

A mathematical understanding of deep learning

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1 – Introduction

Frameworks such as TensorFlow or PyTorch make deep learning developments easy. They have made this field wide spread for every enthusiast. Implementations only needs an instinctive understanding of deep learning. The proper math aspect is little by little forgotten.

The objective is to do a summary of the important propositions. These propositions will be mathematically proven. The subject tackled is a multi-class classification problem with – dense layers, ReLU and Softmax activation layers, Categorical cross-entropy loss, Stochastic gradient descent optimizer. However, all the elements below can be re-used or easily modified to cover a regression problem.

2 – Notation and Nomenclature

Definition 1 – Let $a_{i,j} \in \mathbb{R}$, $i \in \{1,2,\dots,n\}$, $j \in \{1,2,\dots,m\}$. Then the ordered rectangular array

$$A = \begin{bmatrix} a_{1,1} & a_{1,2} & \cdots & a_{1,m} \\ a_{2,1} & a_{2,2} & \cdots & a_{2,m} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n,1} & a_{n,2} & \cdots & a_{n,m} \end{bmatrix}$$

is a real matrix of dimension $n \times m$.

The following notations are considered

$$[A]_{i,j} = a_{i,j} , \quad i \in \{1,2,\dots,n\} , \quad j \in \{1,2,\dots,m\}$$

$$[A]_{:,j} = \begin{bmatrix} a_{1,j} \\ a_{2,j} \\ \vdots \\ a_{n,j} \end{bmatrix} , \quad j \in \{1,2,\dots,m\}$$

$$[A]_{i,:} = [a_{i,1} \ a_{i,2} \ \cdots \ a_{i,n}] \ , \ i \in \{1,2,\dots,n\} \ , \ j \in \{1,2,\dots,m\}$$

The notation $M_{n,m}$ means the real matrix set of dimension $n \times m$.

Convention 1 – A vector is a matrix with only one row. Thus, the real vector set \mathbb{R}^n is equivalent to $M_{1,n}$.

Notation 1 – The matrix transpose operation will be noted as A^T .

Definition 2 – Let $A \in M_{n,m}$, and $B \in M_{m,p}$, and let the product noted $A \times B$ or AB be

$$C = A \times B = AB$$

where C is a $m \times p$ matrix with

$$[C]_{i,j} = \sum_{k=1}^m [A]_{i,k} * [B]_{k,j} \ , \ i \in \{1,2,\dots,n\} \ , \ j \in \{1,2,\dots,p\}$$

3 – Activation functions

Definition 3 – Let $z \in M_{n,m}$, then the vector wise application

$$f : \begin{cases} \mathbb{R}^m \rightarrow \mathbb{R}^m \\ [z]_{i,:} \mapsto f([z]_{i,:}) \ , \ i \in \{1,2,\dots,n\} \end{cases}$$

is an activation function with f continuous and piece-wise differentiable.

Proposition 1 – Let $z \in M_{n,m}$, then the following vector wise applications are activation functions:

$$ReLU : \begin{cases} \mathbb{R}^m \rightarrow \mathbb{R}^m \\ [z]_{i,:} \mapsto \max(0_{\mathbb{R}^m}, [z]_{i,:}) \ , \ i \in \{1,2,\dots,n\} \end{cases}$$

with \max the element wise maximum operation.

$$Softmax : \begin{cases} \mathbb{R}^m \rightarrow \mathbb{R}^m \\ [z]_{i,:} \mapsto \frac{e^{[z]_{i,:}}}{\sum_{j=1}^m e^{[z]_{i,j}}} \ , \ i \in \{1,2,\dots,n\} \end{cases}$$

with e the element wise exponential operation.

The derivatives are the following

$$D(ReLU): \begin{cases} \mathbb{R}^m \rightarrow \mathbb{R}^m \\ [z]_{i,:} \mapsto \begin{bmatrix} 1_{\mathbb{R}_{\setminus\{0\}}+}([z]_{i,1}) & 0 & \dots & 0 \\ 0 & 1_{\mathbb{R}_{\setminus\{0\}}+}([z]_{i,2}) & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ 0 & \dots & 0 & 1_{\mathbb{R}_{\setminus\{0\}}+}([z]_{i,m}) \end{bmatrix} \end{cases}, \quad i \in \{1, 2, \dots, n\}$$

with $1_{\mathbb{R}+}$ the $\mathbb{R}_{\setminus\{0\}}+$ indicator function.

4 – Simple perceptron

Definition 4 – Let $y \in M_{1,m}$ the input vector, and $W \in M_{1,m}$ the weight matrix. Then the simple perceptron is defined as the operation

5 – Neural Network

Definition 2 – Suppose a data set with n samples. Each sample have m features and a corresponding one-hot encoded label among l possible labels.

Let $X \in M_{n,m}$, and $Y \in M_{n,l}$ the matrices defining the features and the labels respectively for each sample.

Suppose a neural network with k layers.

6 – References