

# MATH 2XX3 - Advanced Calculus II

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# 1 Introduction

In this course, we are going to study calculus using the concepts from linear algebra.

## 1.1 Vector norm

**Definition 1.1.** Euclidean norm of  $\vec{x} = (x_1, x_2, \dots, x_n)$  is given as

$$\|\vec{x}\| = \sqrt{\vec{x} \cdot \vec{x}} = \sqrt{\sum_{j=1}^n x_j^2}$$

**Theorem 1.1** (Properties of a norm).

1.  $\|\vec{x}\| \geq 0$  and  $\|\vec{x}\| = 0$  iff  $\vec{x} = \vec{0} = (0, 0, \dots, 0)$ .
2. For all scalars  $a \in \mathbb{R}$ ,  $\|a\vec{x}\| = |a| \cdot \|\vec{x}\|$ .
3. (Triangle inequality)  $\|\vec{x} + \vec{y}\| \leq \|\vec{x}\| + \|\vec{y}\|$ .

We say that this is a property of a norm because there are other norms, which measure distance in  $\mathbb{R}^n$  in different ways!

**Example 1.1.1** (A non-pythagorean norm - The Taxi Cab Norm). Consider the following vector  $\vec{p} = (p_1, p_2) \in \mathbb{R}^2$ . The euclidean norm gives the length of the diagonal line. On the other hand,

$$\|\vec{p}\|_1 = |p_1| + |p_2|$$

gives us the total distance in a rectangular grid system.

For  $\vec{p} = (p_1, p_2, \dots, p_n) \in \mathbb{R}^n$ ,  $\|\vec{p}\|_1 = \sum_{j=1}^n |p_j|$ . Note that the Taxi Cab norm is a valid norm because it satisfies all properties of a norm above. So it also gives us a valid alternative way to measure distance in  $\mathbb{R}^n$ ,  $\text{dist}(\vec{p}, \vec{q}) = \|\vec{p} - \vec{q}\|$ . This way of measuring distance gives  $\mathbb{R}^n$  a different geometry.

**Definition 1.2.** Neighborhood of a point  $\vec{p}$ , or disks centered at  $\vec{p}$  is defined as

$$D_r(\vec{p}) = \{\vec{x} \in \mathbb{R}^n \mid \|\vec{x} - \vec{p}\| < r\}$$

*Remark.* The neighborhood around  $\vec{a}$  of radius  $r$  may be written using any of the following notations:

$$D_r(\vec{a}) = B_r(\vec{a}) = B(\vec{a}, r)$$

**Definition 1.3.** Sphere is defined as

$$S_r(\vec{p}) = \{\vec{x} \in \mathbb{R}^n \mid \|\vec{x} - \vec{p}\| = r\}$$

What neighborhood and sphere look like depends on which norm you choose. First, let's start with the familiar euclidean norm. Then, the sphere is given by

$$\begin{aligned} \|\vec{x} - \vec{p}\| &= r \\ \iff \sqrt{\sum_{j=1}^n (x_j - p_j)^2} &= r \end{aligned}$$

Then, we have

$$\sum_{j=1}^n (x_j - p_j)^2 = r^2$$

If  $n = 3$ , we have  $(x_1 - p_1)^2 + (x_2 - p_2)^2 + (x_3 - p_3)^2 = r^2$ , usual sphere in  $\mathbb{R}^3$  with center  $\vec{p} = (p_1, p_2, p_3)$

If  $n = 2$ , we have  $(x_1 - p_1)^2 + (x_2 - p_2)^2 = r^2$ , usual circle in  $\mathbb{R}^2$  with center  $\vec{p} = (p_1, p_2)$ .

If we replace Euclidean norm by the Taxi Cab norm (for simplicity, take  $\vec{p} = \vec{0}$ ), we have

$$S_r^{\text{taxi}}(\vec{0}) = \left\{ \vec{x} \in \mathbb{R}^n \mid \|\vec{x} - \vec{0}\|_1 = r \right\}$$

In other words, we have

$$\vec{x} \in S_r^{\text{taxi}}(\vec{0}) \iff \sum_{j=1}^n |x_j| = r$$

Looking at it in  $\mathbb{R}^2$ , we have  $\vec{x} = (x_1, x_2)$ . Then,  $r = |x_1| + |x_2|$ . This, in fact, is a diamond.

*Remark.* Note that  $|x_1| + |x_2| = r$  is a *circle* in  $\mathbb{R}^2$  under the Taxi Cab norm. Then, we have

$$\pi = \frac{\text{circumference}}{\text{diameter}} = \frac{8r}{2r} = 4$$

## 1.2 Subset

Let's introduce some properties of *subsets* in  $\mathbb{R}^n$ .  $A \subset \mathbb{R}^n$  means  $A$  is a *collection* of points  $\vec{x}$ , drawn from  $\mathbb{R}^n$ .

**Definition 1.4.** Let  $A \subset \mathbb{R}^n$ , and  $\vec{p} \in A$ . We say  $\vec{p}$  is an *interior point* of  $A$  if there exists a neighbourhood of  $\vec{p}$ , i.e. an open disk, which is entirely contained in  $A$ :

$$D_r(\vec{p}) \subset A.$$

**Example 1.2.1.**

$$A = \left\{ \vec{x} \in \mathbb{R}^n \mid \vec{x} \neq \vec{0} \right\}$$

Take any  $\vec{p} \in A$ , so  $\vec{p} \neq \vec{0}$ . Then, let  $r = \|\vec{p} - \vec{0}\| > 0$ , and  $D_r(\vec{p}) \subset A$ , since  $\vec{0} \notin D_r(\vec{p})$ . (Notice: any smaller disk,  $D_s(\vec{p}) \subset D_r(\vec{p}) \subset A$ , where  $0 < s < r$  works to show that  $\vec{p}$  is an interior point).

So every  $\vec{p} \in A$  is an interior point to  $A$ .

**Definition 1.5.** If every  $\vec{p} \in A$  is an interior point, we call  $A$  an open set.

**Example 1.2.2.**  $A = \{\vec{x} \in \mathbb{R}^n | \vec{x} \neq \vec{0}\}$  is an open set.

**Example 1.2.3.**  $A = D_R(\vec{0})$  is an open set.

*Proof.* If  $\vec{p} = \vec{0}$ ,  $D_r(\vec{0}) \subseteq A = D_R(\vec{0})$  provided  $r \leq R$ . So  $\vec{p} = \vec{0}$  is interior to  $A$ . Consider any other  $\vec{p} \in A$ . It's evident that  $D_r(\vec{p}) \subset A = D_R(\vec{0})$  provided that  $0 \leq r \leq R - \|\vec{p}\|$ . Therefore,  $A = D_R(\vec{0})$  is an open set.  $\square$

**Example 1.2.4.** Suppose we use Taxi Cab disks instead of Euclidean disk. It does not change which points are interior to  $A$  since the diamond is inscribed in a circle. In other words,

$$D_r^{\text{taxi}}(\vec{p}) \subset D_r^{\text{Euclid}}(\vec{p})$$

**Definition 1.6.** The complement of set  $A$  is

$$A^c = \{\vec{x} | \vec{x} \notin A\}$$

**Definition 1.7.**  $\vec{b}$  is a boundary point of  $A$  if for every  $r > 0$ ,  $D_r(\vec{b})$  contains both points in  $A$  and points not in  $A$ :

$$D_r(\vec{b}) \cap A \neq \emptyset \text{ and } D_r(\vec{b}) \cap A^c \neq \emptyset$$

In the example 1.2.3, the set of all boundary points of  $A = D_R(\vec{0})$

$$\{\vec{b} | \|\vec{b}\| = R\}$$

is a sphere of radius  $R$ .

**Definition 1.8.** A set  $A$  is closed if  $A^c$  is open.

**Theorem 1.2.**  $A$  is closed if and only if  $A$  contains all its boundary points.

**Example 1.2.5.** Consider the following set:

$$A = \{(x_1, x_2) \in \mathbb{R}^2 | x_1 \geq 0, x_2 > 0\}$$

If  $\vec{p}_1 = (p_1, p_2)$ , where  $p_1 > 0, p_2 > 0$ , then  $\vec{p}_1$  is an interior point. Take  $r = \min\{p_1, p_2\}$ . Then,  $D_r(\vec{p}) \subset A$ . On the other hand, any  $\vec{p}$  that lies on either axes (including  $\vec{0}$ ) is a boundary point. Since there are boundary points in  $A$ ,  $A$  can't be open.

## 2 Functions

### 2.1 Limits and continuity

In this section, we will be considering vector values functions such that

$$F : A \subseteq \mathbb{R}^n \rightarrow \mathbb{R}^k.$$

We can rewrite this using a matrix notation:

$$F(x_1, x_2, \dots, x_n) = \begin{bmatrix} F_1(x_1, x_2, \dots, x_n) \\ F_2(x_1, x_2, \dots, x_n) \\ \vdots \\ F_k(x_1, x_2, \dots, x_n) \end{bmatrix}$$

**Example 2.1.1.** For a  $(k \times n)$  matrix  $M$ ,

$$F(\vec{x}) = M\vec{x}$$

First, we wish to study limits. What does  $\lim_{\vec{x} \rightarrow \vec{a}} F(\vec{x}) = \vec{L}$  mean? Note that it's not enough to treat the variables  $x_1, x_2, \dots, x_n$  separately.

**Example 2.1.2.** Consider the following function:

$$F(x, y) = \frac{xy}{x^2 + 4y^2},$$

where  $(x, y) \neq (0, 0)$ . First, we can attempt to find its limit by considering them separately.

$$\lim_{x \rightarrow 0} \left( \lim_{y \rightarrow 0} F(x, y) \right) = \lim_{x \rightarrow 0} \left( \frac{0}{x^2} \right) = \lim_{x \rightarrow 0} 0 = 0$$

Similarly, we have

$$\lim_{y \rightarrow 0} \left( \lim_{x \rightarrow 0} F(x, y) \right) = 0$$

However, if  $(x, y) \rightarrow (0, 0)$  along a straight line path with  $y = mx$ , where  $m$  is constant, we have

$$F(x, mx) = \frac{mx^2}{x^2 + 4m^2x^2} = \frac{m}{1 + 4m^2}$$

In this case, we have

$$\lim_{\substack{(x, y) \rightarrow (0, 0) \\ \text{along } y=mx}} F(x, y) = \frac{m}{1 + 4m^2}$$

Therefore, the values of  $F(x, y)$  don't approach any particular value as  $(x, y) \rightarrow (0, 0)$ .

**Example 2.1.3** (Worse). Consider the following function:

$$F(x, y) = \frac{y^2}{x^4 + y^2}.$$

If we approach  $(0, 0)$  along  $y = mx$ , limit equals 1. However, if we approach along a parabola,  $y = mx^2$ , limit equals  $m^2/(1 + m^2)$ . We get different limits along different parabolas.

We showed that computing

$$\lim_{\vec{x} \rightarrow \vec{a}} = \vec{b}$$

is tricky because  $\vec{x} \rightarrow \vec{a}$  has to be more precise. It can't depend on the path or direction on which  $\vec{x}$  approaches  $\vec{a}$ , but only on *proximity*. In other words, we want  $\|F(\vec{x}) - \vec{b}\|$  to go to zero as  $\|\vec{x} - \vec{a}\|$  goes to zero.

**Definition 2.1.** We say  $\lim_{\vec{x} \rightarrow \vec{a}} F(\vec{x}) = \vec{b}$  if for any given  $\varepsilon > 0$ , there exists  $\delta > 0$  such that whenever  $0 < \|\vec{x} - \vec{a}\| < \delta$ , we have  $\|F(\vec{x}) - \vec{b}\| < \varepsilon$ . Therefore,

$$\lim_{\vec{x} \rightarrow \vec{a}} F(\vec{x}) = \vec{b} \iff \lim_{\vec{x} \rightarrow \vec{a}} \|F(\vec{x}) - \vec{b}\| = 0$$

*Remark.* Geometrically, for any given  $\varepsilon > 0$ , there exists  $\delta > 0$  such that

$$F(\vec{x}) \in D_\varepsilon(\vec{b}),$$

where  $\vec{x} \in D_\delta(\vec{a})$ .

Before doing examples, here's a useful observations. Take  $\vec{v} = (v_1, v_2, \dots, v_n) \in \mathbb{R}^n$ . Then, we have

$$\|\vec{v}\| = \sqrt{\sum_{j=1}^n v_j^2} \geq \sqrt{v_i^2} = |v_i|$$

for each coordinate  $i = 1, 2, \dots, n$ .

**Example 2.1.4.** Show

$$\lim_{(x,y) \rightarrow (0,0)} \frac{2x^2y}{x^2 + y^2} = 0$$

*Proof.* Note that  $F : \mathbb{R} \setminus \{\vec{0}\} \rightarrow \mathbb{R}$ ,  $b = 0$ ,  $\vec{a} = (0, 0)$ . Call

$$R = \|\vec{x} - \vec{a}\| = \|\vec{x}\| = \sqrt{x^2 + y^2}$$

Since  $F(\vec{x}) \in \mathbb{R}$ , we have

$$\begin{aligned}
\|F(\vec{x}) - \vec{b}\| &= |F(\vec{x}) - b| \\
&= \left| \frac{2x^2y}{x^2 + y^2} - 0 \right| \\
&= \frac{2|x|^2|y|}{x^2 + y^2} \\
&\leq \frac{2 \cdot R^2 \cdot R}{R^2} \\
&= 2R \\
&= 2\|\vec{x} - \vec{a}\|
\end{aligned}$$

By letting  $\|\vec{x} - \vec{a}\| = \|\vec{x}\| < \varepsilon/2$ , we get  $\|F(\vec{x}) - \vec{b}\| < \varepsilon$ . Therefore, definition is satisfied with  $\delta \leq \varepsilon/2$   $\square$

**Example 2.1.5.** Consider the following function,  $F : \mathbb{R}^3 \setminus \{\vec{0}\} \rightarrow \mathbb{R}$ :

$$\frac{3z^2 + 2x^2 + 4y^2 + 6z^2}{x^2 + 2y^2 + 3z^2}.$$

Determine whether

$$\lim_{(x,y,z) \rightarrow (0,0,0)} F(x,y,z) = 2.$$

*Proof.* We have

$$\begin{aligned}
\|F(x,y,z) - \vec{b}\| &= |F(x,y,z) - 2| \\
&= \left| \frac{3z^3 + 2x^2 + 4y^2 + 6z^2}{x^2 + 2y^2 + 3z^2} - 2 \right| \\
&= \frac{3|z|^3}{x^2 + 2y^2 + 3z^2} \\
&\leq \frac{3R^3}{x^2 + y^2 + z^3} \\
&= \frac{3R^3}{R^2} \\
&= 3R
\end{aligned}$$

Then,

$$\|F(x,y,z) - \vec{b}\| < 3R < \varepsilon$$

provided that

$$R = \|\vec{x} - \vec{0}\| < \delta = \frac{\varepsilon}{3}$$

$\square$

**Definition 2.2.** Consider a function  $F : \mathbb{R}^n \rightarrow \mathbb{R}^k$  with domain  $A \subseteq \mathbb{R}^n$ . For  $\vec{a} \in A$ , we say  $F$  is continuous at  $\vec{a}$  in the domain of  $F$  iff

$$F(a) = \lim_{\vec{x} \rightarrow \vec{a}} F(\vec{a})$$

**Example 2.1.6.** Going back the example 2.1.5, if we redefine  $F$  as follows,

$$F = \begin{cases} \frac{3z^2+2x^2+4y^2+6z^2}{x^2+2y^2+3z^2} & (x, y, z) \neq (0, 0, 0) \\ 2 & (x, y, z) = (0, 0, 0) \end{cases}$$

then  $F$  is continuous at  $(0, 0, 0)$  (and in fact at all  $\vec{x} \in \mathbb{R}$ ).

If  $F$  is continuous at every  $\vec{a} \in A$ , ( $\forall \vec{x} \in A$ ), we say  $F$  is continuous on the set  $A$ . Continuity is always preserved by the usual algebraic operations: sum, product, quotient, and composition of continuous functions is continuous<sup>1</sup>.

## 2.2 Differentiability

**Definition 2.3.** For a function  $f : \mathbb{R} \rightarrow \mathbb{R}$ , its derivative is defined as

$$f'(x) = \lim_{h \rightarrow 0} \frac{f(x+h) - f(x)}{h}.$$

If it exists, we say  $f$  is differentiable at  $x$ .

**Theorem 2.1.** If  $f$  is differentiable at  $x$ ,  $f(x)$  is also continuous at  $x$ .

Note that differentiable functions,  $f(x)$ , are well approximated by their tangent lines (also known as linearization). We wish to extend this idea to  $F : \mathbb{R}^n \rightarrow \mathbb{R}^m$ .

First, we try dealing with the independent variables,  $x_1, x_2, \dots, x_n$ , one at a time by using partial derivatives. We start by introducing the standard basis in  $\mathbb{R}^n$ :

$$\begin{aligned} \vec{e}_1 &= (1, 0, 0, \dots, 0) \\ \vec{e}_2 &= (0, 1, 0, \dots, 0) \\ &\vdots \\ \vec{e}_n &= (0, 0, 0, \dots, 1) \end{aligned}$$

(In  $\mathbb{R}^3$ ,  $\vec{e}_1 = \vec{i}, \vec{e}_2 = \vec{j}, \vec{e}_3 = \vec{k}$ ).

For any  $\vec{x} \in \mathbb{R}^n$ , and  $h \in \mathbb{R}$ ,  $(\vec{x} + h\vec{e}_j)$  moves from  $\vec{x}$  parallel to the  $x_j$  axis by distance  $h$ . In other words,

$$\vec{x} + h\vec{e}_j = (x_1, x_2, \dots, x_j + h, x_{j+1}, \dots, x_n).$$

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<sup>1</sup>Provided we remain in the domain of continuity of both functions and denominators aren't zero



**Definition 2.4.** *Partial derivatives of  $f(x)$  is defined as*

$$\frac{\partial f}{\partial x_j}(\vec{x}) = \lim_{h \rightarrow 0} \frac{f(\vec{x} + h\vec{e}_j) - f(\vec{x})}{h},$$

for all  $j = 1, 2, \dots, n$ .

Partial derivatives calculate the derivatives of  $f$ , treating of  $\vec{x}_j$  as the only variable, and all others treated as constants. For a vector valued function  $F : \mathbb{R}^n \rightarrow \mathbb{R}^m$ :

$$F(\vec{x}) = \begin{bmatrix} F_1(\vec{x}) \\ F_2(\vec{x}) \\ \vdots \\ F_m(\vec{x}) \end{bmatrix},$$

we treat each component  $F_i(\vec{x}) : \mathbb{R}^n \rightarrow \mathbb{R}$  separately as a real valued function. Each has  $n$  partial derivatives, and so  $F : \mathbb{R}^n \rightarrow \mathbb{R}^m$  has  $(m \times n)$  partial derivatives, which form an  $(m \times n)$  matrix:

$$\left( \frac{\partial F_i}{\partial x_j} \right)_{\substack{i=1,2,\dots,m \\ j=1,2,\dots,n}}.$$

We call this the derivative matrix or *Jacobian matrix*,  $DF(\vec{x})$ .

**Example 2.2.1.** Consider a function  $F : \mathbb{R}^2 \rightarrow \mathbb{R}^3$ :

$$F(\vec{x}) = \begin{bmatrix} x_1^2 \\ x_1 x_2 \\ x_2^4 \end{bmatrix}.$$

Jacobian of the function is given by

$$\begin{aligned} DF(\vec{x}) &= \begin{bmatrix} \frac{\partial F_1}{\partial x_1} & \frac{\partial F_1}{\partial x_2} \\ \frac{\partial F_2}{\partial x_1} & \frac{\partial F_2}{\partial x_2} \\ \frac{\partial F_3}{\partial x_1} & \frac{\partial F_3}{\partial x_2} \end{bmatrix} \\ &= \begin{bmatrix} 2x_1 & 0 \\ x_2 & x_1 \\ 0 & 4x_2^3 \end{bmatrix} \end{aligned}$$

Do we get the same properties for  $DF(\vec{x})$  as we did for single-value calculus?

**Example 2.2.2.** Consider the following function:

$$f(x, y) = \begin{cases} \frac{xy}{(x^2+y^2)^2}, & (x, y) \neq (0, 0) \\ 0, & (x, y) = (0, 0) \end{cases}$$

Do the partial derivatives exist at  $(0, 0)$ ?

By definition,

$$\begin{aligned}\frac{\partial f}{\partial x}(0,0) &= \lim_{h \rightarrow 0} \frac{f(0+h,0) - f(0,0)}{h} \\ &= \lim_{h \rightarrow 0} \frac{\frac{h \cdot 0}{(h^2+0^2)^2} - 0}{h} \\ &= \lim_{h \rightarrow 0} \frac{0}{h} = 0\end{aligned}$$

Similarly,  $\frac{\partial f}{\partial y}(0,0) = 0$  (symmetry of  $x, y$ ). Therefore,

$$Df(0,0) = \begin{bmatrix} 0 & 0 \end{bmatrix}$$

Although partial derivatives exist,  $f$  is not continuous at  $(0,0)$ ! (For example,  $f(x, mx) \rightarrow \pm\infty$  as  $x \rightarrow 0^\pm$  for  $m \neq 0$ ).

To get reasonable information from  $Df(\vec{x})$ , we need to say more. First, let's go back to  $f : \mathbb{R} \rightarrow \mathbb{R}$ . Note

$$\begin{aligned}f'(x) &= \lim_{h \rightarrow 0} \frac{f(x+h) - f(x)}{h} \\ \iff \lim_{h \rightarrow 0} \left( \frac{f(x+h) - f(x)}{h} - f'(x) \right) &= 0 \\ \iff \lim_{h \rightarrow 0} \left( \frac{f(x+h) - \overbrace{[f(x) + hf'(x)]}^L}{h} \right) &= 0\end{aligned}$$

Numerator is the difference between  $f(x+h)$  and its linear approximation,  $L$  (i.e. the tangent line). So  $f$  is differentiable at  $x$  if its linear approximation gives an estimate of the values  $f(x+h)$  within an error which is small compared to  $\Delta x = h$ . More precisely, the linearization of  $f(x)$  at  $x = a$  (or the tangent line) is given by

$$L_a(x) = f(a) + f'(a)(x - a)$$

We wish to extend this idea to higher dimensions. For  $F : \mathbb{R}^n \rightarrow \mathbb{R}^m$ ,  $F(\vec{x})$  has  $(m \times n)$  partial derivatives (see definition 2.4). Then, the linearization of  $F$  at  $\vec{a}$  is

$$L_{\vec{a}}(\vec{x}) = \underbrace{F(\vec{a})}_{m \times 1} + \underbrace{DF(\vec{a})}_{m \times n} \underbrace{(\vec{x} - \vec{a})}_{n \times 1}.$$

So,  $L : \mathbb{R}^n \rightarrow \mathbb{R}^m$ , just like  $F$ . The derivative matrix  $DF(\vec{a})$  is a *linear transformation* of  $\mathbb{R}^n \rightarrow \mathbb{R}^m$ .

Notice that when  $n = 2$  and  $m = 1$ , For  $F : \mathbb{R}^2 \rightarrow \mathbb{R}$ , we have

$$DF(\vec{a}) = \begin{bmatrix} \frac{\partial F}{\partial x_1}(\vec{a}) & \frac{\partial F}{\partial x_2}(\vec{a}) \end{bmatrix},$$

a  $(1 \times 2)$  row vector and

$$\vec{x} - \vec{a} = \begin{bmatrix} x_1 - a_1 \\ x_2 - a_2 \end{bmatrix},$$

so we have

$$L_{\vec{a}}(\vec{x}) = F(\vec{a}) + \frac{\partial F}{\partial x_1}(x_1 - a_1) + \frac{\partial F}{\partial x_2}(x_2 - a_2),$$

a familiar equation of the tangent plane to  $z = F(x_1, x_2)$ .

Finally, we can introduce the idea of differentiable:

**Definition 2.5** (Differentiability). *We say  $F : \mathbb{R}^n \rightarrow \mathbb{R}^m$  is differentiable if*

$$\lim_{\vec{x} \rightarrow \vec{a}} \frac{\|F(\vec{x}) - F(\vec{a}) - DF(\vec{a})(\vec{x} - \vec{a})\|}{\|\vec{x} - \vec{a}\|} = 0.$$

*Equivalently,*

$$\lim_{\vec{h} \rightarrow \vec{0}} \frac{\|F(\vec{x} + \vec{h}) - F(\vec{x}) - DF(\vec{x})\vec{h}\|}{\|\vec{h}\|} = 0$$

In summary,  $F$  is differentiable if  $\|F(\vec{x}) - L_{\vec{a}}(\vec{x})\|$  is small compared to  $\|\vec{x} - \vec{a}\|$ . Or,  $F(\vec{x})$  is approximated by  $L_{\vec{a}}(\vec{x})$  with an error which is much smaller than  $\|\vec{x} - \vec{a}\|$ . Note that we write  $o(\|\vec{x} - \vec{a}\|)$  “little-oh” for quantity which is small compared to  $\|\vec{x} - \vec{a}\|$ . Using this notation, differentiability can be written as

$$\|F(\vec{x}) - F(\vec{a}) - DF(\vec{a})(\vec{x} - \vec{a})\| = o(\|\vec{x} - \vec{a}\|).$$

**Example 2.2.3.** Is the following function differentiable at  $\vec{a} = \vec{0}$ ?

$$F(x_1, x_2) = \begin{cases} \frac{x_2^2 \sin x_1}{\sqrt{x_1^2 + x_2^2}}, & \vec{x} \neq \vec{0} \\ 0, & \vec{x} = \vec{0} \end{cases}$$

First, we have

$$\begin{aligned} \frac{\partial F}{\partial x_1}(\vec{0}) &= \lim_{h \rightarrow 0} \frac{F(\vec{0} + h\vec{e}_1) - F(\vec{0})}{h} \\ &= \lim_{h \rightarrow 0} \frac{0 - 0}{h} = 0 \end{aligned}$$

Similarly, we have

$$\frac{\partial F}{\partial x_2}(\vec{0}) = 0$$

So we have

$$DF(\vec{0}) = \begin{bmatrix} \frac{\partial F}{\partial x_1} & \frac{\partial F}{\partial x_2} \end{bmatrix} = \begin{bmatrix} 0 & 0 \end{bmatrix}$$

For differentiability, we have to look at:

$$\begin{aligned} &\left| \frac{x_2^2 \sin x_1}{\sqrt{x_1^2 + x_2^2}} - 0 - \begin{bmatrix} 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \right| \\ &= \frac{x_2^2 |\sin x_1|}{\sqrt{x_1^2 + x_2^2}} \end{aligned}$$

Then,

$$\begin{aligned}\frac{|F(\vec{x}) - L_{\vec{0}}(\vec{x})|}{\|\vec{x} - \vec{0}\|} &= \frac{x_2^2 |\sin x_1|}{\left(\sqrt{x_1^2 + x_2^2}\right)^2} = \frac{x_2^2 |\sin x_1|}{x_1^2 + x_2^2} \\ &\leq \frac{R^2 \cdot R}{R^2} = R = \|\vec{x} - \vec{0}\|\end{aligned}$$

By squeeze theorem, we have

$$\lim_{\vec{x} \rightarrow \vec{0}} \frac{|F(\vec{x}) - L_{\vec{0}}(\vec{x})|}{\|\vec{x} - \vec{0}\|} = 0$$

Therefore,  $F$  is differentiable at  $\vec{x} = \vec{0}$

**Example 2.2.4.** Verify that  $F$  is differentiable at  $\vec{a} = \vec{0}$ .

$$F(\vec{x}) = \begin{bmatrix} 1 + x_1 + x_2^2 \\ 2x_2 - x_1^2 \end{bmatrix}$$

First, note that

$$F(\vec{a}) = F(\vec{0}) = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

We also need to compute the Jacobian at  $\vec{0}$ :

$$DF(\vec{0}) = \begin{bmatrix} 1 & 0 \\ 0 & 2 \end{bmatrix}$$

Then, we get the following linearization of the function:

$$\begin{aligned}L_{\vec{0}}(\vec{x}) &= F(\vec{0}) + DF(\vec{0})(\vec{x} - \vec{0}) \\ &= \begin{bmatrix} 1 \\ 0 \end{bmatrix} + \begin{bmatrix} 1 & 0 \\ 0 & 2 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \\ &= \begin{bmatrix} 1 + x_1 \\ 2x_2 \end{bmatrix}\end{aligned}$$

Then, look at

$$\frac{\|F(\vec{x}) - L_{\vec{0}}(\vec{x})\|}{\|\vec{x} - \vec{0}\|} = \frac{\left\| \begin{bmatrix} x_2^2 \\ -x_1^2 \end{bmatrix} \right\|}{\|\vec{x}\|} = \frac{\sqrt{x_2^4 + x_1^4}}{\sqrt{x_1^2 + x_2^2}} \leq \frac{R^4 + 4}{R} = \sqrt{2}R = \sqrt{2}\|\vec{x} - \vec{0}\|$$

As  $\vec{x} \rightarrow \vec{0}$ ,  $\|\vec{x} - \vec{0}\| = R \rightarrow 0$ , so by the squeeze theorem, the desired limit goes to 0. Therefore,  $F$  is differentiable at  $\vec{0}$ .

**Theorem 2.2.** Suppose  $F : \mathbb{R}^n \rightarrow \mathbb{R}^m$ , and  $\vec{a} \in \mathbb{R}^n$ . If there exists a disk  $D_r(\vec{a})$  in which all the partial derivatives  $\partial(F_i(\vec{x}))/\partial x_j$  exist and are continuous, then  $F$  is differentiable at  $\vec{x} = \vec{a}$ .

**Definition 2.6.** A function which satisfies Theorem 2.2 is called continuously differentiable, of  $C^1$ .

So far as our example, we calculate the partial for  $\vec{x} \neq \vec{0}$ :

$$\begin{aligned}\frac{\partial F}{\partial x_1} &= x_2^2 \left( \cos x_1 (x_1^2 + x_2^2)^{-\frac{1}{2}} + \left( -\frac{1}{2} (x_1^2 + x_2^2)^{-\frac{3}{2}} 2x_1 \right) \sin x_1 \right) \\ &= \frac{x_2^2}{(x_1^2 + x_2^2)^{3/2}} [\cos x_1 (x_1^2 + x_2^2) - x_1 \sin x_1]\end{aligned}$$

which is continuous as long as  $\vec{x} \neq \vec{0}$ . We do the same for  $\frac{\partial F}{\partial x_2}$  and conclude that  $F$  is  $C^1$  at all  $\vec{x} \neq \vec{0}$ . We summarize these ideas in the figure below:

### 2.3 Chain rule

**Definition 2.7.** Suppose  $A \subseteq \mathbb{R}^n$  is open, and we have a function

$$F : A \subseteq \mathbb{R}^n \rightarrow \mathbb{R}^m.$$

Similarly, supposed  $B \subseteq \mathbb{R}^m$  is open, and we have a function

$$G : B \subseteq \mathbb{R}^m \rightarrow \mathbb{R}^p.$$

Assume  $\vec{a} \in A$  and  $F(\vec{a}) = \vec{b} \in B$ . The composition

$$H(\vec{x}) = G \circ F(\vec{x}) = G(F(\vec{x}))$$

is a function  $\mathbb{R}^n \rightarrow \mathbb{R}^p$ .

**Example 2.3.1.** Consider the following linear functions:

$$\begin{cases} F(\vec{x}) = M\vec{x} & M \text{ an } (m \times n) \text{ matrix} \\ G(\vec{y}) = N\vec{y} & N \text{ an } (p \times m) \text{ matrix} \end{cases}$$

Then,

$$H(\vec{x}) = G(F(\vec{x})) = NM\vec{x}$$

is also a linear and represented by the product  $NM$ .

**Theorem 2.3.** Assume  $F : \mathbb{R}^n \rightarrow \mathbb{R}^m$  is differentiable at  $\vec{x} = \vec{a}$  and  $G : \mathbb{R}^m \rightarrow \mathbb{R}^p$  is differentiable at  $\vec{b} = F(\vec{a})$ . Then,  $H = G \circ F$  is differentiable at  $\vec{x} = \vec{a}$  and

$$DH(\vec{a}) = \underbrace{DG(\vec{b})}_{DG(F(\vec{a}))} DF(\vec{a})$$

Note that all of the various forms of Chain Rule done in first year calculus can be derived directly from this general formula.

**Example 2.3.2.** Consider the following functions,  $F : \mathbb{R}^3 \rightarrow \mathbb{R}^2$  and  $G : \mathbb{R}^2 \rightarrow \mathbb{R}^2$ :

$$F(\vec{x}) = \begin{bmatrix} x_1^2 + x_2 x_3 \\ x_1^2 + x_3^2 \end{bmatrix}, G(\vec{y}) = \begin{bmatrix} -y_2^3 \\ y_1 + y_2 \end{bmatrix}$$

Let  $H = G \circ F(\vec{x})$ . Find  $DH(\vec{a})$  where  $a = (1, -1, 0)$ .

First, we have

$$DF(\vec{x}) = \begin{bmatrix} 2x_1 & x_3 & x_2 \\ 2x_1 & 0 & 2x_3 \end{bmatrix}, DF(1, -1, 0) = \begin{bmatrix} 2 & 0 & -1 \\ 2 & 0 & 0 \end{bmatrix}$$

Similarly, we have

$$DG(\vec{y}) = \begin{bmatrix} 0 & -3y_2^2 \\ 1 & 1 \end{bmatrix}, DG(1, 1) = \begin{bmatrix} 0 & -3 \\ 1 & 1 \end{bmatrix}$$

By Chain Rule, we get

$$\begin{aligned} DH(1, -1, 0) &= DG(1, 1)DF(1, -1, 0) \\ &= \begin{bmatrix} 0 & -3 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} 2 & 0 & -1 \\ 2 & 0 & 0 \end{bmatrix} \\ &= \begin{bmatrix} -6 & 0 & 0 \\ 4 & 0 & -1 \end{bmatrix} \end{aligned}$$

## 2.4 Directional derivative

**Definition 2.8.** A path is  $\vec{C} : \mathbb{R} \rightarrow \mathbb{R}^n$  is a vector-valued function of a scalar independent variable, usually,  $t$ :

$$\vec{c}(t) = \begin{bmatrix} c_1(t) \\ c_2(t) \\ \vdots \\ c_n(t) \end{bmatrix}$$

$\vec{c}(t)$  can be thought of as a moving vector. It takes out a curve in  $\mathbb{R}^n$  as  $t$  increases. Basically, path is a way of describing a curve using functions. Note that this is not the only way to describe a curve.

**Example 2.4.1.** A unit circle in  $\mathbb{R}^2$  described as a path is

$$\vec{c}(t) = (\cos t, \sin t),$$

where  $t \in [0, 2\pi)$ . But we could also describe the unit circle *non-parametrically* as

$$x^2 + y^2 = 1$$

Note that the same curve can be described by different paths. Going back to unit circle, we can also write

$$\vec{b}(t) = (\sin(t^2), \cos(t^2)).$$

Using different paths can change (1) time dynamics and (2) direction of the curve. This curve has a non-constant speed and reversed orientation.

If  $\vec{c}$  is differentiable,  $D\vec{c}(t)$  is an  $(n \times 1)$  matrix. Since each component  $\vec{c}_j(t)$  is a real-valued function of only one variable, the *partial-derivative* is the usual derivative:

$$\frac{\partial c_j}{\partial t} = \frac{dc_j}{dt} = c'_j(t) = \lim_{h \rightarrow 0} \frac{c_j(t+h) - c_j(t)}{h}$$

So  $D\vec{c}(t) = \vec{c}'(t)$  is written as a column vector:

$$\begin{aligned} D\vec{c}(t) &= \begin{bmatrix} c'_1(t) \\ c'_2(t) \\ \vdots \\ c'_n(t) \end{bmatrix} \\ &= \lim_{h \rightarrow 0} \frac{\vec{c}(t+h) - \vec{c}(t)}{h} \end{aligned}$$

which is a vector which is tangent to the curve traced out at  $\vec{x} = \vec{x}(t)$ . Physically,  $\vec{c}'(t)$  is the velocity vector for motion along the path.

**Example 2.4.2** (Lines). Given two points,  $\vec{p}_1, \vec{p}_2 \in \mathbb{R}^n$ , there is a unique line connecting them. One path which represents this line is

$$\vec{c}(t) = \vec{p}_1 + t\vec{v},$$

where  $\vec{v} = \vec{p}_2 - \vec{p}_1$ . Velocity is then given by  $\vec{c}'(t) = \vec{v}$ , a constant.

**Definition 2.9.**  $f : \mathbb{R}^n \rightarrow \mathbb{R}$  is a scalar-valued function.

If  $f : \mathbb{R}^n \rightarrow \mathbb{R}$  is differentiable,  $Df(\vec{x})$  is a  $(1 \times n)$  matrix:

$$Df(\vec{x}) = \left[ \frac{\partial f}{\partial x_1} \quad \frac{\partial f}{\partial x_2} \quad \cdots \quad \frac{\partial f}{\partial x_n} \right]$$

We use *paths*  $\vec{c}(t)$  to explore  $f(x)$  by looking at

$$h(t) = f \circ \vec{c}(t) = f(\vec{c}(t)).$$

where  $h : \mathbb{R} \rightarrow \mathbb{R}$ , By chain rule,

$$\begin{aligned} Dh(t) &= h'(t) = \underbrace{Df(\vec{c}(t))}_{1 \times n} \underbrace{D\vec{c}(t)}_{n \times 1} \\ &= Df(\vec{c}(t)) \vec{c}'(t) \\ &= \begin{bmatrix} \frac{\partial f}{\partial x_1} & \frac{\partial f}{\partial x_2} & \cdots & \frac{\partial f}{\partial x_n} \end{bmatrix} \begin{bmatrix} c'_1 \\ c'_2 \\ \vdots \\ c'_n \end{bmatrix} \end{aligned}$$

We can think of this as a dot product of  $\vec{c}'(t)$  with a vector  $Df^T = \nabla f$ , the gradient vector:

$$h'(t) = \nabla f(\vec{c}(t)) \cdot \vec{c}'(t)$$

Suppose  $f : \mathbb{R}^n \rightarrow \mathbb{R}$  is differentiable at  $\vec{a} \in \mathbb{R}^n$ , and we have a path  $\vec{c} : \mathbb{R} \rightarrow \mathbb{R}^n$  with  $\vec{c}(0) = \vec{a}$ . Let  $\vec{v} = \vec{c}'(0)$ . Then,  $h'(0)$  measures rate of change of  $f$  along the path as we cross through  $\vec{a}$ :

$$\begin{aligned} h'(0) &= \nabla f(\vec{c}(0)) \cdot \vec{c}'(0) \\ &= \nabla f(\vec{c}(0)) \cdot \vec{v} \end{aligned}$$

Note that we get the same value for  $h'(0)$  for *any* path  $\vec{c}(t)$  going through  $\vec{a}$  with velocity  $\vec{c}'(t) = \vec{v}$ . In other words,  $h'(0)$  says something about  $f$  at  $\vec{a}$ , and not the path  $\vec{c}(t)$ .

**Definition 2.10** (Directional derivative). *The directional derivative of  $f$  at  $\vec{a}$  in direction  $\vec{v}$  is given by*

$$D_{\vec{v}}f(\vec{a}) = Df(\vec{a})\vec{v} = \nabla f(\vec{a}) \cdot \vec{v}.$$

Now, we can make some observations. Using the Chain Rule, directional derivatives can be rewritten as

$$D_{\vec{v}}f(\vec{a}) = \lim_{t \rightarrow 0} \frac{f(\vec{a} + t\vec{v}) - f(\vec{a})}{t}.$$

Note the similarity to partial derivatives, where  $\vec{v} = \vec{e}_j$ .

Second, notice that  $D_{2\vec{v}}f(\vec{a}) = \nabla f(\vec{a}) \cdot (2\vec{v}) = 2D_{\vec{v}}f(\vec{a})$ . To get the information on how fast  $f$  is changing at  $\vec{a}$ , we need to restrict to unit vectors  $\|\vec{v}\| = 1$ .

Directional derivatives also gives a geometrical interpretation of the gradient vector,  $\nabla f(\vec{a})$ . We use the Cauchy-Schwartz Inequality<sup>2</sup> to do so. By applying the Cauchy-Schwartz inequality, we have

$$D_{\vec{v}}f(\vec{a}) = \nabla f(\vec{a}) \cdot \vec{v} \leq \|\nabla f(\vec{a})\| \cdot \|\vec{v}\| = \|\nabla f(\vec{a})\|.$$

Therefore, we can conclude that the length of  $\|\nabla f(\vec{a})\|$  is the largest of  $D_{\vec{v}}f(\vec{a})$  among all choices of unit directions  $\vec{v}$ . In other words, the direction  $\vec{v}$  in which  $f(\vec{x})$  increases most rapidly is the direction of  $\nabla f(\vec{a})$ , i.e.

$$\vec{v} = \frac{\nabla f(\vec{a})}{\|\nabla f(\vec{a})\|},$$

provided that  $\nabla f(\vec{a}) \neq \vec{0}$ .

Similarly,  $-\nabla f(\vec{a})$  points in the direction of largest of  $f(\vec{x})$ , i.e.

$$\vec{v} = -\frac{\nabla f(\vec{a})}{\|\nabla f(\vec{a})\|},$$

gives the most negative directional derivative.

---

<sup>2</sup>For any vectors  $\vec{u} \cdot \vec{v} \leq \|\vec{u}\|\|\vec{v}\|$ , and equality holds if and only if  $\vec{u} = t\vec{v}$  for a scalar  $t$ .



## 3 Paths and Curves

### 3.1 Parameterized path

A path is a function,  $\vec{v} : \mathbb{R} \rightarrow \mathbb{R}^n$ :

$$\vec{c}(t) = \begin{bmatrix} c_1(t) \\ \vdots \\ c_n(t) \end{bmatrix}.$$

$\vec{c}(t)$  is  $\{\text{continuous, differentiable, and } C^1\}$  provided that each component  $c_j(t), j = 1, 2, \dots, n$  are. Note that  $\{\vec{c}(t) : t \in [a, b]\}$  traces out a curve in  $\mathbb{R}^n$ , with initial endpoint  $\vec{a}$  and final endpoint  $\vec{b}$ . Therefore, the path  $\vec{c}(t)$  *parameterizes* the curve drawn out.

Recall that for any function  $F : \mathbb{R}^k \rightarrow \mathbb{R}^n$ , differentiability means that tangents i.e. linearization) make a good approximation. For a differentiable path,  $\vec{c}'(t)$  is a tangent vector to the curve drawn out when  $\vec{c}'(t) \neq 0$ . We call  $\vec{v}(t) = \vec{c}'(t)$  the velocity vector ( $v = \|\vec{v}\| = \|\vec{c}'(t)\|$  is speed).

Finally, we can define the unit tangent vector:

**Definition 3.1.** *Unit tangent vector is defined as*

$$\vec{T}(t) = \frac{\vec{v}}{\|\vec{v}(t)\|} = \frac{\vec{c}'(t)}{\|\vec{c}'(t)\|}$$

**Example 3.1.1.** Consider a curve  $\vec{c} : \mathbb{R} \rightarrow \mathbb{R}^2$ :

$$\vec{c}(t) = (\cos^3 t, \sin^3 t),$$

where  $t \in [-\pi, \pi]$ . This is a  $C^1$  path<sup>3</sup> and its velocity vector is given by

$$\vec{c}'(t) = (-3\cos^2 t \sin t, 3\sin^2 t \cos t).$$

To find the unit tangent, we have to find its speed:

$$\begin{aligned} v &= \|(-3\cos^2 t \sin t, 3\sin^2 t \cos t)\| \\ &= 3|\sin t \cos t| \|(-\cos t \sin t, \sin t \cos t)\| \\ &= 3|\sin t \cos t| \end{aligned}$$

Finally, its unit tangent is given by

$$\vec{T}(t) = \frac{\vec{v}(t)}{\|\vec{v}(t)\|} = \left( -|\cos t| \frac{\sin t}{|\sin t|}, |\sin t| \frac{\cos t}{|\cos t|} \right)$$

Note that its tangent is undefined when  $\sin t = 0$  or  $\cos t = 0$ , i.e. at multiples of  $\frac{\pi}{2}$ . Worse,  $\frac{\sin t}{|\sin t|}, \frac{\cos t}{|\cos t|}$  flip discontinuously as  $t$  crosses a multiple of  $\pi/2$  from  $-1$  to  $+1$ , or vice versa. Although the path is  $C^1$ , the curve is not smooth! When  $\vec{v}(t) = \vec{c}'(t) = 0$ , it allows the curve to have cusps.

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<sup>3</sup>In fact, it is  $C^\infty$ , differentiable to all orders!

Note that it is possible to have a nice tangent direction even when  $\vec{c}'(t) = 0$ :

**Example 3.1.2.** Consider a parameterized straight line:

$$\vec{c} = \vec{a} + \vec{w}t^3$$

Its velocity vector,  $\vec{c}'(t) = 3\vec{w}t^2$ , is equal to  $\vec{0}$  when  $t = 0$ . However, it still has a tangent direction which is parallel to  $\vec{w}$ .

**Definition 3.2.** We say a parameterized curve is smooth<sup>4</sup> (or regular) if its path is  $C^1$ , i.e. if it can be parameterized by a path  $\vec{c}(t)$ , and  $\|\vec{c}'(t) \neq 0\|$  for any  $t$ .

If  $\vec{c}(t)$  is twice-differentiable,  $\vec{c}''(t) = \vec{a}(t)$  is the acceleration vector. In order to do calculus with path, we use these differentiation rules.

1. If  $f : \mathbb{R} \rightarrow \mathbb{R}$ ,  $\vec{c} : \mathbb{R} \rightarrow \mathbb{R}^n$ , both differentiable,

$$\begin{aligned} \frac{d}{dt} \left( f(t) \vec{c}(t) \right) &= f(t) \vec{c}'(t) + f'(t) \vec{c}(t) \\ &= \sum_{j=1}^n \frac{d}{dt} \left( f(t) \vec{c}_j(t) \right) \vec{e}_j \\ &= \sum_{j=1}^n \frac{d}{dt} \left( f'(t) \vec{c}_j(t) + f(t) \vec{c}_j'(t) \right) \vec{e}_j \end{aligned}$$

2. If  $\vec{c}, \vec{d} : \mathbb{R} \rightarrow \mathbb{R}^n$  are differentiable,

$$\frac{d}{dt} \left( \vec{c}(t) \cdot \vec{d}(t) \right) = \vec{c}'(t) \cdot \vec{d}(t) + \vec{c}(t) \cdot \vec{c}'(t)$$

3. If  $\vec{c}, \vec{d} : \mathbb{R} \rightarrow \mathbb{R}^3$  are differentiable,

$$\frac{d}{dt} \left( \vec{c}(t) \times \vec{d}(t) \right) = \vec{c}(t) \times \vec{d}'(t) + \vec{c}'(t) \times \vec{d}(t),$$

where  $\vec{c} \times \vec{d} = \sum_{i,j,k=1}^3 c_i d_j \vec{e}_k \varepsilon_{ijk}$ .  $\varepsilon_{ijk}$  is defined in the footnotes<sup>5</sup>.

**Example 3.1.3.** Suppose  $\vec{c}$  is a twice differentiable path and  $\vec{a}(t) = k\vec{c}(t)$  for some constant  $k \neq 0$ . Show that  $\vec{c}(t)$  describes a motion in a fixed plane.

Define a vector

$$\vec{n} = \vec{c}(t) \times \vec{v}(t) = \vec{c}(t) \times \vec{c}'(t)$$

---

<sup>4</sup>For a smooth curve, the unit tangent  $\vec{T}(t)$  is continuous.

<sup>5</sup>  $\varepsilon_{ijk} = \begin{cases} 0 & \text{if } i = j \text{ or } j = k \text{ or } k = 1 \\ 1 & \text{if } (i, j, k) \text{ is positively ordered} \\ -1 & \text{if } (i, j, k) \text{ is negatively ordered} \end{cases}$

Notice  $\vec{n} \perp \vec{c}(t)$  and  $\vec{v}(t)$ , i.e.  $\vec{n}$  is normal to the plane.

$$\begin{aligned}\frac{d\vec{n}}{dt} &= \frac{d}{dt} (\vec{c}(t) \times \vec{c}'(t)) = \vec{c}(t) \times \underbrace{\vec{c}''(t)}_{\vec{a}(t)} + \underbrace{\vec{c}'(t) \times \vec{c}'(t)}_{\vec{0}} \\ &= \vec{c}(t) \times k\vec{c}(t) \\ &= \vec{0}\end{aligned}$$

Therefore,  $\vec{n}$  is constant in time!

So  $\vec{c}(t)$  and  $\vec{v}(t)$  are, for all  $t$ , perpendicular to the constant vector  $\vec{n}$ . Then,

$$P = \{\vec{w} \mid \vec{w} \cdot \vec{n} = 0\}$$

is the plane through  $\vec{0}$ . So  $\vec{c}(t) \in P$  for all  $t$ .

**Definition 3.3** (Arclength). *The arclength (or distance travelled along the parameterized curve) for  $a \leq t \leq b$  is*

$$\int_a^b \underbrace{\|\vec{c}'(t)\|}_{\text{speed}} dt$$

For a variable time interval, the arclength function

$$s(t) = \int_a^t \|\vec{c}'(u)\| du$$

is a distance traveled from time  $a$  to time  $t$ .

**Example 3.1.4.** Consider the following curve:

$$\vec{c}(t) = (3 \cos t, 3 \sin t, 4t), \quad t \in [0, 4\pi]$$

Its velocity vector is given by

$$\vec{v}(t) = (-3 \sin t, 3 \cos t, 4).$$

Then, it follows that its speed is exactly equal to 5. Finally, we can compute the arclength:

$$s(t) = \int_0^t v(t) dt = \int_0^t 5 du = 5t$$

Therefore, total arclength is  $s(4\pi) = 20\pi$ .

**Definition 3.4.** *When the path  $\vec{c}(t)$  traces out the curve with speed  $\|\vec{v}(t)\| = 1$  for all  $t$ , we say that the curve is arclength parameterized.*

If a curve is arclength parameterized, arclength function becomes

$$s(t) = t$$

Then, we can use  $s$  instead of  $t$  as a parameterization in the path.

**Example 3.1.5.** In example 3.1.4, helix is not arclength parameterized but we can re-parameterize it so that it is. To do so, we need to solve for  $t = \varphi(s)$  to invert the function  $s(t)$ .

Going back the example, we had  $s(t) = 5t$ . It follows that  $t = \frac{1}{5}s$ . Then,

$$\vec{c}(s) = \vec{c}(\varphi(s)) = \vec{c}\left(\frac{s}{5}\right) = \left(3 \cos\left(\frac{s}{5}\right), 3 \sin\left(\frac{s}{5}\right), \frac{4s}{5}\right)$$

is an arclength parameterization of the original helix, i.e.  $\|\vec{c}'(s)\| = 1, \forall s$ .

### 3.2 Geometry of curves in $\mathbb{R}^3$

Path,

$$\vec{c}(t) = \begin{bmatrix} x(t) \\ y(t) \\ z(t) \end{bmatrix} = (x, y, z)(t),$$

traces out a curve, for  $t \in [a, b]$ , in space, and its velocity vector and speed are given by  $\vec{c}'(t)$  and  $\|\vec{c}'(t)\|$ , respectively. This is a smooth parameterization if  $\vec{c} \in C^1$  and  $\|\vec{c}'(t)\| \neq 0$  for any  $t \in [a, b]$ .

We introduced the arclength function,

$$s(t) = \int_a^t \|\vec{c}'(u)\| du,$$

the total distance along the curve up to time  $t$ .

We also introduced the idea of arclength parameterization, where  $s(t) = t$ . Then, since

$$\frac{ds}{dt} = \|\vec{c}'(t)\|,$$

arclength parameterization is a path that travels along the curve with unit speed,  $ds/dt = 1$ , throughout. Therefore, any path with  $\|\vec{c}'(t)\| \neq 0$  can be parameterized by arclength by inverting  $s = s(t)$  such that  $t = \varphi(s)$ . Note that we can always do this for a smooth path  $ds/dt > 0$  so  $s(t)$  is monotonically increasing. In practice, however, you may not be able to find an explicit formula for the arclength parameterization!

**Example 3.2.1.** Consider the following path:

$$\vec{c}(t) = (t, \frac{1}{2}t^2) :$$

Since  $y = x^2/2$ , it's a parabola. Then, we observe that

$$c'(t) = (1, t), \|\vec{c}'(t)\| = \sqrt{1 + t^2} \geq 1 > 0$$

so the path is smooth. Then, we have

$$s(t) = \int_0^t \|\vec{c}'(u)\| du = \int_0^t \sqrt{1 + u^2} du = \frac{1}{2} \left( \ln \left| \sqrt{1 + t^2} + t \right| + t \sqrt{1 + t^2} \right).$$

Clearly, there's no way we can solve for  $t$  as a function of  $s$ . The way out of this trouble is to treat all  $\vec{c}$  as if they were parameterized by arclength and use Chain rule with  $ds/dt = \|\vec{c}'(t)\|$  to compensate.

Recall that unit tangent vector to  $\vec{c}(t)$  is

$$\vec{T}(t) = \frac{\vec{c}'(t)}{\|\vec{c}'(t)\|}.$$

We wish to understand how direction of the curve changes over time:

**Definition 3.5.** *The curvature of a curve is defined as rate of change of unit tangent:*

$$\kappa = \left\| \frac{d\vec{T}}{ds} \right\|.$$

By chain rule,

$$\frac{d\vec{T}}{dt} = \frac{d\vec{T}}{ds} \cdot \frac{ds}{dt}$$

So, in the original time parameter,  $t$ ,

$$\kappa(t) = \left\| \frac{1}{\frac{ds}{dt}} \frac{d\vec{T}}{dt} \right\| = \frac{\|\vec{T}'(t)\|}{\|\vec{c}'(t)\|}$$

**Example 3.2.2.** Consider a circle of radius  $R > 0$  in  $xy$ -plane:

$$\vec{c}(t) = (R \sin t, R \cos t).$$

Then, we have

$$\vec{c}'(t) = (R \cos t, -R \sin t)$$

$$\|\vec{c}'(t)\| = R$$

Notice that this travels with constant speed but is not arclength parameterized.

Its unit tangent is given by

$$\vec{T}(t) = \frac{\vec{c}'(t)}{\|\vec{c}'(t)\|} = \frac{\vec{c}'(t)}{R} = (\cos t, -\sin t)$$

Then,

$$\vec{N}(t) = \vec{T}'(t) = (-\sin t, -\cos t)$$

Again, notice that  $\vec{N}(t)$  is perpendicular to  $\vec{T}(t)$ .

Finally, we have

$$\kappa(t) = \frac{\|\vec{T}'(t)\|}{\|\vec{c}'(t)\|} = \frac{1}{R}.$$

Therefore, circle with large radius has less curvature.

**Example 3.2.3.** Consider the following helix:

$$\vec{c}(t) = (3 \cos t, 3 \sin t, 4t).$$

Following the same approach as the previous question, we get

$$\begin{aligned}\vec{c}'(t) &= (-3 \sin t, 3 \cos t, 4) \\ \|\vec{c}'(t)\| &= 5 \\ \vec{T}(t) &= \left(-\frac{3}{5} \sin t, \frac{3}{5} \cos t, \frac{4}{5}\right) \\ \vec{T}'(t) &= \left(-\frac{3}{5} \cos t, -\frac{3}{5} \sin t, 0\right)\end{aligned}$$

Then, we get

$$\kappa(t) = \frac{\|\vec{T}'(t)\|}{\|\vec{c}'(t)\|} = \frac{3/5}{5} = \frac{3}{25}$$

We observe that this curve also has a constant curvature.

**Definition 3.6** (Principal normal vector).

$$\vec{N} = \frac{\vec{T}'(s)}{\|\vec{T}'(s)\|} = \frac{\vec{T}'(t)}{\|\vec{T}'(t)\|}$$

Since  $\|\vec{T}(s)\| = 1$  for all  $s$ ,  $\vec{T}(s) \cdot \vec{T}(s) = \|\vec{T}(s)\|^2 = 1$ . By implicit differentiation, we have

$$\begin{aligned}\frac{d}{ds}(1) &= \frac{d}{ds}(\vec{T}(s) \cdot \vec{T}(s)) \\ 0 &= \vec{T}'(s) \cdot \vec{T}(s) + \vec{T}(s) \cdot \vec{T}'(s) \\ &= 2\vec{T}'(s) \cdot \vec{T}(s)\end{aligned}$$

Therefore,  $\vec{T}'(s) \perp \vec{T}(s)$  for all  $s$ . So, as long as  $\vec{T}'(s) \neq 0$ , i.e.  $\kappa \neq 0$ , we have  $\vec{N}(s) \perp \vec{T}(s)$ . In fact,  $\vec{T}'(s) = \|\vec{T}'(s)\|\vec{N} = \kappa\vec{N}$ , so the tangent turns in the direction of  $\vec{N}$ . For motion in a line,  $\kappa(s) = 0$  for all  $s$ ,  $\vec{N}$  cannot be defined!

$\vec{T}, \vec{N}$  determines a plane in  $\mathbb{R}^3$ , the osculating plane. The normal vector to the osculating plane is given by

$$\vec{B} = \vec{T} \times \vec{N}.$$

**Definition 3.7** (Binormal vector).  $\vec{B} = \vec{T} \times \vec{N}$

We observe that  $\vec{B} \perp \vec{T}$ ,  $\vec{B} \perp \vec{N}$ , and

$$\|\vec{B}\| = \|\vec{T}\|\|\vec{N}\|\sin\theta = 1 \cdot 1 \cdot \sin(\pi/2) = 1$$

Therefore,  $\{\vec{T}(s), \vec{N}(s), \vec{B}(s)\}$  is a moving *orthonormal basis* for  $\mathbb{R}^3$  at each point along the curve. This plane is also referred to as *moving frame* or *frenet frame*. Now, we introduce the following consequences:

(1). If curvature  $\kappa(s) = 0$  for all  $s$ , then the curve is a straight line.

To see this,  $\vec{T}'(s) = \kappa\vec{N}(s) = 0$  for all  $s$ . Therefore,  $\vec{T}(s) = \vec{u}$  is a constant vector and

$$\vec{r}(s) = \vec{u}s + \vec{p},$$

a line thorough  $\vec{p} = \vec{r}(0)$  with direction vector  $\vec{u}$ .

(2). When  $\kappa = 0$ ,  $\vec{N}$  and  $\vec{B}$  cannot be defined.

(3). If  $\vec{B}(s)$  is a constant vector, then  $\vec{c}(t)$  ( $\vec{r}(t)$ ) move in a fixed plane, with normal vector  $\vec{B}$ .

Suppose  $\vec{B}(s)$  isn't constant. First,  $\|\vec{B}(s)\| = 1$  for all  $s$ . Then,

$$1 = \|\vec{B}(s)\|^2 = \vec{B}(s) \cdot \vec{B}(s)$$

holds for all  $s$ . So we can do implicit differentiation:

$$0 = \frac{d}{ds}(1) = \frac{d}{ds}(\vec{B} \cdot \vec{B}) = 2\vec{B}' \cdot \vec{B}.$$

Then, it follows that  $\vec{B}' \perp \vec{B}$ , for every  $s$ .

Next, since  $\vec{B}(s) \perp \vec{T}(s)$  for all  $s$ , we have  $\vec{B} \cdot \vec{T} = 0$  for all  $s$ . Then,

$$\frac{d}{ds}(\vec{B} \cdot \vec{T}) = \vec{B}'(s) \cdot \vec{T}(s) + \vec{B}(s) \cdot \vec{T}'(s) = 0.$$

Since  $\vec{T}' = \kappa\vec{N}$  and  $\vec{B} \cdot \vec{N} = 0$ , it follows that

$$\vec{B}'(s) + \vec{T}(s) = 0 \iff \vec{B}'(s) \perp \vec{T}(s)$$

Since  $\{\vec{T}, \vec{N}, \vec{B}\}$  form an orthonormal basis for  $\mathbb{R}^3$ , we must have  $\vec{B}'(s)$  parallel to  $\vec{N}$ . Therefore,

$$\vec{B}'(s) = -\tau(s)\vec{N}(s)$$

for a function  $\tau(s)$  called the *torsion*. Since  $\tau = \left\|d\vec{B}/ds\right\|$ , it measures how fast the normal  $\vec{B}$  to the osculating plane is twisting.

**Definition 3.8** (Torsion).

$$\tau = \left\| \frac{d\vec{B}}{ds} \right\| = \frac{\|\vec{B}'(t)\|}{\|\vec{c}'(t)\|}$$

Putting all the information together we get *Frenet formulas*:

**Theorem 3.1** (Frenet formula).

$$\begin{cases} \frac{d\vec{T}}{ds} = \kappa\vec{N} \\ \frac{d\vec{B}}{ds} = -\tau\vec{N} \\ \frac{d\vec{N}}{ds} = -\kappa\vec{T} + \tau\vec{B} \end{cases}$$

**Example 3.2.4.** Consider the following helix:

$$\vec{c}(t) = (3 \cos t, 3 \sin t, 4t)$$

Then, we have

$$\begin{aligned} \|\vec{c}'(t)\| &= 5, \\ \vec{T}(t) &= \left( -\frac{3}{5} \sin t, \frac{3}{5} \cos t, \frac{4}{5} \right), \\ \vec{T}'(t) &= \left( -\frac{3}{5} \cos t, -\frac{3}{5} \sin t, 0 \right), \\ \kappa &= \frac{3}{25}, \\ \vec{N}(t) &= (-\cos t, -\sin t, 0), \\ \vec{B}(t) &= \vec{T} \times \vec{N} = \left( \frac{4}{5} \sin t, -\frac{4}{5} \cos t, \frac{3}{5} \right), \\ \vec{B}' &= \left( \frac{4}{5} \cos t, \frac{4}{5} \sin t, 0 \right), \\ \tau &= -\frac{4}{5}. \end{aligned}$$

### 3.3 Dynamics

How do these quantities relate to dynamical quantities?  $\vec{c}(t)$  is a position vector along the curve.  $\vec{c}'(t) = \vec{v}(t) = \vec{T}(t)ds/dt$  is a velocity vector, and  $\|\vec{c}'(t)\| = ds/dt$  is speed.

**Definition 3.9** (Acceleration).  $\vec{a}(t) = \vec{v}'(t) = \vec{c}''(t)$

First, observe that

$$\vec{v}(t) = \vec{c}'(t) = \frac{ds}{dt} \vec{T}(t)$$

Then,

$$\begin{aligned} \vec{a}(t) &= \frac{d}{dt} \left( \frac{ds}{dt} \vec{T}(t) \right) = \frac{d^2s}{dt^2} \vec{T}(t) + \frac{ds}{dt} \vec{T}'(t) \\ &= \frac{d^2s}{dt^2} \vec{T} + \frac{ds}{dt} \left( \frac{d\vec{T}}{ds} \cdot \frac{ds}{dt} \right) \end{aligned}$$



So we have

$$\vec{a}(t) = \underbrace{\frac{d^2 s}{dt^2} \vec{T}}_{\text{Linear acceleration}} + \underbrace{\kappa \left( \frac{ds}{dt} \right)^2 \vec{N}}_{\text{Steering-term}}$$

By looking at the steering term, we see that acceleration to turn on a curve is proportional to the curvature and (speed)<sup>2</sup>.

**Example 3.3.1.** Consider the following path

$$\vec{c}(t) = (e^t \cos t, e^t \sin t, e^t)$$

that draws a spiral in  $xy$  direction and monotonically increases along  $z$  coordinate.

First, observe that

$$\begin{aligned} \vec{v}(t) &= \vec{c}'(t) = (-e^t \sin t + e^t \cos t, e^t \cos t + e^t \sin t, e^t) \\ \frac{ds}{dt} &= \|\vec{c}'(t)\| = \sqrt{3}e^t \end{aligned}$$

Then, we have

$$\begin{aligned} \vec{T}(t) &= \frac{\vec{c}'(t)}{\|\vec{c}'(t)\|} = \frac{1}{\sqrt{3}}(-\sin t + \cos t, \cos t + \sin t, 1), \\ \vec{T}'(t) &= \frac{\vec{c}''(t)}{\|\vec{c}'(t)\|} = \frac{1}{\sqrt{3}}(-\cos t - \sin t, -\sin t + \cos t, 0). \end{aligned}$$

Since  $\|\vec{T}'(t)\| = \sqrt{2/3}$ , we can easily find the principal normal vector:

$$\vec{N}(t) = \frac{\vec{T}'(t)}{\|\vec{T}'(t)\|} = \frac{1}{\sqrt{2}}(-\cos t - \sin t, -\sin t + \cos t, 0)$$

Then,

$$\kappa = \frac{\|\vec{T}'(t)\|}{\|\vec{c}'(t)\|} = \frac{\sqrt{2}}{3}e^{-t}.$$

Furthermore,

$$\begin{aligned} \vec{B}(t) &= \vec{T}(t) \times \vec{N}(t) = \dots = \frac{1}{\sqrt{6}}(\cos t - \sin t, -\sin t - \cos t, 2) \\ \vec{B}'(t) &= \frac{1}{\sqrt{6}}(-\sin t - \cos t, -\cos t + \sin t, 0) \end{aligned}$$

Therefore, torsion of the curve is given by

$$\tau(t) = \frac{\|\vec{B}'(t)\|}{\|\vec{c}'(t)\|} = \frac{1}{3}e^{-t}$$

We can then verify formula for  $\vec{a}$  in terms of  $\vec{T}, \vec{N}, \kappa$ , (and verify that it agrees with  $\vec{a} = \vec{v}'(t)$  calculated directly).

Now, we present an alternative equation for curvature using dynamical quantities:

**Theorem 3.2.**

$$\kappa(t) = \frac{\|\vec{c}'(t) \times \vec{c}''(t)\|}{\|\vec{c}'(t)\|^3} = \frac{\|\vec{v}(t) \times \vec{a}(t)\|}{\|\vec{v}(t)\|^3}$$

*Proof.* To verify it, we use the decomposition of  $\vec{a}$ :

$$\begin{aligned} \vec{v} \times \vec{a} &= \vec{v} \times \left( \frac{d^2s}{dt^2} \vec{T} + \kappa \left( \frac{ds}{dt} \right)^2 \vec{N} \right) \\ &= \frac{d^2s}{dt^2} (\vec{v} \times \vec{T}) + \kappa \left( \frac{ds}{dt} \right)^2 (\vec{v} \times \vec{N}) \\ &= \kappa \left( \frac{ds}{dt} \right)^3 (\vec{T} \times \vec{N}) \\ &= \kappa \left( \frac{ds}{dt} \right)^3 \vec{B} \end{aligned}$$

Then,  $\kappa(ds/dt)^3 \|\vec{B}\| = \|\vec{v} \times \vec{a}\|$ . Since  $\vec{B}$  is a unit vector, the desired result has been achieved.  $\square$