

Weekly Exercises 0

Room: 02.09.023

Friday, 15.04.2016, 09:00-11:00, Room 02.09.023

Intro to Sparse Linear Operators in MATLAB

Throughout the course we will work in the finite dimensional setting, i.e. we discretely represent gray value images $f : \Omega \rightarrow \mathbb{R}$ or color images $f : \Omega \rightarrow \mathbb{R}^3$ as (vectorized) matrices $f \in \mathbb{R}^{m \times n}$ ($\text{vec}(f) \in \mathbb{R}^{mn}$) respectively $f \in \mathbb{R}^{m \times n \times 3}$ ($\text{vec}(f) \in \mathbb{R}^{3mn}$). To discretely express functionals like the total variation for smooth f

$$TV(f) := \int_{\Omega} \|\nabla f(x)\| dx$$

you will therefore need a discrete gradient operator

$$\nabla := \begin{pmatrix} D_x \\ D_y \end{pmatrix}$$

for vectorized representations $\text{vec}(f)$ of images $f \in \mathbb{R}^{m \times n}$ so that

$$TV(f) = \|\nabla \text{vec}(f)\|_{2,1} = \sum_{i=1}^{nm} \sqrt{(D_x \cdot \text{vec}(f))_i^2 + (D_y \cdot \text{vec}(f))_i^2}.$$

The aim of this exercise is to derive the gradient operator and learn how to implement it with MATLAB.

Exercise 1. Let $f \in \mathbb{R}^{m \times n}$ be a discrete grayvalue image. Your task is to find matrices \tilde{D}_x and \tilde{D}_y for computing the forward differences f_x, f_y in x and y -direction of the image f with Neumann boundary conditions so that:

$$f_x = f \cdot \tilde{D}_x := \begin{pmatrix} f_{12} - f_{11} & f_{13} - f_{12} & \cdots & f_{1n} - f_{1(n-1)} & 0 \\ f_{22} - f_{21} & \cdots & & & 0 \\ \vdots & & & \vdots & 0 \\ f_{m2} - f_{m1} & \cdots & & f_{mn} - f_{m(n-1)} & 0 \end{pmatrix} \quad (1)$$

and

$$f_y = \tilde{D}_y \cdot f = \begin{pmatrix} f_{21} - f_{11} & f_{22} - f_{12} & \cdots & f_{2n} - f_{1n} \\ f_{31} - f_{21} & \cdots & & f_{3n} - f_{2n} \\ \vdots & & & \vdots \\ f_{m1} - f_{(m-1)1} & \cdots & & f_{mn} - f_{(m-1)n} \\ 0 & \cdots & 0 & 0 \end{pmatrix}. \quad (2)$$

Solution. The corresponding operators \tilde{D}_x and \tilde{D}_y are given as follows:

$$\tilde{D}_x = \begin{pmatrix} -1 & 0 & \dots & 0 & 0 \\ 1 & -1 & \dots & 0 & 0 \\ 0 & 1 & \ddots & 0 & 0 \\ 0 & 0 & \ddots & -1 & 0 \\ 0 & \dots & & 1 & 0 \end{pmatrix} \quad \tilde{D}_y = \begin{pmatrix} -1 & 1 & \dots & 0 & 0 \\ 0 & -1 & 1 & \dots & 0 & 0 \\ 0 & 0 & \ddots & \ddots & 0 & 0 \\ 0 & 0 & & -1 & 1 & 0 \\ 0 & 0 & \dots & & -1 & 1 \\ 0 & 0 & \dots & & 0 & 0 \end{pmatrix} \quad (3)$$

Exercise 2. Implement the derivative operators from the previous exercise using MATLABs `spdiags` command. Load the image from the file `Vegetation-028.jpg` using the command `imread` and convert it to a grayvalue image using the command `rgb2gray`. Finally apply the operators to the image and display your results using `imshow`.

For our algorithms it is more convenient to represent an image f as a vector $\text{vec}(f) \in \mathbb{R}^{mn}$, that means that the columns of f are stacked one over the other.

Exercise 3. Derive a gradient operator

$$\nabla = \begin{pmatrix} D_x \\ D_y \end{pmatrix}$$

for vectorized images so that

$$D_x \cdot \text{vec}(f) = \text{vec}(f_x) \quad D_y \cdot \text{vec}(f) = \text{vec}(f_y)$$

You can use that it holds that for matrices A, X, B

$$AXB = C \iff (B^\top \otimes A)\text{vec}(X) = \text{vec}(C)$$

where \otimes denote the Kronecker (MATLAB: `kron`) product.

Experimentally verify that the results of Ex. 2 and Ex. 3 are equal by reshaping them to the same size using MATLABs `reshape` or the `:` operator, and showing that the norm of the difference of both results is zero.

Solution. We have $f_x = f \cdot \tilde{D}_x = I \cdot f \cdot \tilde{D}_x$, where I is the identity matrix. If we set $A := I$, $X := f$, $B := \tilde{D}_x$ and $C := f_x$ we obtain using the formula,

$$D_x = \tilde{D}_x^\top \otimes I. \quad (4)$$

We have $f_y = \tilde{D}_y \cdot f = \tilde{D}_y \cdot f \cdot I$. We set $A := \tilde{D}_y$, $X := f$, $B := I$ and $C := f_y$ and obtain using the formula:

$$D_y = I \otimes \tilde{D}_y. \quad (5)$$

Exercise 4. Assemble an operator ∇_c for computing the gradient (or more precisely the Jacobian) of a color image $f \in \mathbb{R}^{n \times m \times 3}$ using MATLABs `cat` and `kron` commands.

Solution.

$$\nabla_c := \begin{pmatrix} D_x & 0 & 0 \\ 0 & D_x & 0 \\ 0 & 0 & D_x \\ D_y & 0 & 0 \\ 0 & D_y & 0 \\ 0 & 0 & D_y \end{pmatrix} = \begin{pmatrix} I \otimes D_x \\ I \otimes D_y \end{pmatrix} \quad (6)$$

Exercise 5. Compute the color total variation given as

$$TV(f) = \|\nabla_c \text{vec}(f)\|_{F,1} = \sum_{i=1}^{nm} \left\| \begin{pmatrix} (D_x \cdot \text{vec}(f_r))_i & (D_x \cdot \text{vec}(f_g))_i & (D_x \cdot \text{vec}(f_b))_i \\ (D_y \cdot \text{vec}(f_r))_i & (D_y \cdot \text{vec}(f_g))_i & (D_y \cdot \text{vec}(f_b))_i \end{pmatrix} \right\|_F$$

of the two images `Vegetation-028.jpg` and `Vegetation-043.jpg` and compare the values. What do you observe? Why?