



MSC. DATA SCIENCE & ARTIFICIAL INTELLIGENCE

INVERSE PROBLEMS IN IMAGE PROCESSING

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## Assignment 2

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# 1 Tutorial 5

## 1.1 Exercise 1: Soft-thresholding

The proximal operator of  $\tau f$  is defined as:

$$\text{prox}_{\tau f}(x) = \arg \min_{u \in \mathbb{R}} \frac{1}{2\tau} (u - x)^2 + f(u)$$

which we can apply to the  $\ell_1$  norm to get:

$$\text{prox}_{\tau|\cdot|}(x) = \arg \min_{u \in \mathbb{R}} \frac{1}{2\tau} (u - x)^2 + |u|$$

Let  $h(u)$  be given by:

$$h(u) := \frac{1}{2\tau} (u - x)^2 + |u|$$

The optimality condition states that given that  $h$  is proper, we have:

$$0 \in \partial h(u^*) \iff u^* \in \arg \min_{u \in \mathbb{R}} h(u)$$

then we have:

$$\begin{aligned} \frac{\partial}{\partial u} h(u) &= \frac{\partial}{\partial u} \left[ \frac{1}{2\tau} (u - x)^2 + |u| \right] \\ &= \begin{cases} \frac{1}{\tau}(u - x) - 1, & u < 0 \\ \frac{1}{\tau}(u - x) + 1, & u > 0 \end{cases} \end{aligned}$$

We set the derivative to zero to find the critical points of  $h$ . We have three cases to consider:  $u > 0$ ,  $u < 0$  and  $u = 0$ .

**Case  $u > 0$ .**

$$\begin{aligned} \frac{\partial}{\partial u} h(u^*) &= 0 \\ \implies \frac{1}{\tau}(u^* - x) + 1 &= 0 \\ \implies u^* &= x - \tau \end{aligned}$$

**Case  $u < 0$ .**

$$\begin{aligned} \frac{\partial}{\partial u} h(u^*) &= 0 \\ \implies \frac{1}{\tau}(u^* - x) - 1 &= 0 \\ \implies u^* &= x + \tau \end{aligned}$$

**Case  $u = 0$ .** In this case, we cannot compute the derivative as the function is non-differentiable in  $u = 0$ . We have however that the subdifferential of  $h$  is given by:

$$\partial h(u) = [-1, 1]$$

In particular,  $0 \in \partial h(u)$ , so we can apply the optimality condition. Therefore, the proximal operator is given by:

$$\begin{aligned} \text{prox}_{\tau|\cdot|}(x) &= \begin{cases} x - \tau, & u > 0 \\ x + \tau, & u < 0 \\ 0, & \text{otherwise} \end{cases} \\ &= \begin{cases} x - \tau, & x - \tau > 0 \\ x + \tau, & x + \tau < 0 \\ 0, & \text{otherwise} \end{cases} \\ &= \begin{cases} x - \tau, & x > \tau \\ x + \tau, & x < -\tau \\ 0, & \text{otherwise} \end{cases} \\ &= \begin{cases} x - \tau, & x > \tau \\ x + \tau, & x < -\tau \\ 0, & |x| \leq \tau \end{cases} \end{aligned}$$

We plot this proximal operator in the companion notebook.

## 1.2 Exercise 2: Hard-thresholding

We define  $f$  as the  $\ell_0$  norm:

$$f(x) = |x|_0 = \begin{cases} 0, & x = 0 \\ 1, & x \neq 0 \end{cases}$$

The proximal operator of  $\tau f$  is defined as:

$$\text{prox}_{\tau|\cdot|_0}(x) = \arg \min_{u \in \mathbb{R}} \frac{1}{2\tau} (u - x)^2 + |u|_0$$

Let  $h(u)$  be given by:

$$\begin{aligned} h(u) &:= \frac{1}{2\tau} (u - x)^2 + |u|_0 \\ &= \begin{cases} \frac{1}{2\tau} (u - x)^2 + 1, & u \neq 0 \\ \frac{1}{2\tau} (0 - x)^2 + 0, & u = 0 \end{cases} \\ &= \begin{cases} \frac{1}{2\tau} (u - x)^2 + 1, & u \neq 0 \\ \frac{x^2}{2\tau}, & u = 0 \end{cases} \end{aligned}$$

We have two cases to consider:  $u \neq 0$  and  $u = 0$ .

**Case  $u \neq 0$ .** In this case,  $h$  is differentiable. We will compute its derivative and set it to zero to find the critical points of  $h$ . The derivative of  $h$  is given by:

$$\frac{\partial}{\partial u} h(x) = \frac{1}{\tau}(u - x)$$

We now set this derivative to zero to find the critical points of  $h$ :

$$\begin{aligned}\frac{\partial}{\partial u} h(u^*) &= 0 \\ \implies \frac{1}{\tau}(u^* - x) &= 0 \\ \implies u^* &= x\end{aligned}$$

Therefore, we have:

$$\begin{aligned}h(u^*) &= \frac{1}{2\tau} (u^* - x)^2 + |u^*|_0 \\ &= \frac{1}{2\tau} (x - x)^2 + 1 \\ &= 1\end{aligned}$$

**Case  $u = 0$ .** In this case, we cannot compute the derivative as the function is non-differentiable in  $u = 0$ . We have that  $h$  is given by:

$$h(u) = \frac{x^2}{2\tau}$$

Now, the question is whether it is better to have  $h(u) = \frac{x^2}{2\tau}$  or  $h(u) = 1$ . We compare the two quantities:

$$\begin{aligned}\frac{x^2}{2\tau} < 1 &\implies x^2 < 2\tau \\ &\implies x \in [-\sqrt{2\tau}, \sqrt{2\tau}]\end{aligned}$$

So in order to minimize  $h$ , we prefer having  $h(u) = \frac{x^2}{2\tau}$  as long as  $x \in [-\sqrt{2\tau}, \sqrt{2\tau}]$  and  $h(u) = 1$  otherwise. We need to choose  $u$  appropriately, which means that the proximal operator of  $\tau|\cdot|_0$  is given by:

$$\text{prox}_{\tau|\cdot|_0}(x) = \begin{cases} 0, & x \in [-\sqrt{2\tau}, \sqrt{2\tau}] \\ x, & \text{otherwise} \end{cases}$$

We plot this proximal operator in the companion notebook.

### 1.3 Exercise 3: Non-negativity constraints

#### 1.3.1 Part 1

Let  $\mathbb{R}_+^n$  be the set of vectors with non-negative entries. We define the indicator function of  $\mathbb{R}_+^n$  as:

$$\delta_{\mathbb{R}_+^n}(x) = \begin{cases} 0, & x \in \mathbb{R}_+^n \\ \infty, & \text{otherwise} \end{cases}$$

Therefore the proximal operator of  $\delta_{\mathbb{R}_+^n}$  is given by:

$$\text{prox}_{\delta_{\mathbb{R}_+^n}}(x) = \arg \min_{u \in \mathbb{R}^n} \frac{1}{2} \|u - x\|^2 + \delta_{\mathbb{R}_+^n}(u)$$

We define  $h(u)$  as:

$$h(u) = \frac{1}{2} \|u - x\|^2 + \delta_{\mathbb{R}_+^n}(u)$$

We understand from the definition of the indicator function that no component of  $u$  can be negative, otherwise  $h$  would be infinite.

We have two cases to consider:  $u \in \mathbb{R}_+^n$  and  $u \notin \mathbb{R}_+^n$ .

**Case  $u \in \mathbb{R}_+^n$ .** In this case,  $h$  is differentiable. We will compute its derivative and set it to zero to find the critical points of  $h$ . The derivative of  $h$  is given by:

$$\begin{aligned} \nabla h(u^*) = 0 &\implies u^* - x = 0 \\ &\implies u^* = x \end{aligned}$$

**Case  $u \notin \mathbb{R}_+^n$ .** In this case, as mentioned above,  $h$  is infinite. We cannot choose any component  $u_i$  of  $u$  to be negative, otherwise  $h$  would be infinite because of the indicator function. However, we still want to choose  $u$  to be as close as possible to  $x$ , in order to minimize the  $\|u - x\|^2$  component. We proceed in a component-wise fashion, thanks to the separability of  $h$ . For all  $i$  such that  $x_i < 0$ , we can therefore choose  $u_i = 0$ , which is the point in  $\mathbb{R}_+$  which minimizes the distance to  $x_i$ .

We can summarize the proximal operator of  $\delta_{\mathbb{R}_+^n}$  as:

$$\forall i = 1, \dots, n, \quad \left\{ \text{prox}_{\delta_{\mathbb{R}_+^n}}(x) \right\}_i = \max(0, x_i)$$

#### 1.3.2 Part 2

We now compute the proximal operator of  $\tau|\cdot|_1 + \delta_{\mathbb{R}_+^n}(\cdot)$ , which is given by:

$$\text{prox}_{\tau|\cdot|_1 + \delta_{\mathbb{R}_+^n}}(x) = \arg \min_{u \in \mathbb{R}_+^n} \frac{1}{2\tau} \|u - x\|^2 + |u|_1 + \delta_{\mathbb{R}_+^n}(u)$$

We define  $h(u)$  as:

$$h(u) = \frac{1}{2\tau} \|u - x\|^2 + |u|_1 + \delta_{\mathbb{R}_+^n}(u)$$

We note that  $h$  is separable. We can therefore apply the proximal operator of  $\tau|\cdot|_1$  to each component of  $u$ . Moreover, we can use the same argument as in section 1.3.1 regarding the non-negativity constraint. Indeed once again, as long as one of the component of

$u$  is negative,  $h$  is infinite, so minimizing  $h$  means that all components of  $u$  must be non-negative. For the rest, the minimizer of  $\frac{1}{2\tau}\|u - x\|^2 + |u|_1$  is by definition equal to  $\text{prox}_{\tau|\cdot|_1}(x)$ , that is:

$$\arg \min_{u \in \mathbb{R}^n} \frac{1}{2\tau} \|u - x\|^2 + |u|_1 =: \text{prox}_{\tau|\cdot|_1}(x)$$

and we computed this proximal operator in section 1.1.

Now, the indicator forces all components of  $u$  to be non-negative (this is the same argument as in section 1.3.1 really). As a result, we can summarize the proximal operator of  $\tau|\cdot|_1 + \delta_{\mathbb{R}_+^n}(\cdot)$  as:

$$\forall i = 1, \dots, n, \left( \text{prox}_{\tau|\cdot|_1 + \delta_{\mathbb{R}_+^n}}(\cdot)(x) \right)_i = \max \left( \left( \text{prox}_{\tau|\cdot|_1}(x) \right)_i, 0 \right)$$

where the maximum is taken component-wise.

## 1.4 Exercise 4

Compute  $\text{prox}_f(x)$ .

# 2 Tutorial 6

## 2.1 Question 7