

## Reminder: Euclidean spaces

- We work in  $n$ -dimensional space  $x = (x_1, x_2, \dots, x_n)$ .
- 2D:  $v = (x_1, x_2) = (x, y)$
- 3D:  $v = (x_1, x_2, x_3) = (x, y, z)$

## Scalar product

If we have  $x = (x_1, \dots, x_n)$  and  $y = (y_1, \dots, y_n)$ , then:

$$x \cdot y = \langle x, y \rangle = x_1 y_1 + \dots + x_n y_n$$

## Cross product (3D)

$$x = (x_1, x_2, x_3)$$

$$y = (y_1, y_2, y_3)$$

$$x \times y = (x_2 y_3 - x_3 y_2, x_3 y_1 - x_1 y_3, x_1 y_2 - x_2 y_1)$$

## Scalar Field

A scalar field

$$F : \mathbb{R} \rightarrow \mathbb{R}, x \rightarrow F(x)$$

assigns a scalar value to every point.

Examples: temperature, chemical concentration, pressure, probability distribution.

Given a scalar field  $F^n \rightarrow \mathbb{R}$ , the level set of the value  $c \in \mathbb{R}$  is:

$$\{x \in \mathbb{R}^n : f(x) = c\}$$

## Vector Field

A vector field assigns a vector to each point in space:

$$F : \mathbb{R}^n \rightarrow \mathbb{R}^n, x \rightarrow (F_1(x), \dots, F_n(x))$$

Examples:

- $F : \mathbb{R}^2 \rightarrow \mathbb{R}^2, (x_1, x_2) \rightarrow (-x_2, x_1)$
- $F : \mathbb{R}^2 \rightarrow \mathbb{R}^2, (x_1, x_2) \rightarrow (2x_1, x_2 + x_3, x_1 x_2 x_3)$

How to visualize vector fields? Put one arrow for each point in space.

- constant vector field
- rotational vector field
- source vector field

## Gradient, Hessian, Laplacian

If  $F : \mathbb{R}^n \rightarrow \mathbb{R}$  is a scalar field, then the gradient is the vector field

$$\nabla F = (\partial x_1 f, \partial x_2 f, \dots, \partial x_n f)$$

$$\nabla = \begin{pmatrix} \partial x_1 \\ \partial x_2 \\ \dots \\ \partial x_n \end{pmatrix}$$

$$\text{grad } f = \nabla f = \begin{pmatrix} \partial x_1 f \\ \partial x_2 f \\ \dots \\ \partial x_n f \end{pmatrix}$$

Example:

$$f(x_1, x_2) = x_1^3 + x_1 x_2^5$$

$$\nabla f(x_1, x_2) = (3x_1^2 + x_2^5, x_1 \cdot 5x_2^4)$$

- Geometrically,  $\nabla f$  points in the direction of the steepest increase of  $f$
- The directional derivative of  $f$  in direction  $v \in \mathbb{R}^n$  is:

$$D_v f = \nabla f \cdot v = \partial x_1 f \cdot v + \dots + \partial x_n f \cdot v_n$$

The value  $D_v f$  tells us how  $f$  changes as we move in direction  $v$ .

- Along any level set line, the gradient is orthogonal.

Example:

$$f(x_1, x_2) = x_1^2 + x_2^2$$

$$\nabla f(x_1, x_2) = (2x_1, 2x_2)$$

Level set of  $c = 1$ .

If  $F : \mathbb{R}^n \rightarrow \mathbb{R}$  is a scalar field, then the Hessian of  $f$  is a matrix field:

$$\nabla^2 f = \begin{pmatrix} \partial_1 \partial_1 f & \partial_1 \partial_2 f & \dots & \partial_1 \partial_n f \\ \dots & \dots & \dots & \dots \\ \partial_n \partial_1 f & \dots & \dots & \partial_n \partial_n f \end{pmatrix}$$

- The Hessian is symmetric if all 2nd derivatives are continuous
- Physical/geometric interpretation contains information on the curvature of the scalar field

If  $F : \mathbb{R}^n \rightarrow \mathbb{R}$  is a scalar field, then the Laplacian of  $f$  is the scalar field:

$$\Delta f = \sum_{i=1}^n \partial_i \partial_i f = \partial_1 \partial_1 f + \partial_2 \partial_2 f + \dots + \partial_n \partial_n f$$

- Sum of the diagonal entries of the Hessian
- Physically relevant in modeling diffusion

Poisson problem :  $-\Delta u = f$  ( $u$  is an unknown scalar field, while  $f$  is known, it's a differential equation).

Example:

$$f(x, y, z) = xy^3e^z$$

$$\nabla f(x) = (y^3e^z, 3xy^2e^z, xy^3e^z)$$

$$\partial_x \partial_x f = 0$$

$$\partial_x \partial_y f = 3y^2e^z$$

$$\partial_x \partial_z f = y^3e^z$$

$$\partial_y \partial_y f = 6xye^z$$

$$\partial_y \partial_z f = 3xy^2e^z$$

$$\partial_z \partial_z f = xy^3e^z$$

$$\nabla^2 f = \begin{pmatrix} 0 & 3y^2e^z & y^3e^z \\ 3y^2e^z & 6xye^z & 3xy^2e^z \\ y^3e^z & 3xy^2e^z & xy^3e^z \end{pmatrix}$$

$$\Delta f = 0 + 6xye^z + xy^3e^z = e^z xy(6 + y^2)$$

Example:

$$F(x) = \|x\| = \sqrt{\sum_{i=1}^n x_i^2}, x \in \mathbb{R}^n$$

First partial derivatives:

$$\partial_i F(x) = \partial_i \left( \sum_{i=1}^n x_i^2 \right)^{\frac{1}{2}} = \frac{1}{2} \left( \sum_{i=1}^n x_i^2 \right)^{-\frac{1}{2}} \cdot 2x_i = \frac{1}{\|x\|} x_i = \frac{x_i}{\|x\|}$$

Notice the singularity at  $x = 0$ . It looks like the gradient is not defined but in fact it can be removed by continuous extension of the first derivatives.

Second partial derivatives (case disjunction):

$$\begin{aligned} \partial_i \partial_i f(x) &= \partial_i \left( \frac{x_i}{\|x\|} \right) = \partial_i (x_i \cdot \|x\|^{-1}) = \frac{1}{\|x\|} + x_i \cdot \left( -\frac{1}{\|x\|^2} (\partial_i \|x\|) \right) \\ &= \frac{1}{\|x\|} + x_i \cdot -\frac{1}{\|x\|^2} \cdot \frac{x_i}{\|x\|} = \frac{1}{\|x\|} - \frac{x_i^2}{\|x\|^3} \end{aligned}$$

$$\partial_j \partial_i f(x) = \partial_j \left( \frac{x_i}{\|x\|} \right) = 0 + x_i \cdot -\frac{1}{\|x\|^2} (\partial_j \|x\|) = x_i \cdot -\frac{1}{\|x\|^2} \frac{x_j}{\|x\|} = \frac{-x_i x_j}{\|x\|^3}$$

All partial derivatives of order 2, we can build the Hessian matrix.

We want the Laplacian too:

$$\Delta f(x) = \sum_{i=1}^n \partial_i \partial_i f(x) = \sum_{i=1}^n \frac{1}{\|x\|} - \frac{x_i^2}{\|x\|^3} = \frac{n}{\|x\|} - \frac{\sum_{i=1}^n x_i^2}{\|x\|^3}$$

$$= \frac{n}{\|x\|} - \frac{\|x\|^2}{\|x\|^3} = \frac{n-1}{\|x\|}$$

## Divergence

Given a vector field  $F : \mathbb{R}^n \rightarrow \mathbb{R}^n, x \rightarrow (F_1(x), \dots, F_n(x))$

The divergence is the vector field:

$$\operatorname{div} F = \sum_{i=1}^n \partial_i F_i = \partial_1 F_1 + \partial_2 F_2 + \dots + \partial_n F_n$$

- formally,  $\operatorname{div} F = \nabla \cdot F$
- the Laplacian is the divergence of the gradient:  $\Delta F = \operatorname{div} \nabla F$

Example:

$$\operatorname{div} (x_1^2 x_2, x_2^3, e^{x_3}) = 2x_1 x_2 + 3x_2^2 + e^{x_3}$$

## Rotation or curl of vector fields

If  $F : \mathbb{R}^3 \rightarrow \mathbb{R}^3$  is a 3D vector field,  $F = (F_1, F_2, F_3)$ , then the curl/rotation is a 3D vector field:

$$\operatorname{curl} F = \operatorname{rot} F = \begin{pmatrix} -\partial_3 F_2 + \partial_2 F_3 \\ -\partial_1 F_3 + \partial_3 F_1 \\ -\partial_2 F_1 + \partial_1 F_2 \end{pmatrix}$$

Formally,  $\operatorname{curl} F = \nabla \times F$ .

Only works in 3D. There is a rotation in 2D:

If  $F : \mathbb{R}^2 \rightarrow \mathbb{R}^2$  is a 2D vector field, then the rotation/curl of  $F$  is a scalar field.

$$\operatorname{curl} F = \operatorname{rot} F = -\partial_2 F_1 + \partial_1 F_2$$

Motivation: we formally extend the vector field with a third coordinate  $F_3 = 0$ .

$$\tilde{F} = \begin{pmatrix} F_1 \\ F_2 \\ 0 \end{pmatrix} \Rightarrow \operatorname{curl} F = \begin{pmatrix} -\partial_3 F_2 + \partial_2 F_3 \\ -\partial_1 F_3 + \partial_3 F_1 \\ -\partial_2 F_1 + \partial_1 F_2 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ -\partial_2 F_1 + \partial_1 F_2 \end{pmatrix}$$

Examples: the divergence measures the presence of sinks and sources (“puits et sources”), while rotation measures the presence of a spin.

## Curve

$$\int_a^b f(x) dx = \text{integrate } f \text{ over interval } [a, b]$$

Now we generalize this:

$$\int_{\gamma} f dl = \text{integrate } f \text{ over curve } \gamma$$



A curve is a function

$$\gamma : [a, b] \rightarrow \mathbb{R}^n, t \rightarrow \gamma(t)$$

We may also think as  $\gamma(t)$  as a position in time. The image of  $\gamma(t)$  is written  $\Gamma(t)$ .

Some examples:

$\gamma(t) : [0, T] \rightarrow \mathbb{R}^3$  can be the 3D position of a drone flying.

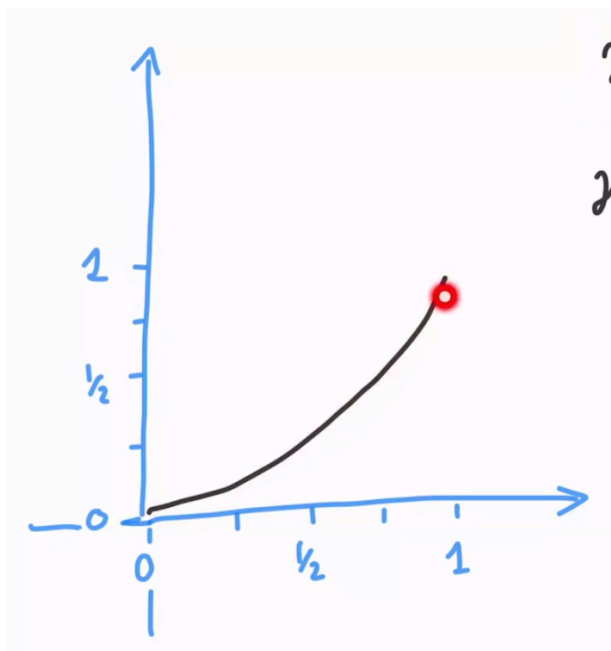
$\gamma(t) : [0, 1] \rightarrow \mathbb{R}^2$  can be the position at  $t\%$  of a car travel on a map.

$\gamma(t) : [0, 2\pi] \rightarrow \mathbb{R}^2, t \rightarrow (\cos(t), \sin(t))$  is the parametrization of the unit circle (as  $t$  progresses, we travel the unit circle).

Two functions can represent the same curve!

$$\gamma_1(t) : [0, 1] \rightarrow \mathbb{R}^2, t \rightarrow (t, t^2)$$

$$\gamma_2(t) : [0, 1] \rightarrow \mathbb{R}^2, t \rightarrow (\sqrt{t}, t)$$



### Notions and definitions

We call a curve

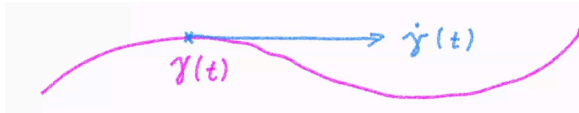
$$\gamma(t) : [a, b] \rightarrow \mathbb{R}^n, t \rightarrow (\gamma_1(t), \gamma_2(t), \dots, \gamma_n(t))$$

- **simple**: if it does not self-intersect (formally,  $\gamma : [a, b] \rightarrow \mathbb{R}^n$  is injective)
- **closed**: if  $\gamma(a) = \gamma(b)$
- **differentiable** if  $\gamma_1(t), \dots, \gamma_n(t)$  are differentiable

- **regular** if the curve is differentiable and the vector  $\forall t (\gamma_1'(t), \dots, \gamma_n'(t)) \neq \vec{0}$  (the derivatives are never 0 all together). It means that curve never comes to a full stop, they always keep moving.

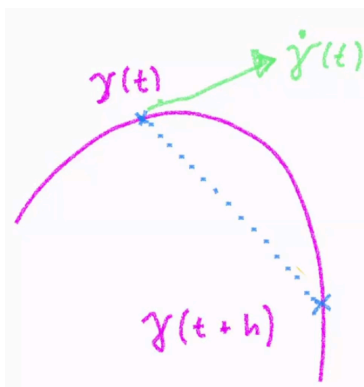
### Tangential vectors and speed

The tangent vector of a curve  $\gamma(t)$  is:  $\dot{\gamma}(t) = (\dot{\gamma}_1(t), \dots, \dot{\gamma}_n(t))$  and the speed is:  $|\dot{\gamma}(t)| = \sqrt{(\dot{\gamma}_1(t))^2 + \dots + (\dot{\gamma}_n(t))^2}$



Similar to the definition of the derivative:

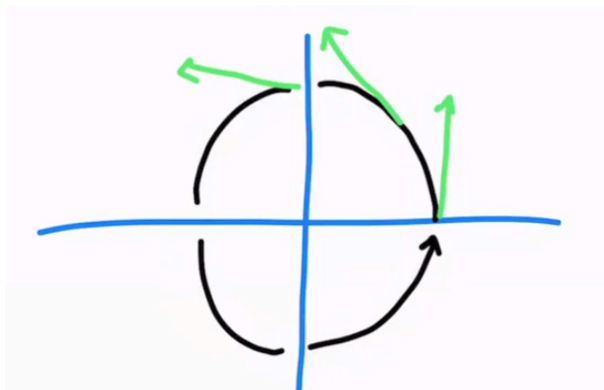
$$\dot{\gamma}(t) = \lim_{h \rightarrow 0} \frac{\gamma(t+h) - \gamma(t)}{h}$$



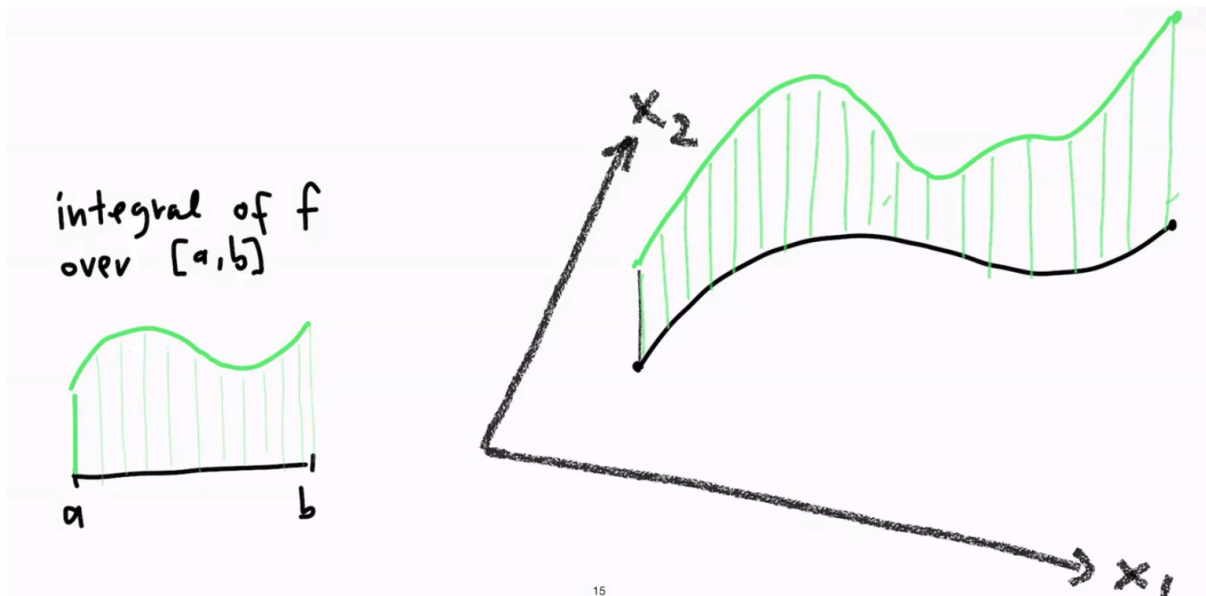
Example:

$$\gamma : [0, 2\pi] \rightarrow \mathbb{R}^2, t \rightarrow (\cos(t), \sin(t))$$

$$\dot{\gamma}(t) = (-\sin(t), \cos(t))$$



## Curve Integrals



Let  $\gamma : [a, b] \rightarrow \mathbb{R}^n$  be a curve Let  $f : \mathbb{R}^n \rightarrow \mathbb{R}$  be a scalar field

The integral of  $f$  over  $\Gamma$  is:

$$\begin{aligned} \int_{\Gamma} f dl &:= \int_a^b (f \circ \gamma)(t) |\dot{\gamma}(t)| dt \\ &= \int_a^b (f \circ \gamma)(t) \sqrt{(\dot{\gamma}_1(t))^2 + \dots + \dot{\gamma}_{n(t)}^2} dt \end{aligned}$$

The curve integral only depends on the curve  $\Gamma$ , not  $\gamma$  (which is what we want, we need the curve, not the parametrization, see eg. where we had 2 functions for one curve).

- where  $\gamma$  is slow,  $\dot{\gamma}$  is small
- where  $\gamma$  is fast,  $\dot{\gamma}$  is large

En fait si la fonction va très lentement, on va “utiliser” une grande partie de notre portion de  $a$  vers  $b$  pour la tracer, mais on réduit dcp le facteur.

If  $\gamma : [a, b] \rightarrow \mathbb{R}^n$  is a simple regular curve, then  $\int_{\Gamma} F dl$  only depends on  $\Gamma$ .

And it should! After all,  $\gamma$  is just a parametrization and  $\Gamma$  is the “physical” object.