regression code using SGD

Compare NN to logistic regression on MNIST data

6. Summarize everything

# Classification and Regression, from linear and logistic regression to neural networks

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(Dated: November 11, 2021)

'Twas a beautiful morning, the sun was shining and the birds were humming. Nothing short of a great start on the day. With work starting in only 2 hours, I ran to the kitchen to assure a sufficient and delicious breakfast before the 8 hour shift of hard labor. As my mother used to say, a great breakfast makes a great man, and I lived for that sentence every day.

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## I. INTRODUCTION

The use of Neural Networks have exploded in academia the last 10 years, and continue to impress with its capabilities in complex problem solving. DeepMind made its AlphaGo, which beat the reigning champion 4/5 games, facial recognition in China is so good now that it works as ID on the subway, and cars can now drive themselves on the road with higher than 99% success rate [3].

Neural Networks and regression have somewhat overlapping area of use, especially in with regards to classification and regression. In fact, logistic regression and a Neural Network with no hidden layers are practically the same thing. Neural Networks can however scale much better in dimensionality, such that it can solve complex problems such as quantum many body problems, image recognition and complex differential equations.

## II. THEORY

### A. Gradient descent

The essence of Machine learning is in a sense, just a cost minimization problem with respect to some parameters. For machine learning these parameters are the weights and the biases, but for now we just consider a general parameter  $\theta = \{\theta_1, \theta_2, \dots, \theta_n\}$  for  $n$  dimensions. The goal is to choose  $\theta$  such that we minimize a given cost function  $C(\theta)$  from a set of data points in the design matrix  $\mathbf{X}$  and corresponding target values  $\mathbf{t}$ . One common approach to such a problem is the Ordinary Least Squares method (OLS) for which we find the optimal  $\theta_{opt}$  that minimize the cost function as

$$\theta = (\mathbf{X}^T \mathbf{X})^{-1} \mathbf{X}^T \mathbf{t}$$

This is the main workhorse behind many regression problems, but as the number of data points increases the matrix inversion becomes computationally expensive. Furthermore, the matrix product  $\mathbf{X}^T \mathbf{X}$  might be singular and thus the above approach needs additional computations to work out. The concept of gradient descent provides a computationally efficient alternative to this problem.

#### 1. Regular Gradient descent

For a given cost function  $C(\theta)$  we can approach the minimum by calculating the gradient  $\nabla_{\theta} C$  with respect to the unknown parameters  $\theta$ . When evaluating the gradient in a specific point  $\theta_i$  in the parameter space, the negative of the gradient will correspond to the direction for which a small change  $d\theta$  in the parameter space will

result in the biggest decrease in the cost function. By choosing a step size  $\eta$ , better known as the learning rate, we can iterate forward in the parameter space as

$$\theta_{i+1} = \theta_i - \eta \nabla_{\theta} C(\theta_i). \quad (1)$$

In order to get convergence towards a minimum we must choose the learning rate  $\eta$  to be sufficiently small such that it does not "step over" the minimum point. The usual approach to choosing  $\eta$  is simply to define it as a hyperparameter and run the gradient descent scheme for different  $\eta$ 's and choose the one that yields the best result.

For some simpler cases, where we are able to calculate the so-called Hessian matrix, we can compute an approximation for the optimal learning rate. For a convex problem the gradient is only equal to zero at the global minimum for which the optimal parameter must satisfy.

$$g(\theta) = \nabla_{\theta} C(\theta) = 0.$$

By using Newton-Raphson's method we can iterate towards the root for the gradient by following the tangent line (1. order approximation) as

$$\theta_{i+1} = \theta_i - \frac{g(\theta_i)}{g'(\theta_i)},$$

where

$$g'(\theta_i) = \frac{\partial g(\theta_i)}{\partial \theta_i} = \nabla_{\theta}^2 C(\theta_i) = \mathbf{H}$$

The final iteration scheme reads

$$\theta_{i+1} = \theta_i - \mathbf{H}^{-1} \nabla_{\theta} C(\theta_i)$$

which resemble equation 1 with  $\eta = \mathbf{H}^{-1}$ . Thus the best learning parameter for a first order approximation is found as the inverse of the hessian. Notice that this is only applicable in cases where the cost function is twice differentiable and where we can compute the inverse of the Hessian. However, for a convex problem the hessian is symmetric and positive definite for convex problems for which the matrix is always invertible.

source for the other stuff: (<http://www.cs.cornell.edu/courses/cs4780/2015fa/web/lecturenotes/lecturenote07.html>).

#### 2. Stochastic gradient descent

A variation of the regular gradient descent is the Stochastic gradient Descent (SGD) for which we introduce the concept of mini batches. For each step we divide the data into randomly into mini batches of size  $m$ . For each batch  $j$  we compute the gradient and the contribution for the updated parameter  $\theta_{i+1}^j$  using to equation

1. Conventionally one would then sum up all such contributions and update the final parameter as the mean value

$$\theta_{i+1} = \sum_j \theta_{i+1}^j,$$

but in our implementation we are going to simply update  $\theta$  for each batch as it yields practically identical results for a slight memory storage benefit.

The main benefit of using SGD is that the computation of the gradient can become computational expensive when dealing with increasing data. Since the gradient calculation involves a number of matrix operations it becomes computational beneficial to perform more gradient calculations of the reduced mini batches rather than one for the whole data set at once.

## B. Neural Networks

We define a general neural network having a total of  $L$  layers and  $n_l$  nodes on the  $l$ th layer. The first layer  $l = 1$  is the input layer for which the number of nodes should match the number of features in the training data. The output layer  $l = L$  gives us the prediction values  $y$  which ideally should fit the target values  $t$ . Thus we should have the same number of nodes as there are categories in the target data. For instance, in the case of a binary classification we only have one category which we can be either true or false given as 1 or 0. In between the input and output layer we have  $L - 2$  hidden layers.

### 1. Feeding Forward

We assume a dense neural network meaning that each node in a hidden layer  $l$  is connected to each and every node in layer  $l - 1$  and layer  $l + 1$ . The strength of the connection is managed with the so-called weights  $w$  and biases  $b$ , which should be tweaked such that the network performance well on a certain type of prediction task. In addition we introduce an activation function which maps the input from a previous layer to a certain domain. Originally it was most common to use the Sigmoid function which maps into the range  $[0, 1]$  which intuitively corresponds to an activation level between completely on (1) and completely off (0). The input layer takes values from a given data set, such that each feature is assigned to a specific node. When having a design matrix  $X \in \mathbb{R}^{N \times n_1}$ , with  $N$  data points and  $n_1$  features, this corresponds to assigning each columns of  $X$  to a input node. The information is then feed forward throughout the densely connected layers to produce a final output  $y$ . The feed forward mechanism is defined such that the (activation) value of all the nodes from the previous layer  $a^{l-1}$  is summed up to  $z$  using predefined

weights  $w$  and a bias  $b$  as

$$z_j^l = \sum_{i=1}^{n_{l-1}} w_{ij}^l a_i^{l-1} + b_j^l.$$

where  $z_j^l$  is the input value to node  $j$  in layer  $l$ ,  $w_{ij}^l$  is the weight connecting node  $i$  in layer  $l - 1$  to node  $j$  in layer  $l$ ,  $a_i^{l-1}$  is the activation value from node  $i$  in layer  $l - 1$  and  $b_j^l$  is the bias associated with node  $j$  in layer  $l$ . By defining

$$W^l = \begin{bmatrix} w_{11}^l & w_{21}^l & \dots & w_{n_{l-1}1}^l \\ w_{12}^l & w_{22}^l & \dots & w_{n_{l-1}2}^l \\ \vdots & \vdots & & \vdots \\ w_{1n_l}^l & w_{2n_l}^l & \dots & w_{n_{l-1}n_l}^l \end{bmatrix},$$

$$(W^l)^T = \begin{bmatrix} w_{11}^l & w_{21}^l & \dots & w_{n_{l-1}1}^l \\ w_{12}^l & w_{22}^l & \dots & w_{n_{l-1}2}^l \\ \vdots & \vdots & & \vdots \\ w_{1n_l}^l & w_{2n_l}^l & \dots & w_{n_{l-1}n_l}^l \end{bmatrix},$$

$$A^l = \begin{bmatrix} a_1^l \\ a_2^l \\ \vdots \\ a_{n_l}^l \end{bmatrix}, \quad B^l = \begin{bmatrix} b_1^l \\ b_2^l \\ \vdots \\ b_{n_l}^l \end{bmatrix}, \quad Z^l = \begin{bmatrix} z_1^l \\ z_2^l \\ \vdots \\ z_{n_l}^l \end{bmatrix}.$$

We get

$$Z^l = (W^l)^T A^{l-1} + B^l.$$

This is then feed through the activation function to produce the activation value  $a_j^l$  for node  $j$  in layer  $l$  as

$$a_j^l = \sigma(z_j^l), \quad A^l = \sigma(Z^l)$$

By following this approach we can feed forward into the layer and produce an output value  $y$  (see figure 1)

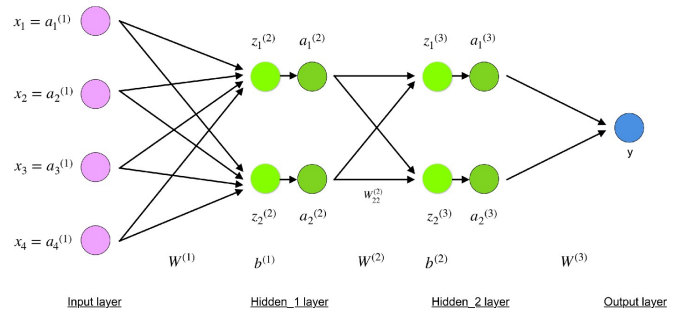


Figure 1: Illustration of simple 4-layer neural network. Source: [towardsdatascience.com](https://towardsdatascience.com).

for the We can initialize the network by choosing random values for the weights and biases in a reasonable range, but in order to arrive at a set of values for which the output value approximates a given set of target values  $t$  we need to train the network.

## 2. Back Propagation

We now assume to have a neural network with initialized weights and biases. When training the network we present it to some training data with  $N$  input points in the design matrix  $X$  and  $N$  corresponding target values  $t$ . We define a cost function  $C(y)$  which will evaluate how close the NN-prediction  $y$  comes to the target values  $t$ . A common choice is the mean squared error as

$$C(y) = (y - t)^2,$$

but one can choose from a wide selection of cost functions, so we keep this general.

When training the network we feed all the training data through the network, and then we want to calculate the gradient  $C$  with respect to all the weights and biases. That is

..

such that we can update towards finding a minimum for  $C$ . When having this gradient we can simply follow the steps from the gradient or stochastic gradient descent method. The goal is to compute  $\partial C / \partial w_{ik}^l$  and  $\partial C / \partial b_j^l$ . For the weight  $w_{ij}^l$  connection the  $i$ th node in layer  $l-1$  to the  $j$ th node in layer  $l$  we can use the chain rule... We begin by looking at the last layer  $l = L$ .

$$\frac{\partial C}{\partial w_{ij}^L} = \frac{\partial C}{\partial a_j^L} \frac{\partial a_j^L}{\partial z_j^L} \frac{\partial z_j^L}{\partial w_{ij}^L}.$$

We remember that

$$a_j^L = \sigma(z_j^L), \quad z_j^L = \sum_{i=1}^{n_{L-1}} w_{ij}^L a_i^{L-1} + b_j^L,$$

such that we get

$$\frac{\partial C}{\partial w_{ij}^L} = \frac{\partial C}{\partial a_j^L} \sigma'(z_j^L) a_i^{L-1},$$

Notice that the remaining derivatives can easily be calculated when deciding on a choice for the cost and activation function. For the bias we simply get

$$\frac{\partial C}{\partial b_j^L} = \frac{\partial C}{\partial a_j^L} \frac{\partial a_j^L}{\partial z_j^L} \frac{\partial z_j^L}{\partial b_j^L} = \frac{\partial C}{\partial a_j^L} \sigma'(z_j^L) \cdot 1$$

We use this to motivate the definition of the local gradient

$$\delta_j^l \equiv \frac{\partial C}{\partial z_j^l},$$

such that

$$\delta_j^L = \frac{\partial C}{\partial z_j^L} = \frac{\partial C}{\partial a_j^L} \frac{\partial a_j^L}{\partial z_j^L} = \frac{\partial C}{\partial a_j^L} \sigma'(z_j^L).$$

This yields the more compact expressions

$$\frac{\partial C}{\partial w_{ij}^L} = \delta_j^L a_i^{L-1} \quad \frac{\partial C}{\partial b_j^L} = \delta_j^L$$

$\delta_j^l$  is also commonly called the "error" since it says something about how big an influence the  $j^{\text{th}}$  node in layer  $l$  influence the cost function. We let  $\delta^l$  denote the vector containing all the local gradients associated with layer  $l$  and we can write it in matrix form as

$$\delta^L = \nabla_a C \odot \frac{\partial \sigma}{\partial z^L}, \quad \nabla_a C = \left[ \frac{\partial C}{\partial a_1^L}, \frac{\partial C}{\partial a_2^L}, \dots, \frac{\partial C}{\partial a_{n_L}^L} \right]^T$$

We can define the local gradient  $\delta_j^l$  for the  $j^{\text{th}}$  node on a general layer  $l$  in terms of  $\delta_k^{l+1}$  for the  $k^{\text{th}}$  node on the next layer  $l+1$  by using the chain rule

$$\begin{aligned} \delta_j^l &\equiv \frac{\partial C}{\partial z_j^l} \\ &= \sum_k \frac{\partial C}{\partial z_k^{l+1}} \frac{\partial z_k^{l+1}}{\partial z_j^l} \\ &= \sum_k \frac{\partial z_k^{l+1}}{\partial z_j^l} \delta_k^{l+1} \end{aligned}$$

We remember

$$z_k^{l+1} = \sum_{j=1}^{n_l} w_{jk}^{l+1} a_j^l + b_k^{l+1} = \sum_{j=1}^{n_l} w_{jk}^{l+1} \sigma(z_j^l) + b_k^{l+1}$$

Differentiating, we obtain

$$\frac{\partial z_k^{l+1}}{\partial z_j^l} = w_{jk}^{l+1} \sigma'(z_j^l),$$

And by substituting back we find

$$\delta_j^l = \sum_k \delta_k^{l+1} w_{jk}^{l+1} \sigma'(z_j^l)$$

The back propagation algorithm then becomes

- Compute

$$\delta_j^L = \frac{\partial C}{\partial a_j^L} \sigma'(z_j^L).$$

- for  $l = L - 1, L - 2, \dots, 1$  compute:

$$\delta_j^l = \sum_k \delta_k^{l+1} w_{jk}^{l+1} \sigma'(z_j^l)$$

Finally we update weights and biases:

$$\begin{aligned} w_{jk}^l &\leftarrow w_{jk}^l - \eta \delta_j^l a_i^{l-1} \\ b_j^l &\leftarrow b_j^l - \eta \delta_j^l \end{aligned}$$

There is a risk associated with updating the weights as shown above, as there is no control for exploding weights from exploding gradients. One way to avoid this, is to introduce a regularization parameter,  $\lambda$ , which scales the weights. The weights are thus updated in the following way:

$$\begin{aligned} w_{jk}^l &\leftarrow w_{jk}^l - \eta (\delta_j^l a_i^{l-1} + \lambda w_{jk}^l) \\ b_j^l &\leftarrow b_j^l - \eta \delta_j^l, \end{aligned}$$

which is appropriate when using Regular stochastic gradient descent. From [II A 2](#) we split the data into batches, thus when using Stochastic gradient descent, we have to divide the weights correction with the batch size:

$$\begin{aligned} w_{jk}^l &\leftarrow w_{jk}^l - \frac{\eta}{b_{size}} (\delta_j^l a_i^{l-1} + \lambda w_{jk}^l) \\ b_j^l &\leftarrow b_j^l - \eta \delta_j^l. \end{aligned}$$

Work in progress: I will distribute the text into appropriate sections above after writing down my string of thoughts in the following.  
Some notation to use:

- $y$ : Output, the prediction / values on last nodes of our network
- $t$ : target, the values that we try to match the output values  $y$  to
- $C$ : Cost function, evaluates how well the output  $y$  fits the target  $t$
- $W$  Weights
- $B$ : Bias
- $\sigma$ : Activation function, fx the sigmoid
- $a$ : activation output
- $z$ : the value going into the activation function  $\sigma$  to produce the activation output  $a$
- $L$ : Number of layers in total (with  $L - 2$  hidden layers).
- $n_l$ : number of nodes in a given layer  $l$

We define our general NN to have  $L$  layers in total for which the first layer is the input layer and the last layer is the output layer. This means that we have  $L - 2$  so-called hidden layers. The input layer must have the same numbers of nodes as there are features in the training data and the last layer must have the same number of nodes as there are categories associated with the target values. For instance in the a case of binary classification, meaning true or false, 1 or 0, etc. we could simple have one output node which can take value in the range  $[0,1]$  and thus be rounded of to either 0 or 1 for the prediction. In another case of the MNIST data set where we want to classify handwritten number between 0 and 9, we would instead chose to have 10 output nodes, one for each possible number  $\{0,1,2,3,4,5,6,7,8,9\}$ .

$$Z^L = W^L a^{L-1} + B^L$$

$$a^L = \sigma(Z^L)$$

Lets assume that we simple have on node in each layer. We choose the cost function to be the mean squared error

$$C = (y - t)^2$$

We should choose the weights and bias such that  $C$  is minimized. How do we do this? The idea is the find the gradient, for which changing the weights and biases in a small step in the direction of the negative gradient, we will lower  $C$ . The gradient with respect to its weights is ...

### C. Logistic regression (not sure where to put it)

Logistic function definition

$$p(t) = \frac{1}{1 + e^{-t}} = \frac{e^t}{1 + e^t}$$

We look at the binary case where  $y_i = 0$  or  $y_i = 1$ . We define polynomial model on order  $n$  as

$$\hat{y}_i = \beta_0 + \beta_1 x_i + \beta_2 x_i^2, \dots, \beta_n x_i^n$$

We define the probabilities of getting  $y_i = 0 \vee 1$  given a input point  $x_i$  and beta values  $\beta = (\beta_0, \beta_1, \dots, \beta_n)$

$$p(y_i = 1 | x_i, \beta) = \frac{e^{\hat{y}_i}}{1 + e^{\hat{y}_i}}$$

$$p(y_i = 0 | x_i, \beta) = 1 - p(y_i = 1 | x_i, \beta)$$

We want to choose the parameters  $\beta$  such that we maximum the likelihood of saying the observed data  $\mathcal{D} \in \{x_i, y_i\}$ , that is the Maximum Likelihood Principle (MLE) principle. The likelihood of having the observed data  $\mathcal{D}$  given  $\beta$

$$P(\mathcal{D} | \beta) = \prod_{i=1}^n \left( p(y_i = 1 | x_i, \beta) \right)^{y_i} \left( 1 - p(y_i = 1 | x_i, \beta) \right)^{1-y_i}$$

In order to minimize computations we can define the log-likelihood as

$$\log(P(\mathcal{D} | \beta)) = \sum_{i=1}^n y_i \log \left( p(y_i = 1 | x_i, \beta) \right) + (1 - y_i) \log \left( 1 - p(y_i = 1 | x_i, \beta) \right),$$

and in order to get the cost function on the more conventional form os minimization problem we define the cost function as the negative log-loikelihood:

$$C(\beta) = -\log P(\mathcal{D} | \beta).$$

We find the gradients

$$\frac{\partial C(\beta)}{\partial \beta} = - \sum_{i=1}^n \begin{pmatrix} y_i - p(\hat{y}_i) \\ x_i y_i - x_i p(\hat{y}_i) \\ \vdots \\ x_i^n y_i - x_i^n p(\hat{y}_i) \end{pmatrix} = -X^T (\mathbf{y} - P(X\beta))$$

For the L2 regularization we add the L2-norm to the costfunction as

$$C(\beta) = -\log P(\mathcal{D} | \beta) + \lambda \|\beta\|_2^2, \quad \lambda > 0$$

where

$$\lambda \|\beta\|_2^2 = \lambda \sum_{i=1}^n \beta_i^2 \implies \frac{\partial \lambda \|\beta\|_2^2}{\partial \beta} = 2\lambda \beta$$

This gives the full gradient expression with L2 regularization as

$$\frac{\partial C(\beta)}{\partial \beta} = -X^T (\mathbf{y} - P(X\beta)) + 2\lambda \beta$$

### III. IMPLEMENTATION

The code can be found on this [Github address](#).

#### A. Data sets

##### 1. Franke's function

In the rapport we will be doing both regression and classification analysis. For the regression we will be using Franke's function. The Franke's function,  $f(x,y)$ , is an analytical function often used in machine learning. The function is a weighted sum of four exponentials which we will study in the domain  $x, y \in [0,1]$ . The function reads as follows

$$\begin{aligned} f(x,y) = & \frac{3}{4} \exp \left( -\frac{(9x-2)^2}{4} - \frac{(9y-2)^2}{4} \right) \\ & + \frac{3}{4} \exp \left( -\frac{(9x+1)^2}{49} - \frac{(9y+1)}{10} \right) \\ & + \frac{1}{2} \exp \left( -\frac{(9x-7)^2}{4} - \frac{(9y-3)^2}{4} \right) \\ & - \frac{1}{5} \exp \left( -(9x-4)^2 - (9y-7)^2 \right). \end{aligned} \quad (2)$$

For more on the Franke's function, see [2].

##### 2. Breast cancer

For classification we will first be using scikit learns breast cancer data. The data is structured such that each point of the input variables are different attributes (30 in total) of a tumor and the output data is a binary, malignant or benign. Given the number of attributes and the binary nature of the data, the network must contain 30 features and 1 category. The data set includes, in total 569 datapoints.

##### 3. MNIST

The MNIST data set contains 1797 images of handwritten number between 0-9. Each image has a resolution of  $8 \times 8$  pixels. An example of the data is shown in figure 2.

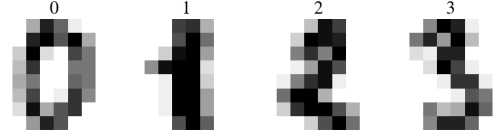


Figure 2: A set of four datapoints from scikit learns breast cancer data. Each point with the corresponding value written above.

The MNIST output data, or target is original structured as a list with 1797 elements, where each element is a number between 0-9. This means that the Network still would have 9 categories. As we want the output to be a binary classification case, we restructure the data such that each number is replaced with a 10 dim array. Each array is filled with binary values, where the index equal to the original number is set to 1. For example:

$$\begin{aligned} 3 \rightarrow & \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} & 7 \rightarrow & \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1 \\ 0 \\ 0 \\ 0 \end{bmatrix} & \text{or } 5 \rightarrow & \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \end{aligned} \quad (3)$$

#### B. Custom functions

Say something about our method for decreasing eta.

### IV. RESULTS AND DISCUSSION

#### A. Validation

##### 1. SGD

Note: Say that we choose same seed for repeated experiments for a fair comparison...

We begin by validating and testing the implementation of our SGD method. For this we use Franke's function, which we analyzed in project 1 (REFERENCE). We use a default  $100 \times 100$  meshgrid ( $10^4$  data points), a complexity of  $n = 5$ , referring to the highest polynomial order, and add normal distributed noise to the output with standard deviation  $\sigma = 0.2$ . When



comparing train and test results we use a default split of 80% training data and 20% test data.

First, we take on analyzing non-momentum OLS-gradient SGD. We investigate the convergence of the model as a function of epochs regarding the hyperparameters: Batch size  $m$  and learning rate  $\eta$ . We do this by keeping one parameter constant and changing the other respectively. For this we use the whole data set, and thus the MSE is for the training data. The result for varying batch size and fixed learning rate is shown in figure 3 and the results for varying learning rate and constant batch size is shown in figure 4

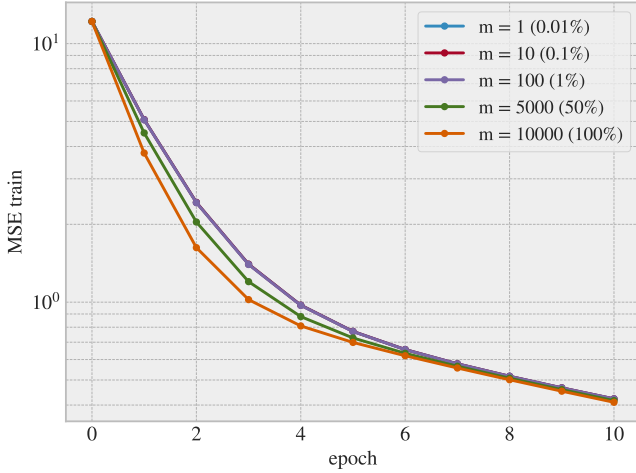


Figure 3: MSE on train data for SGD regression on Franke's function (default settings) with fixed learning rate  $\eta = 0.1$  and varying batch size  $m$ . The percentage denotes the batch size relative to the number total number of data points.

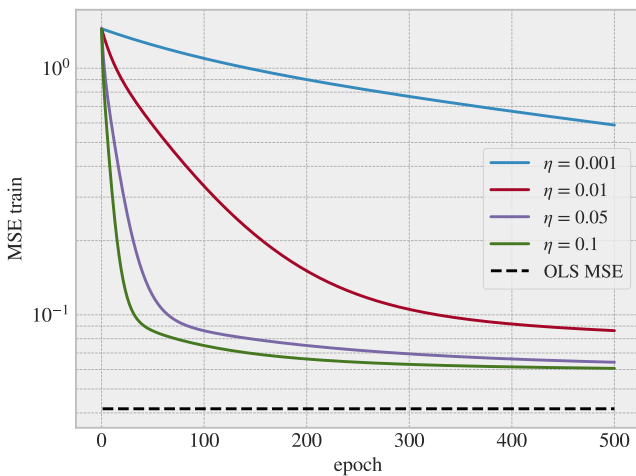


Figure 4: MSE on train data for SGD regression on Franke's function (default settings) with full gradient descent ( $m = 10^4$ ) and varying learning rate  $\eta$ . The black-dotted line indicates the MSE for OLS regression.

From figure 3 we see that the convergence rate is only slightly affected by the batch size, with a small benefit of having the biggest batch size. But the difference becomes negligible already at the 10<sup>th</sup> epoch onwards. However, from figure 4 we see that the learning rate has a much more distinct impact on the convergence rate. To get a better understanding of the influence from the learning rate we compute the final MSE after  $10^3$  epochs for both training and test data (default split: 0.2) as a function of the learning rate with full gradient descent (see figure 5).

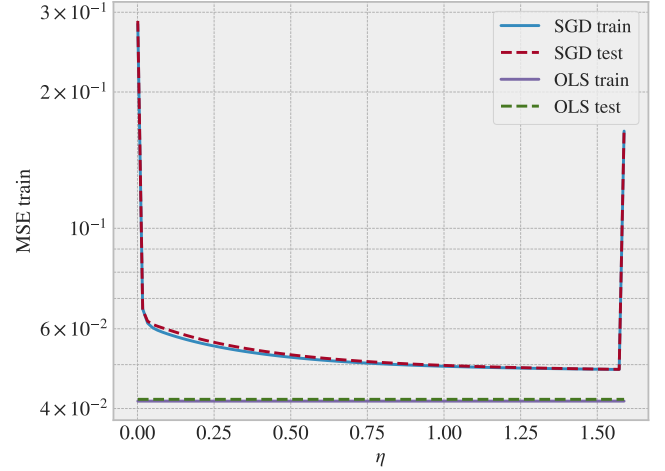


Figure 5: MSE on train and test data for SGD regression on Franke's function (default settings) with full gradient descent ( $m = 10^4$ ) for  $10^3$  epochs as a function of learning rate  $\eta$ . This is compared to OLS regression for train and test data seen in the bottom of the plot.

From figure 5 we see that the best performance from the SGD is found with a quite high learning rate. We compute the minimum to be

$$\arg \min_{\eta} (\text{MSE test}) = 1.57 \pm 0.02$$

With a resolution of 0.02 in the learning rates, the minimum point occurs on the second last index of the tested learning rates, while the last index correspond to the peak on the right-hand side of the plot. Thus we see an apparently non-continuous behaviour (considering our resolution) where the best learning rate comes just before a critical limit where the learning rate will yield poor convergence. However, when running similar test on other data sets we see that this limit changes quite a lot, and thus one should be careful of using a too high learning rate. For the following results we use  $\eta = 0.1$  as a safe bet.

We now compare OLS and SGD for different model complexities. Notice that we used  $n = 5$  up to this point but now we take on a smaller data set of  $20 \times 20$  (400 data points) and  $n = [1, 20]$ . For SGD we use full gradi-

ent descent and  $10^4$  epochs. We continue to use a split of 0.2 and noise  $\sigma = 0.2$ . The results are shown in figure 6

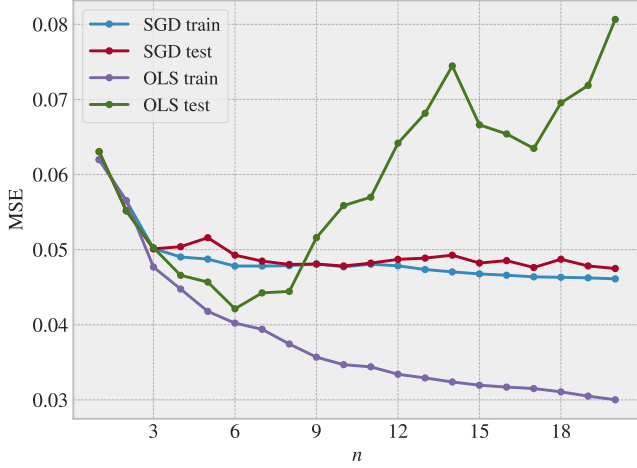


Figure 6: Comparison of SGD and OLS on Franke's function for varying model complexity  $n$ . SGD uses full gradient descent with  $10^4$  epochs and learning rate  $\eta = 0.1$ . The data consists of 400 data points.

As expected from earlier results, we see that OLS outperforms SGD on the low model complexity which we have already seen for  $n = 5$  in figure 5. However, as the model complexity increases the OLS regression results in overfitting and thus the test MSE increases considerable. SGD does not really prone to overfitting in this particular case, and we see that the MSE is steady, actually slightly decreasing, for increasing model complexity.

Until now we have mostly been using full gradient descent as we saw (from figure 3) that this gives a slightly better convergence on a short scale of epochs. When introducing the Neural Network we expect to deal with far bigger gradients (for weights and biases) which will result in heavier matrix operations. For smaller batch sizes we reduce the size of these matrix operations with a cost of having to run through a for-loop for more iterations. In order to get an idea of this computational balance of for-loop iteration and matrix operations we time the algorithm for increasing sizes of the design matrix. We fix  $n = 10$ , resulting in 66 features and increase the size of the meshgrid from  $100 \times 100$  ( $10^4$  data points) to  $1000 \times 1000$  ( $10^6$  data points) while measuring the time pr. epoch. averaged over 10 epochs. We use  $\eta = 0.1$  and initialize from same random seed each time. The results are shown in figure 7

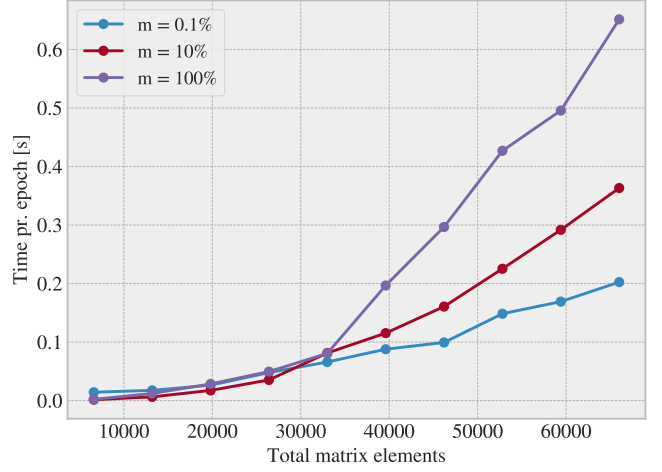


Figure 7: Timing of SGD as a function of the total number of elements in the design matrix for different batch size (given as a percentage of the total number of data points). While keeping  $n = 10$ , corresponding to 66 features, we varied number of data points in the interval  $N \in N = [10^4, 10^6]$  and measured the computation time pr. epoch. We ran each SGD-regression for 10 epochs starting from the same random seed. We see that small mini batches gets computational beneficial for big matrices.

From figure 7 we see that for big matrix sizes, the smallest batch size yields the lowest computation time. For smaller matrices, the small batches actually gives a slightly longer computation time, and the intersection between these domains is visually determined to be around 30,000 matrix elements.

We also want to compare Ridge regression and SGD with Ridge gradient computation. In order to do this we begin by studying the optimal hyperparameters for SGD with Ridge gradient. When fixing the batch size to full gradient descent we are left with learning rate  $\eta$  and the regularization parameter  $\lambda$  as the main hyperparameters. We go back to using the default data set, as stated in the beginning of this section, and compute the MSE on the test data for different combinations of  $\eta$  and  $\lambda$ . The result is shown in figure 8

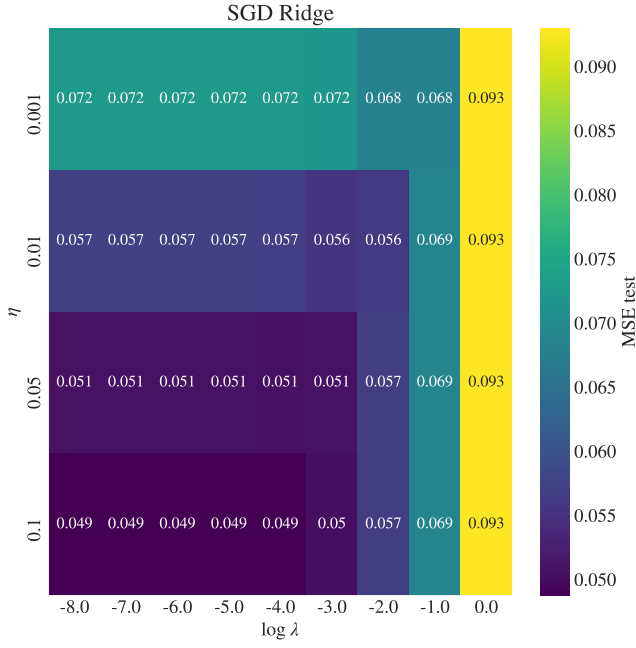


Figure 8: MSE test for SGD with Ridge gradient for different combinations of learning rates  $\eta$  and Ridge regularization parameter  $\lambda$  on Franke's function. We use the default data set with full gradient descent.

From figure 8 we see that the best MSE test is found at the highest tested learning rate  $\eta = 0.1$  and the lowest regularization values  $\lambda \leq 10^{-4}$ . Looking back to figure 5 one could theorize that we have a similar dependence on the learning rate as we had with the OLS gradient.

This we fix the learning rate to  $\eta = 0.1$  and compute the MSE on test date (default data) for different  $\lambda$ -values using  $10^4$  epochs for the SGD. The result is shown in figure 9.

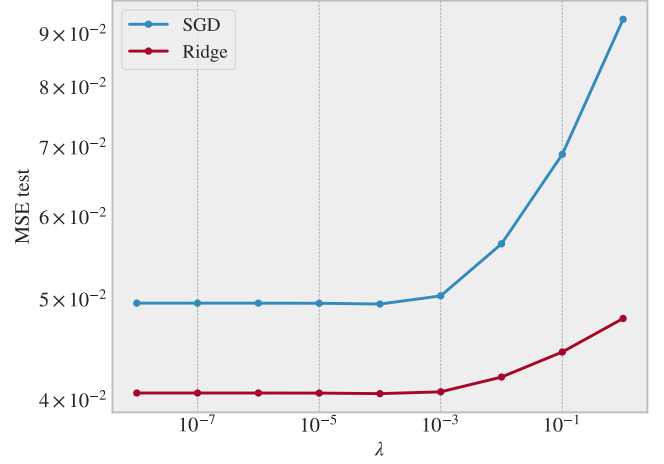


Figure 9: MSE test for SGD (Ridge gradient) and Ridge regression as a function of  $\lambda$  on Franke's function. We used  $10^4$  epochs and  $\eta = 0.1$  with full gradient descent on the default data set.

From figure 9 we see that the lowest MSE is achieved for decreasingly values of  $\lambda$  this reducing the comparison to the one of OLS.

Finally we introduce the SGD with momentum. We use full gradient descent on the default data and investigate the convergence rate for different learning rates and momentum paramter  $\gamma$ . The result is shown in figure 10.

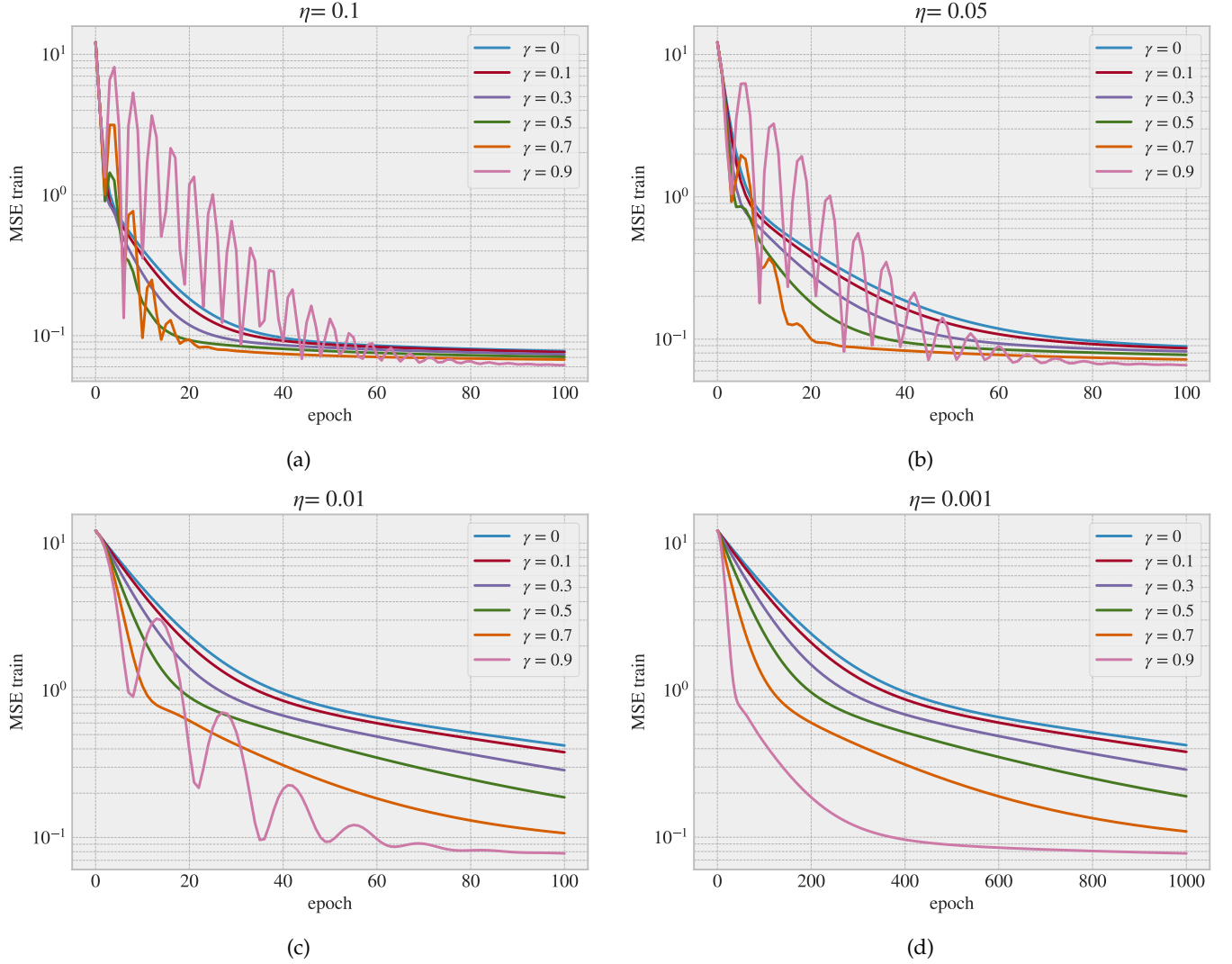


Figure 10: MSE train for different momentum parameters  $\gamma$  and learning rates  $\eta$  as a function of epochs. We used full gradient descent on the default Franke's function data set.

From figure 10 we see that momentum parameter has a quite significant influence on the convergence rate. For the small learning rate  $\eta = 0.001$  (see 10d the highest tested  $\gamma = 0.9$  showcased a clear advantage. However, for bigger learning rates,  $\eta = 0.1$  (figure 10a the higher  $\gamma$ 's gave an oscillation MSE and  $\gamma = 0.9$  converged the slowest, meaning that it decreases more slowly. But as the oscillations settle down we actually get the lowest MSE after 100 epochs with  $\gamma = 0.9$  for all learning rates tested. When increasing  $\gamma$  to 0.99 we see the same effect but on a much bigger scale of epochs.

## 2. Neural Network

Table I: Logic gates: AND, OR and XOR

Input		Output		
$x_1$	$x_2$	AND	OR	XOR
0	0	0	0	0
0	1	0	1	1
1	0	0	1	1
1	1	1	1	0

In this part we study our implementation of the Neural network. As a starting point we choose three logic gates: AND, OR, XOR (exclusive or) which is represented as the data points in table I

When performing standard OLS we get the predic-

tions shown in table II, where we get 100% accuracy on the AND and OR gate but only 75% on the XOR gate. When displaying the data points graphically it is clear to see that the data points of the XOR-gate cannot be separated by a single straight line (see figure 11). Hence it is clear that OLS will never give a satisfactory prediction on this nonlinear problem.

Table II: OLS predictions on the logic gates: AND, OR and XOR

Gates	Predictions	Accuracy
AND	$y = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix}$	100%
OR	$y = \begin{pmatrix} 0 \\ 1 \\ 1 \\ 1 \end{pmatrix}$	100%
XOR	$y = \begin{pmatrix} 0 \\ 1 \\ 1 \\ 1 \end{pmatrix}$	75%

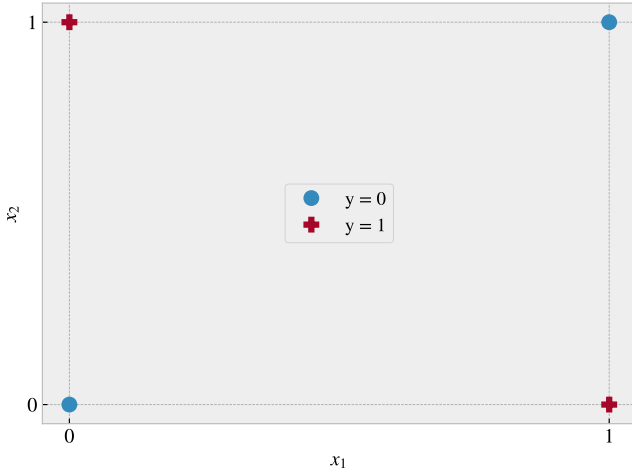


Figure 11: Data points for the XOR-gate. Showcases graphical how we cannot separate the 0's (blue) and 1's (red) by a single straight line

Hence we now use the XOR gate as benchmark for our neural network. We choose a simple architecture with 1 hidden layer containing 4 hidden nodes. Notice that it is possible to solve the XOR-problem with only 2 hidden nodes, but we found that having 4 nodes made the training simpler. We use full gradient descent,  $\eta = 1$  and  $\lambda = \gamma = 0$  with sigmoid as activation function and cross entropy as the cost function. We manage to get a perfect fit, 100 % accuracy, on the training data after roughly 90 epochs. The learning accuracy development is shown in figure ??.

Next we study regression on the Franke's Function from section III A 1 data using our Neural Network. We used the same initial conditions for the Neural Network as with the linear regression models[1], and got the following results:

Table III: Table with R2 and MSE score for our Neural Net, OLS regression and Ridge regression with  $N = 30$ ,  $\sigma = 0.2$ ,  $\lambda = 10^{-4}$ ,  $\gamma = 0$ ,  $\eta = 10^{-1}$ , 3 hidden layers, 42 nodes, batch size = 25 and at the most 400 epochs.

Score	NN	OLS	Ridge
MSE	0.032	0.034	0.034
R2	0.844	0.838	0.841

Here we see that our Neural Network performs as well as OLS and Ridge regression on the Franke's function data. This is however the optimized version, and needed two hyperparameter grid searches, as shown in the images below.

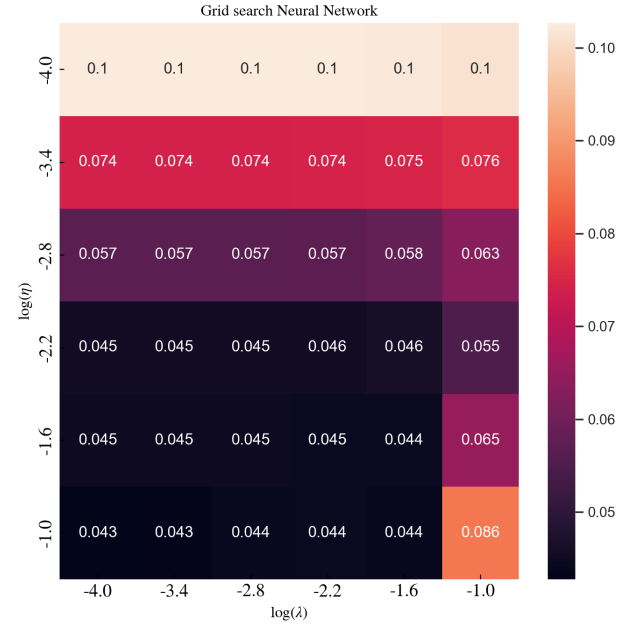


Figure 12: Heatmap showing MSE score for different hyperparameters  $\lambda \in [10^{-4}, 10^1]$  and  $\eta \in [10^{-4}, 10^1]$ . Max number of epochs is 400, batch size 25, 2 hidden layers and 70 hidden nodes

Here we find the optimal hyper parameters  $\lambda = 10^{-4}$  and  $\eta = 10^{-1}$ . The regularization constant  $\lambda$  acts in the same way as it does for Ridge regression, which further validates our findings of the MSE, given that  $\lambda$  is so small. The next hyper parameter grid search is for number of hidden layers and number of hidden nodes per hidden layer.

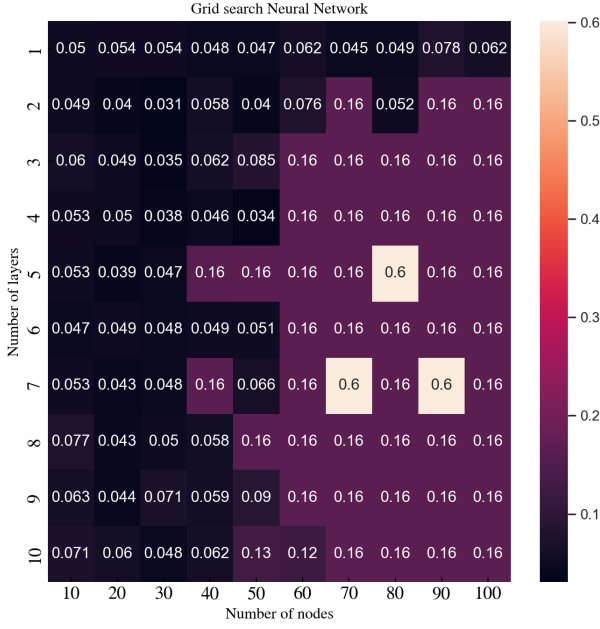


Figure 13: Heatmap showing MSE score for different hyperparameters  $\lambda = 10^{-4}$  and  $\eta = 10^{-1}$ . Max number of epochs is 400, batch size 25, hidden layers  $\in [1, 10]$  and hidden nodes  $\in [10, 100]$

From this image we see that 4 hidden layers and 50 nodes per layer is the optimal choice for the Franke's function data. The grid is spaced with a 10 node and 10 layer increase for each iteration, and this could mean that the actual lowest combination is somewhere in between say 40 and 50, or 50 and 60 nodes. The following image show that there are combinations with lower MSE:

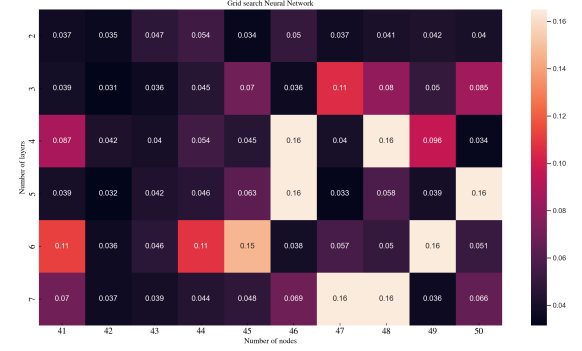
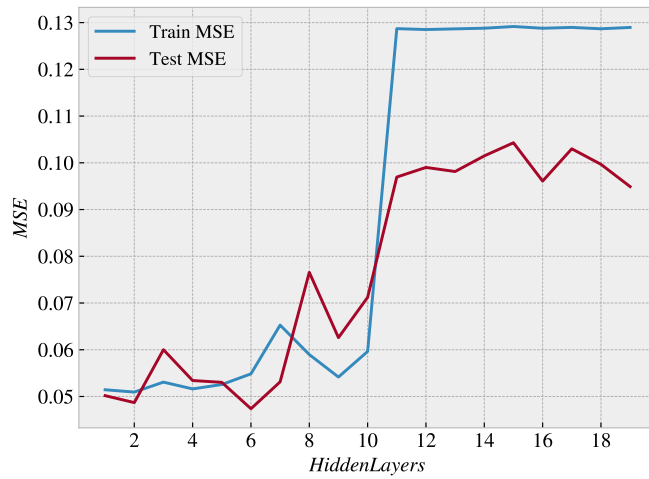


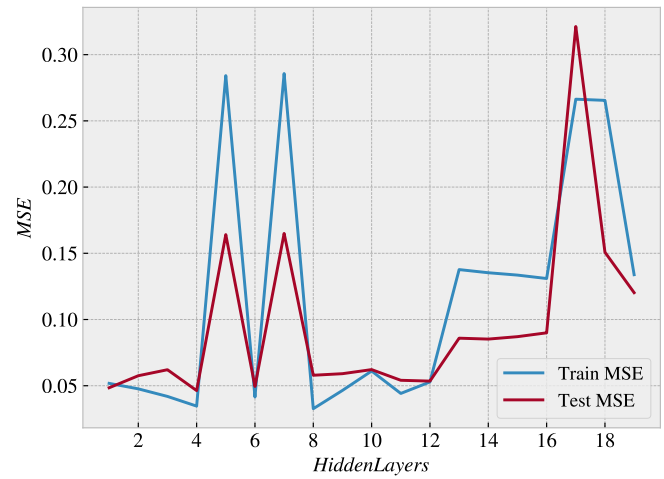
Figure 14: Heatmap showing MSE score for different hyperparameters  $\lambda = 10^{-4}$  and  $\eta = 10^{-1}$ . Number of epochs 400, batch size 25, hidden layers  $\in [2, 7]$  and hidden nodes  $\in [41, 50]$

Here we see that upon further inspection with a much smaller and specified set of nodes, we find the ideal combination of nodes and layers is in fact 3 layers and 42 nodes.

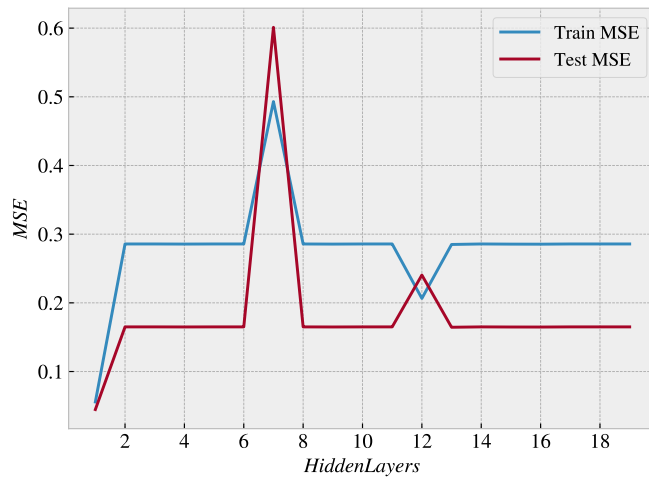
There are certain combinations of the two hyper parameter grid searches that gives a "much" larger MSE score than the optimal parameter combination, and so the images below thus checks if the network is overfitting. If there was any overfitting we would expect the test MSE to diverge from the train MSE for an increase in layers. But as the images show, we see little to no signs of overfitting. Given these results we feel confident that our network is good enough to solve more complex problems, such as breast cancer classification and number recognition.



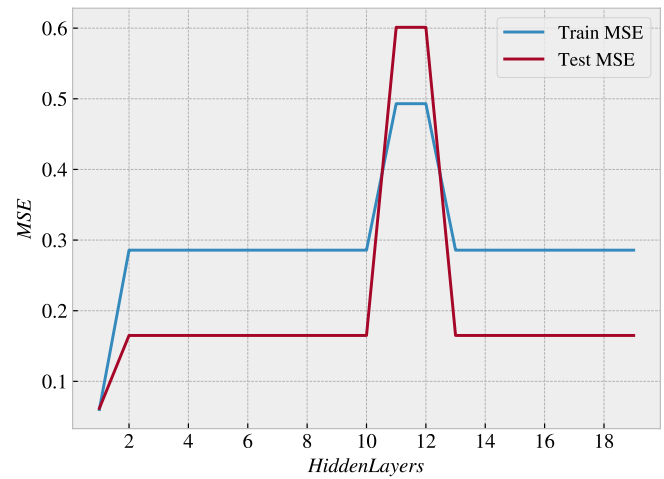
(a) 10 nodes



(b) 40 nodes



(c) 70 nodes



(d) 100 nodes

Figure 15: MSE as function of hidden layers for both training and test data. Top left corner has 10 nodes, top right has 40 nodes, bottom left has 70 nodes and bottom right has 100 nodes. We also have  $\eta = 0.1$ ,  $\lambda = 10^{-4}$ , batch size = 25 and at most 400 epochs.



With these hyperparameters fixed, we plotted our prediction on a new dataset, with the same seed, and got the following results

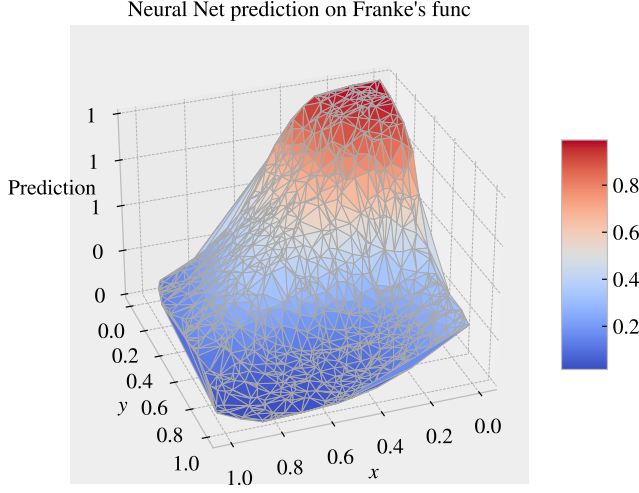


Figure 16: Heatmap for hyperparameters  $\lambda = 10^{-4}$  and  $\eta = 10^{-1}$ . Max number of epochs 200, batch size 25, 2 hidden layers and 30 hidden nodes.

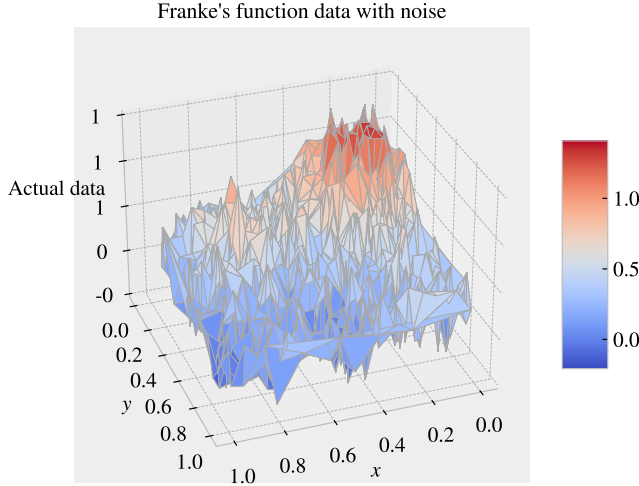


Figure 17: Heatmap for hyperparameters  $\lambda = 10^{-4}$  and  $\eta = 10^{-1}$ . Max number of epochs 200, batch size 25, 2 hidden layers and 30 hidden nodes.

Here we see that our network makes a very good fit to the noisy data. This is further evidence of good validation of our network, and expected, given the MSE and R2 score from table IV A 2.

## B. Breast cancer classification

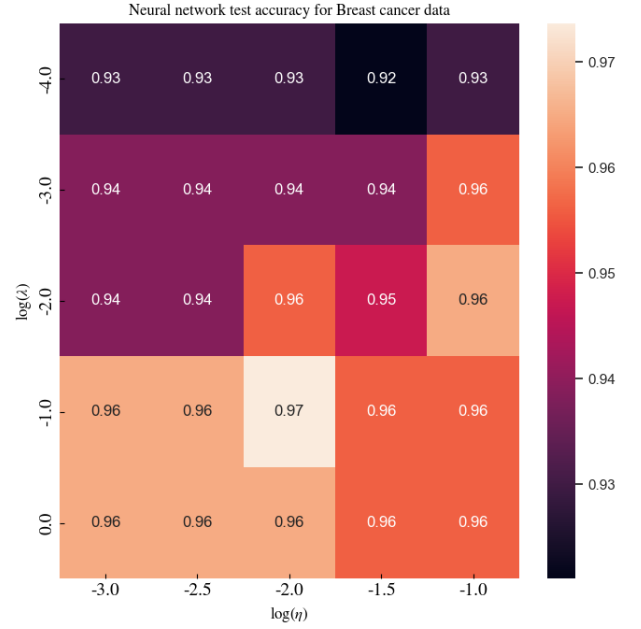


Figure 18: Heatmap for hyperparameters  $\lambda \in [10^{-4}, 1]$  and  $\eta \in [10^{-4}, 10^{-1}]$ . Number of epochs 200, batch size 25, 2 hidden layers and 30 hidden nodes.

	Neural network	Scikit learn
Accuracy	97 %	96 %

Table IV: Comparison between the Neural network and Scikit learn. Both with 2 hidden layers with 30 nodes each, batch size equal to 50 and with a maximum of 100 epochs.

## C. MNIST classification

As stated in section (INSERT SECTION) we will be comparing our Neural Network to our logistic regression solver. All calculations and comparisons will be done using the MNIST data set.

By running a grid search for the hyper-parameters  $\eta$  and  $\lambda$  we find the grid shown in figure (22). The training of the network was done on training data and the accuracy test was done on test data.



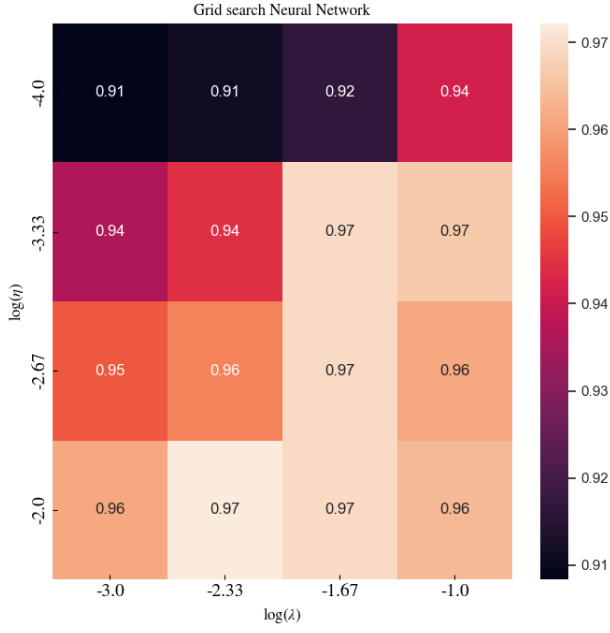


Figure 19: Neural Network heatmap for hyperparameters  $\lambda \in [10^{-3}, 10^{-1}]$  and  $\eta \in [10^{-4}, 10^{-2}]$ . Maximum number of epochs 200, batch size 35, 2 hidden layers and 20 hidden nodes.

From (22) we see that the optimal values for our Neural Network are  $\lambda = 10^{-2.33}$  and  $\eta = 10^{-2}$ . By doing the same grid search for

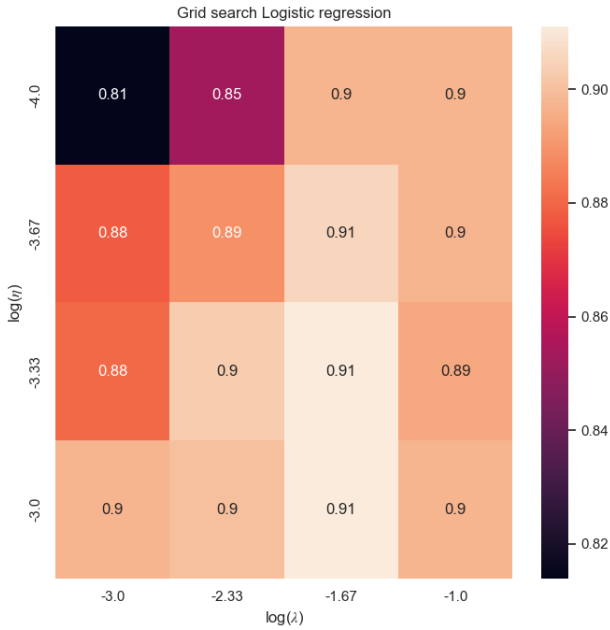


Figure 20: Logistic regression heatmap for hyperparameters  $\lambda \in [10^{-3}, 10^{-1}]$  and  $\eta \in [10^{-4}, 10^{-3}]$ . Number of epochs 200, batch size 35, 2 hidden layers and 20 hidden nodes.



Figure 21: Digits in test data with the Neural Networks predicted values. Green digits indicate correct prediction, red indicate incorrect. The Neural Network was trained with 2 hidden layers with 35 nodes each, batch size 50,  $\eta =$ ,  $\lambda =$  and after 50 epochs.



Figure 22: 64 digits from the test data with the Neural Networks predicted values. Green digits indicate correct prediction, red indicate incorrect. The Neural Network was trained with 2 hidden layers with 35 nodes each, batch size 50 and after a maximum 200 epochs. The hyper-parameters were chosen from a grid search.

## V. CONCLUSION

## REFERENCES

- [1] Frette et al. *Project 1 on Machine Learning*. URL: [https://github.com/Gadangadang/Fys-Stk4155/blob/main/Project%201/article/Project\\_1\\_current.pdf](https://github.com/Gadangadang/Fys-Stk4155/blob/main/Project%201/article/Project_1_current.pdf). (accessed: 10.11.2021).
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