Spatially varying and anisotropic Diffusion

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Spatially varying diffusion

- Diffusion flux at point (x, y)

$$J(x, y) = K(x, y)\nabla u$$

- Heat equation becomes

$$\begin{aligned} u_t &= \nabla \cdot J(x, y), \\ &= \nabla \cdot (K(x, y)\nabla u). \end{aligned}$$

Spatially varying diffusion - 1D

- In one dimension, this would be

$$u_t = (K(x)u_x)_x.$$

- A common approach to discretizing this is to use a *forward difference* $D_+^x \approx u_x$ on the u_x term, evaluate $K(x)$ at the midpoint: $K(x_{i+\frac{1}{2}})$, and then use a *backwards difference* to calculate the outside gradient. i.e.

$$(K(x)u_x)_x \approx D_-^x(K(x_{i+\frac{1}{2}})D_+^x u) = ...$$

- What is this for constant diffusion $K(x) = K$?

Spatially varying diffusion - 2D

For two dimensions, the spatially varying heat equation is

$$u_t = (K(x,y)u_x)_x + (K(x,y)u_y)_y.$$

- this can be discretized in a similar fashion ...

- If only the nodal values for $K(x, y)$ are known, then a reasonable approximation is to use the average of two neighbouring grid points

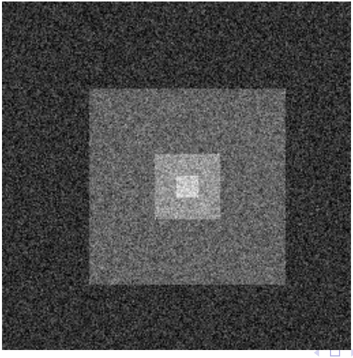
$$K(x_i, y_{j+\frac{1}{2}}) = \frac{1}{2}(K_{i,j+1} + K_{i,j})$$
$$K(x_{i+\frac{1}{2}}, y_j) = \frac{1}{2}(K_{i+1,j} + K_{i,j})$$

put it all together with $\Delta x = \Delta y = 1$, this simplifies to

$$\begin{aligned}
u_{i,j}^{n+1} =& u_{i,j}^{n} + \frac{1}{2}\Delta t(\\
& (K_{i+1,j} + K_{i,j})u_{i+1,j} + (K_{i-1,j} + K_{i,j})u_{i-1,j} \\
& (K_{i,j+1} + K_{i,j})u_{i,j+1} + (K_{i,j-1} + K_{i,j})u_{i,j-1} \\
& -(K_{i+1,j} + K_{i-1,j} + K_{i,j+1} + K_{i,j-1} + 4K_{i,j})u_{i,j})
\end{aligned}$$

Anisotropic Diffusion

- Motivation: diffusion parameter D is constant over the entire domain. While this smooths out noise, it also smooths out image features, most notably edges
- Goal: we wish to reduce diffusion across (or perpendicular) to the edge while keeping normal diffusion along (tangential) to the edge.



New coordinate system near edge

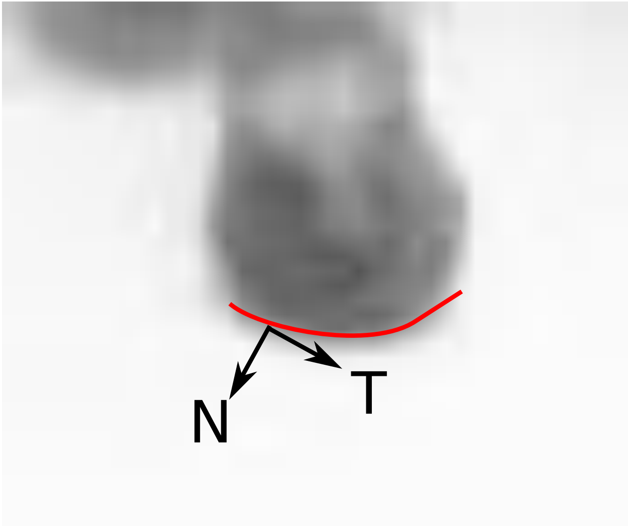


Figure : vector N is normal to the edge and T is tangential

New coordinate system near edge

- The unit vector N normal to Γ and the tangential vector T are given by

$$N = \frac{1}{|\nabla u|}\nabla u = \frac{1}{|\nabla u|}\begin{pmatrix} u_x \\ u_y \end{pmatrix}$$
$$T = N^{\perp} = \frac{1}{|\nabla u|}\begin{pmatrix} -u_y \\ u_x \end{pmatrix}$$

- We can then define the first and second derivatives of u with respect to N and T.

$$u_N = N \cdot \nabla u, \qquad u_{NN} = N \cdot H(u) N,$$
$$u_T = T \cdot \nabla u, \qquad u_{TT} = T \cdot H(u) T,$$

Anisotropic diffusion tensor

- Define new diffusion constant to be used in the coordinate system of N and T

$$K = \begin{pmatrix} \alpha & 0 \\ 0 & \beta \end{pmatrix}.$$

- Defining $\nabla u = \begin{pmatrix} u_N \\ u_T \end{pmatrix}$, the heat equation becomes

$$u_t = \nabla \cdot (K \nabla u) = \nabla \cdot \left(\begin{pmatrix} \alpha & 0 \\ 0 & \beta \end{pmatrix} \begin{pmatrix} u_N \\ u_T \end{pmatrix} \right)$$

$$u_t = \alpha u_{NN} + \beta u_{TT}$$

- (**exercise**) The above in terms of x and y derivatives is

$$u_t = \frac{Au_{xx} + Bu_{xy} + Cu_{yy}}{u_x^2 + u_y^2},$$

where

$$\begin{aligned} A &= \alpha u_x^2 + \beta u_y^2 \\ B &= (\alpha - \beta) u_x u_y \\ C &= \beta u_x^2 + \alpha u_y^2 \end{aligned}$$

Finite Difference

- We can discritize the single derivatives using a *central difference* $D_c^x u \approx u_x$

$$u_x \approx D_c^x u = \frac{u_{i+1,j} - u_{i-1,j}}{2\Delta x}$$

- The mixed derivative u_{xy} can be constructed by using the central difference operator twice on x and y

$$u_{xy} = (u_x)_y \approx D_c^y(D_c^x u) \quad = \frac{u_{i+1,j+1} - u_{i-1,j+1} - u_{i+1,j-1} + u_{i-1,j-1}}{4\Delta x \Delta y}.$$

- Note: can derive u_{xx} and u_{yy} using a combination of *forward difference* D_+^x and *backwards difference* D_-^x operators.

$$u_{xx} \approx D_-^x(D_+^x u) = \frac{u_{i+1,j} - 2u_{i,j} + u_{i-1,j}}{\Delta x^2}$$

$$u_{yy} \approx D_-^y(D_+^y u) = \frac{u_{i,j+1} - 2u_{i,j} + u_{i,j-1}}{\Delta y^2}$$

MATLAB code