

# Gradients manipulations

## Optimization for Machine Learning — Exercise 01

Monday 17<sup>th</sup> April, 2023

Recall that the gradient of a differentiable function  $f: \mathbb{R}^m \rightarrow \mathbb{R}$  at  $x \in \mathbb{R}^m$  is a vector in  $\mathbb{R}^m$ , usually denoted by  $\nabla f(x)$ , such that

$$\nabla f(x) = \begin{pmatrix} \partial_{x_1} f(x) \\ \vdots \\ \partial_{x_n} f(x) \end{pmatrix},$$

where  $\partial_{x_i} f(x) := \frac{\partial f(x)}{\partial x_i}$  is the partial derivative of  $f$  at  $x$  with respect to  $x_i$  for  $i \in [n] := \{1, \dots, n\}$ .

When  $f$  is multivalued, i.e.  $f: \mathbb{R}^m \rightarrow \mathbb{R}^n$ , its *Jacobian* at  $x$ , denoted by  $J_f(x)$ , is the  $n \times m$  matrix such that, if  $y = f(x) \in \mathbb{R}^n$ ,

$$J_f(x) = \left( \frac{\partial y_i}{\partial x_j} \right)_{(i,j) \in [n] \times [m]} = \begin{pmatrix} \frac{\partial y_1}{\partial x_1} & \frac{\partial y_1}{\partial x_2} & \dots & \frac{\partial y_1}{\partial x_m} \\ \frac{\partial y_2}{\partial x_1} & \ddots & & \vdots \\ \vdots & & & \frac{\partial y_n}{\partial x_m} \end{pmatrix} = \begin{pmatrix} \partial_x y_1 \\ \partial_x y_2 \\ \vdots \\ \partial_x y_n \end{pmatrix} = \partial_x f(x),$$

where  $\partial_x y$  is understood as having as **column indices** the indices from  $x$ , and **row indices** the indices of  $y$ . This notation might be confusing, but is sometimes useful, see e.g. Exercise 2c.

When  $n = 1$ , note that we have  $\nabla f(x) = (J_f(x))^\top = (\partial_x f(x))^\top$ .

**Product rule** Similar to the 1D case, a product rule exists for multivariate functions.

1. a) If  $f: \mathbb{R}^d \rightarrow \mathbb{R}^n$  and  $g: \mathbb{R}^d \rightarrow \mathbb{R}^n$ , show that  $\nabla(f^\top g)(x) = J_f(x)^\top g(x) + J_g(x)^\top f(x)$ .

b) What happens with  $n = 1$ ?

**Answer**

1. a) With  $f: \mathbb{R}^d \rightarrow \mathbb{R}^n$ ,  $g: \mathbb{R}^d \rightarrow \mathbb{R}^n$ , and for  $x \in \mathbb{R}^d$  where  $f$  and  $g$  are differentiable,  $f(x)^\top g(x) = \sum_{k=1}^n f_k(x)g_k(x)$ . Therefore, for an index  $i \in [d]$ ,

$$\begin{aligned}\partial_{x_i}(f^\top g)(x) &= \partial_{x_i}(f(x)^\top g(x)) = \partial_{x_i} \sum_{k=1}^n f_k(x)g_k(x) \\ &= \sum_{k=1}^n \partial_{x_i} f_k(x)g_k(x) + f_k(x)\partial_{x_i} g_k(x) \\ &= \sum_{k=1}^n J_f(x)_{ki}g_k(x) + J_g(x)_{ki}f_k(x) \\ &= \sum_{k=1}^n J_f(x)_{ik}^\top g_k(x) + J_g(x)_{ik}^\top f_k(x) \\ &= J_f^\top(x)_{i,:}g(x) + J_g^\top(x)_{i,:}f(x),\end{aligned}$$

where  $A_{i,:}$  stand for the row  $i$  of a matrix  $A$ . Since this is true for all  $i \in [d]$ , and  $i$  is a row index on both sides, we can write

$$\implies \nabla_x(f^\top g)(x) = J_f^\top(x)g(x) + J_g^\top(x)f(x).$$

**Always check the dimensions!**

- b) In the case  $n = 1$ , then  $J_f^\top = \nabla f$  and  $J_g^\top = \nabla g$ , therefore

$$\nabla(fg)(x) = \nabla f(x)g(x) + f(x)\nabla g(x)$$

**Chain rule** The chain rule for Jacobian is, for  $f: \mathbb{R}^m \rightarrow \mathbb{R}^k$ , and  $g: \mathbb{R}^k \rightarrow \mathbb{R}^n$ ,  $J_{g \circ f}(x) = J_g(f(x))J_f(x)$  (when the composition makes sense, and everything is differentiable). Compare with the chain rule in the 1D case:  $(g \circ f)'(x) = g'(f(x)) \cdot f'(x)$ .

2. a) Compute the gradient of  $g \circ f$  at  $x \in \mathbb{R}^m$ , when  $f: \mathbb{R}^m \rightarrow \mathbb{R}^k$  and  $g: \mathbb{R}^k \rightarrow \mathbb{R}$ , as a function of  $J_f(x)$  and  $\nabla g(f(x))$  (note the difference between  $\nabla(g \circ f)(x)$  and  $\nabla g(f(x))$ ).
- b) Compute the gradient of  $h_2 \circ h_1 \circ f$ , when  $h_1: \mathbb{R} \rightarrow \mathbb{R}$  and  $h_2: \mathbb{R} \rightarrow \mathbb{R}$  are single valued functions, and  $f: \mathbb{R}^d \rightarrow \mathbb{R}$  is a vector function.
- c) Assume that  $x(w), y(w), z(w)$  are function of  $w \in \mathbb{R}^p$ , and that  $\mathcal{L}: \mathbb{R}^3 \rightarrow \mathbb{R}$  is a function of  $x, y, z$ . Show that  $\nabla_w \mathcal{L}(x(w), y(w), z(w)) = \frac{\partial \mathcal{L}(x, y, z)}{\partial x} \nabla x(w) + \frac{\partial \mathcal{L}(x, y, z)}{\partial y} \nabla y(w) + \frac{\partial \mathcal{L}(x, y, z)}{\partial z} \nabla z(w)$ .

**Answer**

2. a) Since  $g \circ f: \mathbb{R}^m \rightarrow \mathbb{R}$  is real-valued, we have

$$\nabla(g \circ f)(x) = (J_{g \circ f}(x))^\top = J_f(x)^\top J_g(f(x)) = J_f(x)^\top \nabla g(f(x)),$$

since  $g: \mathbb{R}^k \rightarrow \mathbb{R}$  is real valued.

b) Applying the previous rule with  $g = h_2 \circ h_1$ , we get

$$\begin{aligned}\nabla(h_2 \circ h_1 \circ f)(x) &= J_f(x)^\top \nabla(h_2 \circ h_1)(f(x)) \\ &= \nabla f(x) \cdot (h_2 \circ h_1)'(f(x)) \\ &= \nabla f(x) \cdot h_2'(h_1(f(x))) \cdot h_1'(f(x)),\end{aligned}$$

since  $h_1, h_2$  are 1D functions and  $f$  is real valued.

c) We write the parametrization of  $x, y, z$  as  $\phi: \mathbb{R}^p \rightarrow \mathbb{R}^3$ ,  $w \mapsto \phi(w) = \begin{pmatrix} x(w) \\ y(w) \\ z(w) \end{pmatrix}$ .

The function on  $w$  is then  $(\mathcal{L} \circ \phi)(w)$ , of which we can take the gradient

$$\begin{aligned}\nabla_w(\mathcal{L} \circ \phi)(w) &= J_\phi^\top(w) \nabla \mathcal{L}(\phi(w)) \\ &= \begin{pmatrix} \partial_w x(w) \\ \partial_w y(w) \\ \partial_w z(w) \end{pmatrix}^\top \begin{pmatrix} \partial_x \mathcal{L}(\phi(w)) \\ \partial_y \mathcal{L}(\phi(w)) \\ \partial_z \mathcal{L}(\phi(w)) \end{pmatrix} \quad (\text{Recall the notation } \partial_w x(w) = (\nabla_w x(w))^\top) \\ &= \begin{pmatrix} \nabla_w x(w) & \nabla_w y(w) & \nabla_w z(w) \end{pmatrix} \begin{pmatrix} \partial_x \mathcal{L}(x, y, z) \\ \partial_y \mathcal{L}(x, y, z) \\ \partial_z \mathcal{L}(x, y, z) \end{pmatrix} \\ &= \partial_x \mathcal{L}(x, y, z) \nabla_w x(w) + \partial_y \mathcal{L}(x, y, z) \nabla_w y(w) + \partial_z \mathcal{L}(x, y, z) \nabla_w z(w),\end{aligned}$$

where the dependency on  $w$  for  $x, y, z$  has been dropped where it was not relevant.

**Classical vector functions** Often, the functions that will appear are build from simpler ones, such as the linear product  $\langle a, b \rangle = a^\top b$ , or a matrix-vector multiplication  $A \cdot b$ , etc. The easiest to find the gradient of such function is usually to go back to the expression with the indices, e.g.  $\langle a, b \rangle = \sum_i a_i b_i$ . Another method, especially for more complex cases, is to look up if the formula is in the Matrix Cookbook.

3. a) Let  $a \in \mathbb{R}^n$ . Show that  $\nabla_x \langle a, x \rangle = a$ ,
- b) Let  $A \in \mathbb{R}^{n \times m}$ , and  $f: \mathbb{R}^m \rightarrow \mathbb{R}^n$ ,  $x \mapsto Ax$ . Show that  $J_f(x) = A$ .
- c) What is  $\nabla_x \langle x, Ax \rangle$ ? ( $A \in \mathbb{R}^{n \times n}$ )
- d) What is  $\nabla_A \langle x, Ax \rangle$ ? ( $A \in \mathbb{R}^{n \times n}$ )

**Answer**

3. a) With  $a \in \mathbb{R}^n$ ,  $x \in \mathbb{R}^n$ , we have  $\langle a, x \rangle = \sum_{j=1}^n a_j x_j$ , and therefore, for  $i \in [n]$ ,

$$\partial_{x_i} \langle a, x \rangle = \partial_{x_i} \sum_{j=1}^n a_j x_j = \sum_{j=1}^n a_j \partial_{x_i} x_j = \sum_{j=1}^n a_j \delta_{ij},$$

where  $\delta_{ij} = \begin{cases} 1 & \text{if } i = j, \\ 0 & \text{otherwise} \end{cases}$ . Therefore, the only non-zero term in the sum is when  $j = i$ , and

$$\partial_{x_i} \langle a, x \rangle = a_i \implies \nabla_x \langle a, x \rangle = a,$$

since  $i$  is a row index on both sides of the equation.

b) With  $A = (a_{ij})_{i=1,j=1}^{n,m} \in \mathbb{R}^{n \times m}$ ,  $x \in \mathbb{R}^m$ , and  $i \in [n]$ , we have that  $(Ax)_i = \sum_{k=1}^m a_{ik}x_k$ , and therefore, for  $(i, j) \in [n] \times [m]$ , one gets

$$\begin{aligned} \partial_{x_j} (f(x))_i &= \partial_{x_j} (Ax)_i = \partial_{x_j} \sum_{k=1}^m a_{ik}x_k \\ &= \sum_{k=1}^m a_{ik} \partial_{x_j} x_k \\ &= \sum_{k=1}^m a_{ik} \delta_{jk} \\ &= a_{ij}. \end{aligned}$$

Since  $i$  (resp.  $j$ ) is a row (resp. column) index on both sides of the equation, we can conclude that

$$J_f(x) = A$$

- c) We can use the product formula (Exercise 1a) with  $f(x) = x$  and  $g(x) = Ax$ :  $\nabla_x \langle x, Ax \rangle = J_f(x)^\top Ax + J_g(x)^\top x = I_n Ax + A^\top x = (A + A^\top)x$ .
- d) Here, similar to the gradient of a real-valued vector function, the definition of the gradient of a real-valued **matrix** function  $f: \mathbb{R}^{n \times m} \rightarrow \mathbb{R}$  with respect to its input is implied to be a matrix (of same size as the input), such that

$$\nabla_A f(A) = (\partial_{a_{ij}} f(A))_{i=1,j=1}^{n,m} = \begin{pmatrix} \partial_{a_{11}} f(A) & \cdots & \\ \vdots & \ddots & \\ & & \partial_{a_{nm}} f(A) \end{pmatrix}.$$

It comes up in some situations in machine learning, typically when the weights with respect to which we are computing the gradient are organized in matrices.

Here,  $A \in \mathbb{R}^{n \times n}$ , so we compute, for  $(i, j) \in [n] \times [n]$ ,

$$\begin{aligned} \partial_{a_{ij}} f(A) &= \partial_{a_{ij}} \langle x, Ax \rangle = \partial_{a_{ij}} \sum_{k,l} x_k x_l a_{kl} \\ &= \sum_{k,l} x_k x_l \partial_{a_{ij}} a_{kl} \\ &= \sum_{k,l} x_k x_l \delta_{ik} \delta_{jl} \end{aligned}$$

again with  $\delta_{ij} = \mathbb{1}(i = j)$ , since  $\partial_{a_{ij}} a_{kl} = \begin{cases} 1 & \text{if } k = i \text{ and } l = j \\ 0 & \text{otherwise} \end{cases}$ . Therefore

$$\partial_{a_{ij}} f(A) = x_i x_j.$$

The matrix that have entries  $x_i x_j$  for  $i$  a row index and  $j$  a column index is the matrix  $xx^\top$ . Therefore,

$$\nabla_A \langle x, Ax \rangle = xx^\top.$$

## General functions

4. Compute the gradients of the functions:

a)  $f: \mathbb{R}^3 \rightarrow \mathbb{R}, (x, y, z) \mapsto \frac{1}{2}x^2 + yz - \ln(1 + \exp(x^2 y^3 z))$

b)  $g: \mathbb{R}^d \rightarrow \mathbb{R}, x \mapsto \frac{1}{2}\|x\|^2 = \frac{1}{2}x^\top x = \frac{1}{2} \sum_{i=1}^d x_i^2$

c)  $h: \mathbb{R}^d \times \mathbb{R}^d \rightarrow \mathbb{R}, (x, w) \mapsto \ln(1 + \exp(-w^\top x))$ . Compute the gradient with respect to  $w$ :  $\nabla_w h(x, w)$ .

## Answer

4. a) One computes

$$\nabla f(x, y, z) = \begin{pmatrix} x - \frac{2xy^3z}{1+\exp(x^2 y^3 z)} \\ z - \frac{3y^2 x^2 z}{1+\exp(x^2 y^3 z)} \\ y - \frac{x^2 y^3}{1+\exp(x^2 y^3 z)} \end{pmatrix}$$

b) i. One way to compute is to use the product rule 1a with  $f = g = \text{id}$ :

$$\nabla_x \left( \frac{1}{2} x^\top x \right) = \frac{1}{2} (I_d x + I_d x) = x$$

ii. Another way is to go back to the definition  $\frac{1}{2}\|x\|^2 = \sum_i x_i^2$ , and evaluate at each coordinate  $j \in [d]$ :  $\partial_{x_j} \frac{1}{2}\|x\|^2 = \frac{1}{2} \sum_i \partial_{x_j} x_i^2 = x_j$ .

c) For this  $h$ , the formula found in Exercise 2b is adapted:

$$\nabla_w h(x, w) = \frac{\nabla_w \exp(-x^\top w)}{1 + \exp(-x^\top w)} = -\frac{\exp(-x^\top w)}{1 + \exp(-x^\top w)} x.$$