

Neural networks

10.1 Draw a neural network

Draw the graph corresponding to a two-layer dense neural network for regression with p input variables x_1, \dots, x_p , one hidden layer with U units, activation function $h : \mathbb{R} \mapsto \mathbb{R}$ in the layer, and output $\hat{y} \in \mathbb{R}$. How many parameters does the model have (including offsets)?

10.2 Vectorization over units

Mathematically, the model above can be described as

$$q_i = h \left(b_i^{(1)} + \sum_{j=1}^p W_{ij}^{(1)} x_j \right), \quad i = 1, \dots, U \quad (10.1a)$$

$$\hat{y} = b^{(2)} + \sum_{\ell=1}^U W_{\ell}^{(2)} q_{\ell} \quad (10.1b)$$

where each node contains a linear regression model, and where each node in the hidden layer is squeezed through an activation function h . When we implement this in code, we prefer to use a *vectorized* version of these equations since it runs faster than loops and explicit sums. Vectorize the equations in (10.1) by introducing the variables

$$\mathbf{x} = \begin{bmatrix} x_1 \\ \vdots \\ x_p \end{bmatrix}, \quad \mathbf{q} = \begin{bmatrix} q_1 \\ \vdots \\ q_U \end{bmatrix}, \quad \mathbf{b}^{(1)} = \begin{bmatrix} b_1^{(1)} \\ \vdots \\ b_U^{(1)} \end{bmatrix}, \quad \mathbf{W}^{(1)} = \begin{bmatrix} W_{11}^{(1)} & \dots & W_{1p}^{(1)} \\ \vdots & & \vdots \\ W_{U1}^{(1)} & \dots & W_{Up}^{(1)} \end{bmatrix}, \quad \mathbf{b}^{(2)} = [b^{(2)}], \quad \mathbf{W}^{(2)} = \begin{bmatrix} W_1^{(2)} & \dots & W_U^{(2)} \end{bmatrix},$$

i.e. write (10.1) on a matrix form

$$\hat{y} = f(\mathbf{x}), \quad (10.2)$$

which does not include any explicit summation \sum or looping over $\ell = 1, \dots, U$.

10.3 Vectorization over data points

When processing many data points $\{\mathbf{x}_i\}_{i=1}^n$, we have the relation (10.2) for each data point $i = 1, \dots, n$

$$\hat{\mathbf{y}}_i = f(\mathbf{x}_i), \quad i = 1, \dots, n. \quad (10.3)$$

Vectorize the equations in (10.3) by introducing the variables

$$\mathbf{X} = \begin{bmatrix} \mathbf{x}_1^\top \\ \vdots \\ \mathbf{x}_n^\top \end{bmatrix}, \quad \hat{\mathbf{Y}} = \begin{bmatrix} \hat{\mathbf{y}}_1^\top \\ \vdots \\ \hat{\mathbf{y}}_n^\top \end{bmatrix}, \quad \text{and} \quad \mathbf{Q} = \begin{bmatrix} \mathbf{q}_1^\top \\ \vdots \\ \mathbf{q}_n^\top \end{bmatrix}, \quad (10.4)$$

i.e. write (10.3) on a matrix form

$$\hat{\mathbf{Y}} = f(\mathbf{X}), \quad (10.5)$$

which does not include any explicit looping $i = 1, \dots, n$.

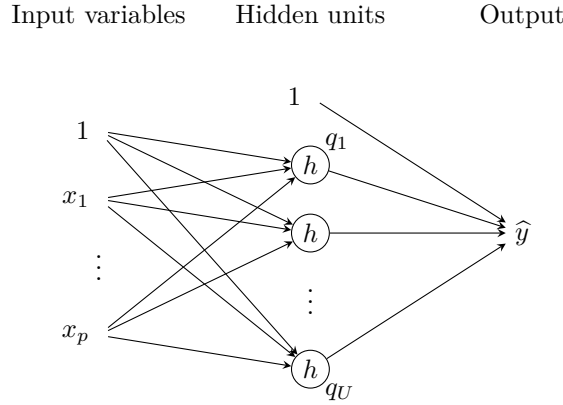
10.4 Linear activation function

Show that the model in the (10.1) reduces to a linear regression model if $h(x) = x$. Specifically, show how the parameters of the entire neural network relate to the parameters of the single linear regression model

$$\hat{y} = \theta_0 + \sum_{j=1}^p \theta_j x_j.$$

Solutions

10.1 A dense neural network for regression with one hidden layer can be illustrated as



Each link represents a multiplication of its incoming unit with a parameter. The parameters are different for each link. The number of links in the graph (=number of parameters in the model) is consequently $(p + 1) \cdot U + 1 + U$.

10.2 By stacking the equations in (10.1a) as rows in vectors we get

$$\begin{bmatrix} q_1 \\ \vdots \\ q_U \end{bmatrix} = \begin{bmatrix} h \left(b_1^{(1)} + \sum_{j=1}^p W_{1j}^{(1)} x_j \right) \\ \vdots \\ h \left(b_U^{(1)} + \sum_{j=1}^p W_{Uj}^{(1)} x_j \right) \end{bmatrix} \quad (10.6a)$$

$$\hat{y} = b^{(2)} + \sum_{i=1}^U W_i^{(2)} q_i \quad (10.6b)$$

Further, by replacing the summations with matrix-vector multiplications we can write this as

$$\underbrace{\begin{bmatrix} q_1 \\ \vdots \\ q_U \end{bmatrix}}_{\mathbf{q}} = h \left(\underbrace{\begin{bmatrix} W_{11}^{(1)} & \dots & W_{1p}^{(1)} \\ \vdots & & \vdots \\ W_{U1}^{(1)} & \dots & W_{Up}^{(1)} \end{bmatrix}}_{\mathbf{W}^{(1)}} \underbrace{\begin{bmatrix} x_1 \\ \vdots \\ x_p \end{bmatrix}}_{\mathbf{x}} + \underbrace{\begin{bmatrix} b_1^{(1)} \\ \vdots \\ b_U^{(1)} \end{bmatrix}}_{\mathbf{b}^{(1)}} \right), \quad (10.7a)$$

$$\hat{y} = \underbrace{\begin{bmatrix} W_1^{(2)} & \dots & W_U^{(2)} \end{bmatrix}}_{\mathbf{W}^{(2)}} \underbrace{\begin{bmatrix} q_1 \\ \vdots \\ q_U \end{bmatrix}}_{\mathbf{q}} + \underbrace{b^{(2)}}_{\mathbf{b}^{(2)}}. \quad (10.7b)$$

By identifying all the matrices and vectors, we can in a more compact and vectorized manner write these equations as

$$\mathbf{q} = h \left(\mathbf{W}^{(1)} \mathbf{x} + \mathbf{b}^{(1)} \right), \quad (10.8a)$$

$$\hat{y} = \mathbf{W}^{(2)} \mathbf{q} + \mathbf{b}^{(2)} \quad (10.8b)$$

Note that the activation function h acts element-wise here.

10.3 Following the solutions from the previous exercise, the equations we are about to vectorize are

$$\mathbf{q}_i = h \left(\mathbf{W}^{(1)} \mathbf{x}_i + \mathbf{b}^{(1)} \right), \quad i = 1, \dots, n, \quad (10.9a)$$

$$\hat{y}_i = \mathbf{W}^{(2)} \mathbf{q}_i + \mathbf{b}^{(2)}, \quad i = 1, \dots, n. \quad (10.9b)$$

We start by taking the transpose of these equations

$$\mathbf{q}_i^\top = h \left(\mathbf{x}_i^\top \mathbf{W}^{(1)\top} + \mathbf{b}^{(1)\top} \right), \quad i = 1, \dots, n, \quad (10.10a)$$

$$\hat{\mathbf{y}}_i^\top = \mathbf{q}_i^\top \mathbf{W}^{(2)\top} + \mathbf{b}^{(2)\top}, \quad i = 1, \dots, n. \quad (10.10b)$$

We continue by stacking these equations in rows

$$\begin{bmatrix} \mathbf{q}_1^\top \\ \vdots \\ \mathbf{q}_n^\top \end{bmatrix} = \begin{bmatrix} h \left(\mathbf{x}_1^\top \mathbf{W}^{(1)\top} + \mathbf{b}^{(1)\top} \right) \\ \vdots \\ h \left(\mathbf{x}_n^\top \mathbf{W}^{(1)\top} + \mathbf{b}^{(1)\top} \right) \end{bmatrix}, \quad (10.11a)$$

$$\begin{bmatrix} \hat{\mathbf{y}}_1^\top \\ \vdots \\ \hat{\mathbf{y}}_n^\top \end{bmatrix} = \begin{bmatrix} \mathbf{q}_1^\top \mathbf{W}^{(2)\top} + \mathbf{b}^{(2)\top} \\ \vdots \\ \mathbf{q}_n^\top \mathbf{W}^{(2)\top} + \mathbf{b}^{(2)\top} \end{bmatrix}. \quad (10.11b)$$

By bringing the weight matrices and offset vectors outside we get

$$\begin{bmatrix} \mathbf{q}_1^\top \\ \vdots \\ \mathbf{q}_n^\top \end{bmatrix} = h \left(\begin{bmatrix} \mathbf{x}_1^\top \\ \vdots \\ \mathbf{x}_n^\top \end{bmatrix} \mathbf{W}^{(1)\top} + \mathbf{b}^{(1)\top} \right), \quad (10.12a)$$

$$\begin{bmatrix} \hat{\mathbf{y}}_1^\top \\ \vdots \\ \hat{\mathbf{y}}_n^\top \end{bmatrix} = \begin{bmatrix} \mathbf{q}_1^\top \\ \vdots \\ \mathbf{q}_n^\top \end{bmatrix} \mathbf{W}^{(2)\top} + \mathbf{b}^{(2)\top}. \quad (10.12b)$$

Note that in these equations we add $+\mathbf{b}^{(1)\top}$ and $+\mathbf{b}^{(2)\top}$ to each row. In python-language we call that *broadcasting* and is heavily used in deep learning implementations.

Now we can identify the matrices in the problem description and write these equations as

$$\mathbf{Q} = h \left(\mathbf{X} \mathbf{W}^{(1)\top} + \mathbf{b}^{(1)\top} \right), \quad (10.13a)$$

$$\hat{\mathbf{Y}} = \mathbf{Q} \mathbf{W}^{(2)\top} + \mathbf{b}^{(2)\top}, \quad (10.13b)$$

which now is in a format suitable for efficient vectorized implementation in code. For the implementation you might want to consider using the transposed version of $\mathbf{W}^{(1)}$, $\mathbf{W}^{(2)}$, $\mathbf{b}^{(1)}$ and $\mathbf{b}^{(2)}$ as your weight matrices and offset vectors to avoid taking transpose in each layer.

10.4 Alternative 1

The mathematical model corresponding to the neural network above is

$$q_i = h \left(b_i^{(1)} + \sum_{j=1}^p W_{ij}^{(1)} x_j \right), \quad i = 1, \dots, U$$

$$\hat{y} = b^{(2)} + \sum_{\ell=1}^U W_{\ell}^{(2)} q_{\ell}$$

If we consider a linear activation function $h(x) = x$ in (10.1) we get

$$\begin{aligned} \hat{y} &= b^{(2)} + \sum_{\ell=1}^U W_{\ell}^{(2)} \left(b_{\ell}^{(1)} + \sum_{j=1}^p W_{\ell j}^{(1)} x_j \right) \\ &= b^{(2)} + \sum_{\ell=1}^U W_{\ell}^{(2)} b_{\ell}^{(1)} + \sum_{j=1}^p \sum_{\ell=1}^U W_{\ell}^{(2)} W_{\ell j}^{(1)} x_j, \end{aligned}$$

which is a linear regression model

$$\hat{y} = \theta_0 + \sum_{j=1}^p \theta_j x_j$$

where

$$\theta_0 = b^{(2)} + \sum_{\ell=1}^U W_{\ell}^{(2)} b_{\ell}^{(1)} \quad \text{and} \quad \theta_j = \sum_{\ell=1}^U W_{\ell}^{(2)} W_{\ell j}^{(1)}. \quad (10.14)$$

Alternative 2

We can also solve the exercise by starting from the vectorized version of the model in (10.2). With $h(x) = x$ we get

$$\mathbf{q} = \mathbf{W}^{(1)} \mathbf{x} + \mathbf{b}^{(1)}, \quad (10.15a)$$

$$\hat{y} = \mathbf{W}^{(2)} \mathbf{q} + \mathbf{b}^{(2)} \quad (10.15b)$$

which gives us

$$\hat{y} = \mathbf{W}^{(2)} \mathbf{W}^{(1)} \mathbf{x} + \mathbf{W}^{(2)} \mathbf{b}^{(1)} + \mathbf{b}^{(2)} \quad (10.16)$$

This can be compared with the linear regression model

$$\begin{aligned} \hat{y} &= \theta_0 + \sum_{j=1}^p \theta_j x_j \\ &= \boldsymbol{\theta}_{-0}^T \mathbf{x} + \theta_0 \end{aligned} \quad (10.17)$$

where $\boldsymbol{\theta}_{-0} = [\theta_1, \dots, \theta_p]^T$. By comparing (10.16) and (10.17) we get that

$$\boldsymbol{\theta}_{-0} = \mathbf{W}^{(1)T} \mathbf{W}^{(2)T}, \quad \text{and} \quad \theta_0 = \mathbf{W}^{(2)} \mathbf{b}^{(1)} + \mathbf{b}^{(2)} \quad (10.18)$$

and by using the definitions in Exercise 10.2 this is

$$\begin{bmatrix} \theta_1 \\ \vdots \\ \theta_p \end{bmatrix} = \begin{bmatrix} W_{11}^{(1)} & \dots & W_{U1}^{(1)} \\ \vdots & & \vdots \\ W_{1p}^{(1)} & \dots & W_{Up}^{(1)} \end{bmatrix} \begin{bmatrix} W_1^{(2)} \\ \vdots \\ W_U^{(2)} \end{bmatrix}, \quad \text{and} \quad \theta_0 = \begin{bmatrix} W_1^{(2)} & \dots & W_U^{(2)} \end{bmatrix} \begin{bmatrix} b_1^{(1)} \\ \vdots \\ b_U^{(1)} \end{bmatrix} + b^{(2)} \quad (10.19)$$

which is equivalent with the solution in (10.14).