

# Distance, curvature

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## 1 Normals and curvature

There is a deep link between the evolution of the normal vector along a curve and the curvature itself.

Let  $C$  be a planar curve. To define the curvature at a point, we can consider the case of a straight line. We can admit that in this case the curvature is zero along the line. For a portion of a circle, the curvature is defined to be inversely proportional to the radius of the circle:

$$\kappa = \frac{1}{R} \quad (1)$$

More precisely, for any curve, we can locally approximate a sufficiently regular curve ( $\mathcal{C}^2$  is enough) at a point by a circle that best approximates it locally (see Fig. 1). This circle is tangent to  $C$  and is called an *osculating circle*. The radius of this circle defines the curvature.

Another way to define the curvature is to consider a point moving at a constant speed along the curve  $C$ . The variation of the tangent vector along the curve defines the curvature. This is equivalent to specifying the acceleration of the point.

$$\kappa = \frac{d\mathbf{T}}{ds}, \quad (2)$$

where  $s$  is a parametrisation of the curve. Both definition of the curvature are in fact equivalent (see Fig. 2).

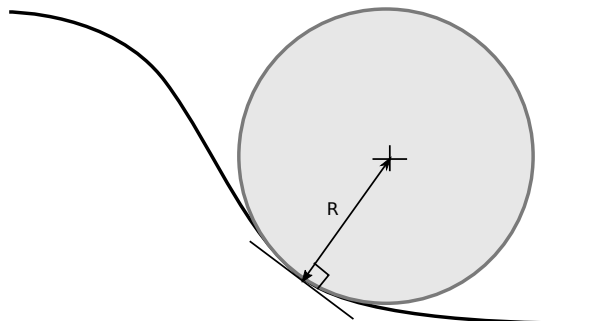


Figure 1: The notion of an osculating circle (best local approximation) defines the curvature as the inverse of the radius of the circle.

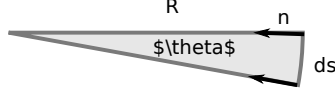


Figure 2: We can write  $\sin d\theta \approx d\theta = \frac{ds}{R}$ . As  $ds$  tends to zero, we have  $R = \frac{d\theta}{ds} = \frac{d\mathbf{T}}{ds}$ .

## Parametrisation

Let  $\gamma(t)$  be a parametrisation of the curve  $C$ , i.e.

$$\gamma(t) = (x(t), y(t)) \quad (3)$$

This defines the position of a point on the curve over time. We assume an injective parametrisation, i.e. such that the speed  $\gamma'(t)$  is never zero. This means

$$\forall t, \|\gamma'(t)\|^2 = x'(t)^2 + y'(t)^2 > 0 \quad (4)$$

In this case, we can re-parametrise the curve with curvilinear abscissa  $s$  in such a way that the speed is constant and equal to one.

$$\forall s, \gamma'(s)^2 = x'(s)^2 + y'(s)^2 = 1 \quad (5)$$

In this parametrisation,  $\gamma'$  is the unit tangent velocity vector  $\mathbf{T}$ . If  $\mathbf{N}$  is the unit normal vector to the curve, we have

$$\mathbf{T}'(s) = \kappa(s)\mathbf{N}(s) \quad (6)$$

We note that instead of deriving the unit tangent vector, we can also consider deriving the unit normal vector. This is because  $\mathbf{N}$  is  $\mathbf{T}$  rotated by  $\frac{\pi}{2}$ , i.e.  $\mathbf{N}(x, y) = (-y'(s), x'(s))$ . This yields

$$\mathbf{N}'(s) = \kappa(s)\mathbf{T}(s) \quad (7)$$

We will make use of that fact in the next section.

## Level sets

In imaging it can be difficult to represent a parametric curve because of discretization effects. It is common to represent it by a *level set* (see Fig. 3).

Let  $\phi(x, y)$  be a  $\mathcal{C}^2$  function in a domain  $\Omega$ . We define the curve  $\Gamma$  as the zero-level-set of this function

$$\Gamma = \{(x, y), \phi(x, y) = 0\} \quad (8)$$

$\Gamma$  is a set and no longer a parametrized curve, however we can manipulate it by working on the underlying  $\phi$  function. This is the main idea behind the level-set method [?].

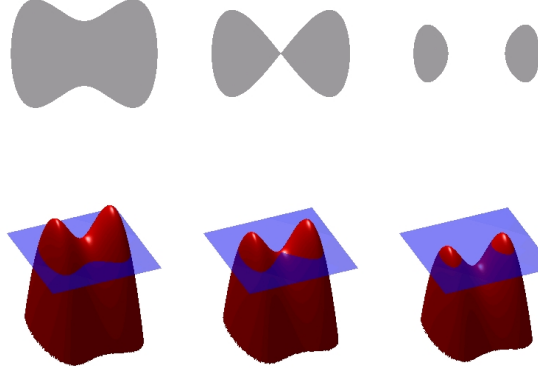


Figure 3: Representing a curve by a level set.

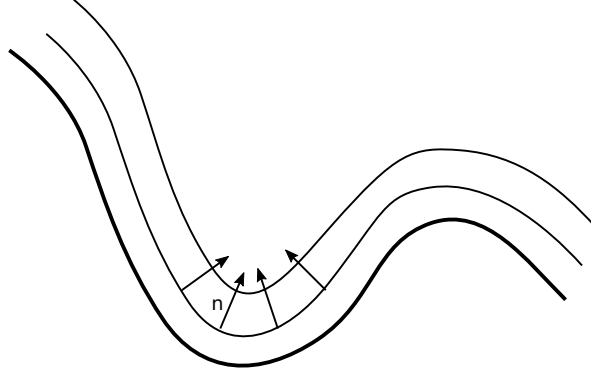


Figure 4: The faster the normal evolves along a curve, the higher the curvature.

## Level sets and curvature

Curvature is easy to define in the level set case. For any point  $(x, y)$  in  $\Omega$ ,  $\nabla\phi(x, y)$  is the gradient at  $(x, y)$ . If we consider the level-set at  $(x, y, \phi(x, y))$ , i.e. the curve that passes through  $(x, y)$  at level  $\phi(x, y)$ , then  $\nabla\phi(x, y)$  is the normal vector to this curve at  $(x, y)$ . The unit normal is given by

$$\mathbf{n}(x, y) = \frac{\nabla\phi}{|\nabla\phi|}(x, y) \quad (9)$$

The curvature is given by the derivative of this expression. However this is a multidimensional derivative. Since  $\nabla\phi$  is a vector, we must use the divergence operator  $\nabla \cdot \mathbf{F} \equiv \sum_i^d \frac{\partial \mathbf{F}_i}{\partial x_i}$ :

$$\kappa = \nabla \cdot \frac{\nabla\phi}{|\nabla\phi|} \quad (10)$$

This is in particular true for the computation of the curvature of  $\Gamma$ .

## 2 Application to our problem

Here we assume a non-convex territory with two nested surfaces as borders. Every point  $p$  of the territory is associated with a value  $\omega(p)$  so that  $\omega(p) = 0$  if  $p$  belongs to the inner surface, and  $\omega(p) = 1$  on the outer surface. Numerically,  $\omega$  can for example be computed from solving the electrostatic Poisson equation, i.e. a random walker. Our formulations and illustrations are in 2D but carry over to 3D without significant changes.

Let  $[p_1 p_2]$  be the segment defined by the points  $\{p_1, p_2\}$ . We want to define how to sample this segment, so that we can conclude with high confidence whether or not the whole segment is located inside a non-convex territory. The number of samples  $(k + 1)$  shall be optimized in order to avoid too many tests (minimize computation time) but also to guarantee the result within a reasonable tolerance (maximize test accuracy).

### 2.1 First approach

We can estimate  $k$ , the number of samples along the segment, from:

$$k \propto \frac{|p_2 - p_1|}{R} \quad (11)$$

$R$  is an approximation of the local radius of curvature along the segment by estimating the divergence at each point  $p_1$  and  $p_2$ , called  $\kappa_1$  and  $\kappa_2$  respectively :

$$R = \max(|\frac{1}{\kappa_1}|, |\frac{1}{\kappa_2}|) \quad (12)$$

The figure 5 illustrates the relationship between  $D = |p_2 - p_1|$ ,  $R_1 = \frac{1}{|\kappa_1|}$ ,  $R_2 = \frac{1}{|\kappa_2|}$  and  $k$ .

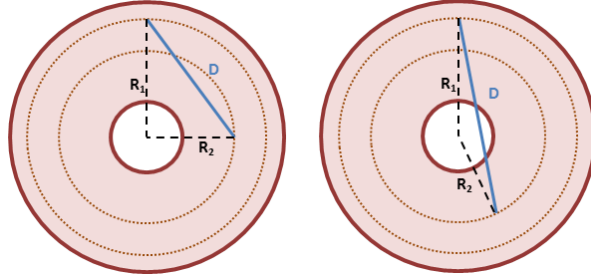


Figure 5: When  $D$  becomes larger relatively to  $\max(|R_1, R_2|)$ , the value of  $k$  is also higher to detect if the segment crosses the perfusion territory.

The divergence of a continuously differentiable vector field  $\mathbf{w} = (w_x, w_y)$  is equal to the scalar value function:

$$\text{div}(\mathbf{w}) = \left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}\right) \cdot (w_x, w_y) \quad (13)$$

$$\text{div}(\mathbf{w}) = (w_x(x, y) - w_x(x - 1, y)) + (w_y(x, y) - w_y(x, y - 1)). \quad (14)$$

Since we are interested in estimating a curvature, the field  $\mathbf{w}$  is the normalized gradient of  $\omega$ .

$$w_x = \frac{\nabla_x \omega}{\|\nabla \omega\|} = \frac{\omega(x + 1, y) - \omega(x, y)}{\sqrt{(\nabla_x \omega)^2 + (\nabla_y \omega)^2}} \quad (15)$$

and

$$w_y = \frac{\nabla_y \omega}{\|\nabla \omega\|} = \frac{\omega(x, y+1) - \omega(x, y)}{\sqrt{(\nabla_x \omega)^2 + (\nabla_y \omega)^2}} \quad (16)$$

This approach does not take into account the position of  $p_1$  and  $p_2$  within the territory, and so it is easy to find counter-examples where this approach fails.

## 2.2 Second approach

Here we consider an iterative process to take into account the curvature along a segment.

### 2.2.1 Interpolating the point along the segment line that crosses the concavity

We calculate the distances  $\lambda_1, \lambda_2$  that solves:

$$\omega(p_1) + \lambda_1 \langle \nabla \omega(p_1), \vec{p_1 p_2} \rangle = 0, \quad (17)$$

and symmetrically for  $\lambda_2$ .

Then we select:

$$\lambda = \min(\lambda_1, \lambda_2) \quad (18)$$

to obtain :

$$k = \left\lceil \frac{1}{\lambda} \right\rceil, \quad (19)$$

where  $\lceil \cdot \rceil$  denotes the ceiling operator, i.e. the function that maps a real number to the smallest integer that is larger or equal to it.

If  $\lambda < 0$  or  $\lambda > 1$ , it means the line  $(p_1 p_2)$  crosses the concavity outside of the segment  $[p_1 p_2]$ . We could consider that there is actually no need of refining the test along the segment. But we have to keep in mind that this interpretation comes only from a linear local approximation. In Fig. 6, we show a counter-example, where this approach fails.

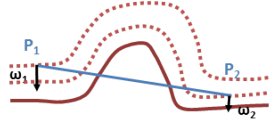


Figure 6: Specific situation where the local gradient doesn't help detecting the concavity.

Also, this method would fail for any case where the dot product  $\langle \nabla \omega(p_1), \vec{p_1 p_2} \rangle \simeq 0$ , and in some specific situations such as the figure 2.2.1. Hence we need to define a global boundary:

$$k \geq \frac{\|\vec{p_1 p_2}\|}{R_{\max}} \quad (20)$$

with  $R_{\max}$  the maximal curvature radius of both inner and outer surfaces.

Note: if the segmentation is noisy, we might actually measure non-physical very high curvatures, i.e.  $R_{\max}$  close to zero, hence it is necessary to consider a tolerance  $t$  so that

$$R_{\max}^* = R_{\max} - t \quad (21)$$

The semi-cord  $c$  defined by  $R_{\max}^*$  and  $t$  is calculated as:

$$c = \sqrt{R_{\max}^2 - R_{\max}^{*2}} \quad (22)$$

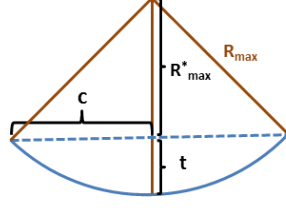


Figure 7: The maximally inscribed radius and tolerance  $t$  define a semi-cord  $c$ .

That can be simplified as:

$$c = \sqrt{R_{max}^2 - (R_{max} - t)^2} \quad (23)$$

The global boundary follows this tolerance:

$$k \geq \frac{\|\vec{p_1 p_2}\|}{c} \quad (24)$$

We take the largest  $k$  between maximal curvature and gradient method. This provides a robust sampling definition considering both local and global informations, see figure 2.2.1.

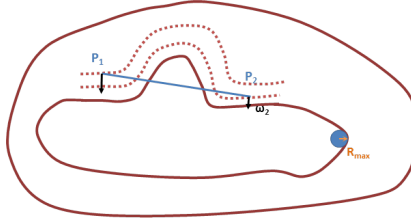


Figure 8: In this situation, considering the global maximum curvature will allow us to detect the concavity between  $p_1$  and  $p_2$ .

### 2.2.2 Estimating a sampling distance from the projection of the border

Given  $p_1$  and  $p_2$ , we want to find length  $M_1$  in Fig. 9 from local information.

First we denote  $p_0$  the intersection of the steepest descent from  $p_1$  with the 0-surface, the surface where  $\omega = 0$ . since  $\nabla\omega(p_1)$  and  $\vec{p_0 p_1}$  are co-linear, to first order we can write

$$\nabla\omega(p_1) \approx \frac{\omega(p_0) - \omega(p_1)}{\vec{p_1 p_0}} \quad (25)$$

Point  $p_0$  is actually unknown, but  $\omega(p_0) = 0$ , so we have:

$$\vec{p_1 p_0} \approx \frac{-\omega(p_1)}{\nabla\omega(p_1)} \quad (26)$$

Then we can project this vector  $\vec{p_1 p_0}$  on the segment  $\vec{p_1 p_2}$ :

$$M_1 = \frac{\langle \vec{p_1 p_0}, \vec{p_1 p_2} \rangle}{\|\vec{p_1 p_2}\|} \quad (27)$$

