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* $\vec{x} = (x_1, x_2, \ldots, x_n)$ *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* $\vec{x} = \vec{0} = (0, 0, \ldots, 0)$.
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-pythagorian 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 $\vec{p} = (p_1, p_2, \ldots, p_n) \in \mathbb{R}^n$, $\|\vec{p}\|_1 = \sum_{j=1}^{n} |p_j|$. 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 $\mathbb{R}^n$, $\mathrm{dist}(\vec{p}, \vec{q}) = \|\vec{p} - \vec{q}\|$. 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*

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

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*

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

What neighboorhood 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 $\mathbb{R}^n$ 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

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

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 disk, which is entirely contained in A:*

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

Example 1.2.1.

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

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 cal A an* open set*.*

Example 1.2.2. $A = \left\{\vec{x} \in \mathbb{R}^n | \vec{x} \neq \vec{0}\right\}$ 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 $A = D_R(\vec{0})$

$$\left\{\vec{b} \,\middle|\, \|\vec{b}\| = R\right\}$$

is a sphere of radius R.

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

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

Example 1.2.5. Consider the following set:

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

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

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

We can rewrite this using a matrix notation:

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

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 $\lim_{\vec{x}\to\vec{a}} F(\vec{x}) = \vec{L}$ mean? Note that it's not enough to treat the variables $x_1, x_2, \ldots x_n$ 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.

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

Similarly, we have

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

However, if $(x, y) \to (0, 0)$ 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

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

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

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 alond different parabolas.

We showed that computing

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

is tricky because $\vec{x} \to \vec{a}$ 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* $\lim_{\vec{x}\to\vec{a}} F(\vec{x}) = \vec{b}$ *if for any given* $\varepsilon > 0$*, there exists* $\delta > 0$ *such that whenever* $0 < \|\vec{x} - \vec{a}\| < \delta$*, we have* $\|F(x) - \vec{b}\| < \varepsilon$*. Therefore,*

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

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 $\vec{v} = (v_1, v_2, \ldots, v_n) \in \mathbb{R}^n$. Then, we have

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

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

Example 2.1.4. Show

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

Proof. Note that $F : \mathbb{R} \setminus \{\vec{0}\} \to \mathbb{R}$, $b = 0$, $\vec{a} = (0, 0)$. 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 $\delta \leq \varepsilon/2$ □

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

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

Determine whether

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

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

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

□

Definition 2.2. *Consider a function $F : \mathbb{R}^n \to \mathbb{R}^k$ 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*

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

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 [1] .

2.2 Differentiability

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

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

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 theire tangent lines (also known as linearization). We wish to extend this idea to $F : \mathbb{R}^n \to \mathbb{R}^m$.

First, we try dealing with the independent varaibles, $x_1, x_2, \dots, x_n$, 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,

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

[1] 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*

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

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

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

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

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

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

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

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

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

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,

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

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 cotinuous at $(0,0)$! (For example, $f(x,mx)\to\pm\infty$ as $x\to 0^{\pm}$ for $m\neq 0$).

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

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

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 $F:\mathbb{R}^n\to\mathbb{R}^m$, $F(\vec{x})$ has $(m\times n)$ partial derivates (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, $L:\mathbb{R}^n\to\mathbb{R}^m$, just like F. The derivative matrix $DF(\vec{a})$ is a *linear transformation* of $\mathbb{R}^n\to\mathbb{R}^m$.

Notice that when $n=2$ and $m=1$, For $F:\mathbb{R}^2\to\mathbb{R}$, 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 (1×2) 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* $F : \mathbb{R}^n \to \mathbb{R}^m$ *is* differentiable *if*

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

Equivalently,

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

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 and error which is much smaller than $\|\vec{x}-\vec{a}\|$. Note that we write $o\left(\|\vec{x}-\vec{a}\|\right)$ "little-oh" for quantity which is small compred to $\|\vec{x}-\vec{a}\|$. Using this notation, differentiability can be written as

$$\|F(\vec{x}) - F\left(\vec{a} - Df(\vec{a})(\vec{x}-\vec{a})\right)\| = o(\|\vec{x}-\vec{a}\|).$$

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

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

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

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

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:

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

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

Theorem 2.2. *Suppose $F:\mathbb{R}^n\to\mathbb{R}^m$, 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 $\vec{x} \neq \vec{0}$:

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

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*

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

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

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

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

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

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

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,

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

is also a linear and represented by the product NM.

Theorem 2.3. *Assume $F : \mathbb{R}^n \to \mathbb{R}^m$ is differentiable at $\vec{x} = \vec{a}$ and $G : \mathbb{R}^m \to \mathbb{R}^p$ 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, $F : \mathbb{R}^3 \to \mathbb{R}^2$ and $G : \mathbb{R}^2 \to \mathbb{R}^2$:

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

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

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

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 derivatve

Definition 2.8. *A* path *is $\vec{C} : \mathbb{R} \to \mathbb{R}^n$ 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 diffrent paths. Going back to unit circle, we can also write

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

Using different paths can change (1) time dyanmics 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 compoenent $\vec{c}_j(t)$ is a real-valued function of only one variable, the *partial-derivative* is the usual derivative:

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

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

$$\begin{aligned} D\vec{c}(t) &= \begin{bmatrix} c_1'(t) \\ c_2'(t) \\ \vdots \\ c_3'(t) \end{bmatrix} \\ &= \lim_{h \to 0} \frac{\vec{c}(t+h) - \vec{c}(t)}{h} \end{aligned}$$

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

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

$$Df(\vec{x}) = \begin{bmatrix} \frac{\partial f}{\partial x_1} & \frac{\partial f}{\partial x_2} & \cdots & \frac{\partial f}{\partial x_n} \end{bmatrix}$$

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

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

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

$$\begin{aligned} Dh(t) = h'(t) &= \underbrace{Df(\vec{c}(t))}_{1 \times n} \underbrace{D\vec{c}(t)}_{n \times 1} \\ &= Df\left(\vec{c}(t)\right) \vec{c}\,'(t) \\ &= \begin{bmatrix} \frac{\partial f}{\partial x_1} & \frac{\partial f}{\partial x_2} & \cdots & \frac{\partial f}{\partial x_n} \end{bmatrix} \begin{bmatrix} c_1' \\ c_2' \\ \vdots \\ c_n' \end{bmatrix} \end{aligned}$$

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 $f : \mathbb{R}^n \to \mathbb{R}$ is differentiable at $\vec{a} \in \mathbb{R}^n$, and we have a path $\vec{c} : \mathbb{R}^n \to \mathbb{R}$ 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

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

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[2] to do so. By applying the Cauchy-Schwartz inequality, we have

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

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.

[2]For any vectors $\vec{u} \cdot \vec{v} \leq \|\vec{y}\|\|\vec{v}\|$, 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, $\vec{v} : \mathbb{R} \to \mathbb{R}^n$:

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

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

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

Finally, we can define the unit tangent vector:

Definition 3.1. *Unit tangent vector is defined as*

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

Example 3.1.1. Consider a curve $\vec{c} : \mathbb{R} \to \mathbb{R}$:

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

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

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

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

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

Finally, its unit tanget is given by

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

Note that its tanget 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 $\vec{\mathrm{v}}(t) = \vec{c}\,'(t) = 0$, it allows the curve to have cusps.

[3] In fact, it is C^∞, 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[4] *(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 $f : \mathbb{R} \to \mathbb{R}$, $\vec{c} : \mathbb{R} \to \mathbb{R}^n$, both differentiable,

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

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

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

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

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

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

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

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

[4] For a smooth curve, the unit tangent $\vec{T}(t)$ is continuous.

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

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

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

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*

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

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:

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

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:

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

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 invent 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

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

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

$$\begin{aligned} \vec{c}\,'(t) &= (R\cos t, -R\sin t) \\ \|\vec{c}\,'(t)\| &= R \end{aligned}$$

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)**.** $\vec{N} = \frac{\vec{T}\,'(s)}{\|\vec{T}\,'(s)\|}$

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 thorugh $\vec{p} = \vec{r}(0)$ 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:

$$0 = \frac{d}{dS}(1) = \frac{d}{dS}\left(\vec{B} \cdot \vec{B}\right) = 2\vec{B}\,' \cdot \vec{B}.$$

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,

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

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 $\left\{\vec{T}, \vec{N}, \vec{B}\right\}$ form a orthonormal basis for $\mathbb{R}^3$, we must hve $\vec{B}\,'(s)$ parallel to $\vec{N}$. Therefore,

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

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

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 know that

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