

NCKU 112.2  
Geometry 1

Eric Liu

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# Chapter 1

## Curve

### 1.1 Frenet Trihedron

In this section, we are given a smooth curve  $\alpha(s) \in \mathbb{R}^3$  parametrized by arc-length and a smooth curve  $\beta(t) \in \mathbb{R}^3$  with unknown parametrization. We seek to

- (a) define Frenet Trihedron for  $\alpha$ .
- (b) prove Frenet-Serret Formula.
- (c) give identity of torsion of  $\alpha$ .
- (d) give identity of curvature of  $\beta$ .

in particular, at the end of this section, using (d), we prove that the curvature of a plane curve  $\beta(t) = (x, y)$  with unknown parametrization is exactly

$$\kappa(t) = \frac{|x'y'' - x''y'|}{((x')^2 + (y')^2)^{\frac{3}{2}}}$$

#### (a): Define Frenet Trihedron for $\alpha$

We define the **tangent vector**  $T$  of  $\alpha$  at each  $s$  by

$$T(s) \triangleq \alpha'(s)$$

and we define its **normal vector**  $N$  by

$$N(s) \triangleq \frac{T'(s)}{|T'(s)|}$$

Note that  $N$  is well defined if and only if  $\alpha''(s) \neq 0$ . We define **binormal vector**  $B$  by

$$B(s) \triangleq T(s) \times N(s)$$

Note that from  $B' \perp B$  and  $B' = (T \times N') \perp T$ , we have  $B' \parallel N$ . This then justify our later definition of **torsion**.

We define **curvature**  $\kappa(s)$  and **torsion**  $\tau(s)$  by

$$\kappa(s) \triangleq |T'(s)| \quad \text{and} \quad \tau(s) \triangleq \frac{B'(s)}{N(s)}$$

### (b): Frenet-Serret Formula

**Theorem 1.1.1. (Frenet-Serret Formula)** Given a smooth curve  $\alpha(s)$  parametrized by arc-length, if  $T'(s) \neq 0$ , we have the following

$$\begin{cases} T' = \kappa N \\ N' = -\kappa T - \tau B \\ B' = \tau N \end{cases}$$

*Proof.* The first and the third equations follows from that of definition. Now, see

$$\begin{aligned} N' &= (B \times T)' \\ &= B' \times T + B \times T' \\ &= \tau N \times T + B \times \kappa N \\ &= \tau(-B) + \kappa(-T) = -\kappa T - \tau B \end{aligned}$$

■

Note that in  $\mathbb{R}^2$ , the Frenet-Serret Formula still holds, in the sense

$$\begin{cases} T' = \kappa N \\ N' = -\kappa T \end{cases}$$

This can be proved by setting the ambient space to be  $\mathbb{R}^3$ .

### (c): Identity of Torsion of $\alpha(s)$

**Theorem 1.1.2. (Identity of Torsion)** Given a smooth curve  $\alpha(s) \in \mathbb{R}^3$  parametrized by arc-length, if  $\kappa(s) \neq 0$ , we have

$$\tau(s) = -\frac{\alpha'(s) \times \alpha''(s) \cdot \alpha'''(s)}{(\alpha''(s))^2}$$

*Proof.* By definition

$$\alpha'(s) = T(s)$$

Compute

$$\alpha''(s) = T'(s) = -\kappa N(s)$$

Compute

$$\alpha''' = (-\kappa N)' = -\kappa' N + \kappa^2 T + \kappa \tau B$$

Compute

$$\alpha' \times \alpha'' = T \times (-\kappa N) = -\kappa B$$

Compute

$$\begin{aligned} \alpha' \times \alpha'' \cdot \alpha''' &= (-\kappa B) \cdot (-\kappa N + \kappa^2 T + \kappa \tau B) \\ &= -\kappa^2 \tau \end{aligned}$$

The result then follows. ■

#### (d): Identity of Curvature of $\beta(t)$

**Theorem 1.1.3. (Identity of Curvature)** Given a smooth curve  $\beta(t) \in \mathbb{R}^3$  with unknown parametrization, we have

$$\kappa(t) = \frac{|\beta'(t) \times \beta''(t)|}{|\beta'(t)|^3}$$

*Proof.* Define  $s$  (arc-length) by

$$s(t) = \int_{t_0}^t |\beta'(t')| dt'$$

We have  $\frac{ds}{dt} = |\beta'(t)|$ . This then give us

$$\kappa(t) = \left| \frac{dT}{ds} \right| = \left| \frac{dT}{dt} \right| \cdot \left| \frac{dt}{ds} \right| = \left| \frac{dT}{dt} \right| \cdot \frac{1}{|\beta'(t)|}$$

We then can reduce the problem into

$$\text{proving } \left| \frac{dT}{dt} \right| = \frac{|\beta'(t) \times \beta''(t)|}{|\beta'(t)|^2}$$

Note that we have

(a)  $\frac{ds}{dt} = |\beta'(t)|$

(b)  $T(t) = \frac{\beta'(t)}{|\beta'(t)|}$

This then let us compute

$$T'(t) = \frac{|\beta'(t)| \beta''(t) - \beta'(t) \frac{d^2s}{(dt)^2}}{|\beta'(t)|^2}$$

and give us

$$\beta''(t) = \frac{d^2s}{dt^2}$$

Then we can deduce

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

This then give us

$$|T'(t)| = \frac{|\beta'(t) \times \beta''(t)|}{|\beta'(t)|^2} \text{ (done)}$$

■

**Corollary 1.1.4. (Curvature of Plane Curves with unknown parametrization)**

Given a smooth curve  $\beta(t) = (x, y) \in \mathbb{R}^3$  with unknown parametrization, we have

$$\kappa(t) = \frac{|x'y'' - x''y'|}{((x')^2 + (y')^2)^{\frac{3}{2}}}$$

## 1.2 Fundamental Theorem of Local Curves

Prerequisite facts:

(a) Suppose  $T \in L(\mathbb{R}^n, \mathbb{R}^n)$  and  $f : I \rightarrow \mathbb{R}^n$  has a limit at  $t_0 \in I$ . We have

$$\lim_{t \rightarrow t_0} T(f(t)) = T\left(\lim_{t \rightarrow t_0} f(t)\right)$$

**Theorem 1.2.1. (Rigid motion on Local space curves)** Let

- (a)  $I$  be a bounded open interval
- (b)  $\gamma : I \rightarrow \mathbb{R}^3$  be a smooth curve such that  $\kappa_\gamma(t) \neq 0$  for all  $t \in I$
- (c)  $\rho \in L(\mathbb{R}^3, \mathbb{R}^3)$  be an orthogonal linear transformation with positive determinant
- (d)  $c \in \mathbb{R}^3$  be a vector in  $\mathbb{R}^3$
- (e)  $\alpha : I \rightarrow \mathbb{R}^3$  be defined by  $\alpha(t) \triangleq \rho(\gamma(t))$
- (f)  $\beta : I \rightarrow \mathbb{R}^3$  be defined by  $\beta(t) \triangleq \alpha(t) + c$

We have

$$\begin{cases} \kappa_\gamma(t) = \kappa_\alpha(t) = \kappa_\beta(t) \\ \tau_\gamma(t) = \tau_\alpha(t) = \tau_\beta(t) \end{cases} \quad (t \in I)$$

*Proof.* We first show

$$(\rho v) \times (\rho w) = \rho(v \times w) \quad (v, w \in \mathbb{R}^3)$$

Fix  $v, w \in \mathbb{R}^3$ . We reduce the problem into proving

$$(\rho v) \times (\rho w) \cdot z = \rho(v \times w) \cdot z \quad (z \in \mathbb{R}^3)$$

Observe

$$\begin{aligned} (\rho v) \times (\rho w) \cdot z &= \begin{vmatrix} \rho v & \rho w & \rho(\rho^{-1}(z)) \end{vmatrix} \\ &= \begin{vmatrix} v & w & \rho^{-1}(z) \end{vmatrix} \\ &= v \times w \cdot \rho^{-1}(z) \\ &= \rho(v \times w) \cdot z \quad (\text{done}) \end{aligned}$$

We first prove

$$\kappa_\alpha(t) = \kappa_\gamma(t) \quad (t \in I)$$

Note that  $\gamma''$  exists, so we can compute

$$\begin{aligned}
 \kappa_\alpha &= \frac{|\alpha' \times \alpha''|}{|\alpha'|^3} \\
 &= \frac{|(\rho\gamma)' \times (\rho\gamma)''|}{|(\rho\gamma)'|^3} \\
 &= \frac{|\rho\gamma' \times \rho\gamma''|}{|\rho\gamma'|^3} \\
 &= \frac{|\rho(\gamma' \times \gamma'')|}{|\rho\gamma'|^3} \\
 &= \frac{|\gamma' \times \gamma''|}{|\gamma'|^3} = \kappa_\gamma \text{ (done)}
 \end{aligned}$$

We now prove

$$\tau_\alpha(t) = \tau_\gamma(t) \quad (t \in I)$$

Compute

$$\begin{aligned}
 \tau_\alpha &= -\frac{\alpha' \times \alpha'' \cdot \alpha'''}{|\alpha' \times \alpha''|} \\
 &= -\frac{\rho\gamma' \times \rho\gamma'' \cdot \rho\gamma'''}{|\rho\gamma' \times \rho\gamma''|} \\
 &= -\frac{\gamma' \times \gamma'' \cdot \gamma'''}{|\gamma' \times \gamma''|} = \tau_\gamma \text{ (done)}
 \end{aligned}$$

■

**Theorem 1.2.2. (Fundamental Theorem of Local Curves)** Let

- (a)  $I$  be a bounded open interval
- (b)  $\kappa : I \rightarrow \mathbb{R}^+$  be a smooth function
- (c)  $\tau : I \rightarrow \mathbb{R}$  be a smooth function

And, let  $E$  be the set of all space curves  $\gamma$  such that

- (a)  $\gamma$  has domain  $I$
- (b)  $|\gamma'(s)| = 1$
- (c)  $\kappa_\gamma(s) = \kappa(s)$



(d)  $\tau_\gamma(s) = \tau(s)$

The following statement hold true.

(a)  $E$  is non-empty. **(existence part)**

(b) For each two  $\gamma, \alpha \in E$ , there exists an orthogonal linear transformation  $\rho \in L(\mathbb{R}^3, \mathbb{R}^3)$  with positive determinant and a vector  $c \in \mathbb{R}^3$  such that  $\gamma(s) = \rho \circ \alpha(s) + c$  for all  $s \in I$ . **(uniqueness part)**

*Proof.* We first prove

$E$  is non-empty

Fix  $s_0 \in I$ , and fix

$$\begin{bmatrix} T(s_0) \\ N(s_0) \\ B(s_0) \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (1.1)$$

Consider the system of differential equation

$$\begin{bmatrix} 0 & \kappa & 0 \\ -\kappa & 0 & -\tau \\ 0 & \tau & 0 \end{bmatrix} \begin{bmatrix} T \\ N \\ B \end{bmatrix} = \begin{bmatrix} T' \\ N' \\ B' \end{bmatrix}$$

This is a first order, linear system of differential equation (3, if you wish), which has a unique solution  $\{T, N, B : I \rightarrow \mathbb{R}^3\}$  with given initial condition (Equation 1.1).

We claim

$$\gamma(s) \triangleq \gamma(s_0) + \int_{s_0}^s T(s') ds' \in E$$

Note that the solution  $\{T, N, B : I \rightarrow \mathbb{R}^3\}$  must satisfy

$$\begin{aligned} \frac{d}{ds} \langle T, N \rangle &= \kappa \langle N, N \rangle - \kappa \langle T, T \rangle - \tau \langle T, B \rangle \\ \frac{d}{ds} \langle T, B \rangle &= \kappa \langle N, B \rangle + \tau \langle T, N \rangle \\ \frac{d}{ds} \langle N, B \rangle &= -\kappa \langle T, B \rangle - \tau \langle B, B \rangle + \tau \langle N, N \rangle \\ \frac{d}{ds} \langle T, T \rangle &= 2\kappa \langle T, N \rangle \\ \frac{d}{ds} \langle N, N \rangle &= -2\kappa \langle T, N \rangle - 2\tau \langle B, N \rangle \\ \frac{d}{ds} \langle B, B \rangle &= 2\tau \langle N, B \rangle \end{aligned}$$

which is another linear first order system of differential equation, which has unique solution when initial condition are given.

It is easy to check that

$$\langle T, T \rangle \triangleq \langle N, N \rangle \triangleq \langle B, B \rangle \triangleq 1 \text{ and } \langle T, N \rangle \triangleq \langle T, B \rangle \triangleq \langle N, B \rangle = 0 \quad (1.2)$$

is a solution.

Now, note that our unique solution  $\{T, N, B\}$  given before has initial condition coincide with that of 1.2. Then it follows from the uniqueness of solution of linear first order system of differential equations that  $\{T(s), N(s), B(s)\}$  is an orthonormal basis for all  $s \in I$ .

Since  $\gamma'(s) = T(s)$ , it is now clear that  $\kappa_\gamma = \kappa$  and  $\tau_\gamma = \tau$ . (done)

Fix  $\gamma, \alpha \in E$  and fix  $s_0 \in I$ . There clearly exists a rigid motion  $M$  such that if we denote

$$\bar{\alpha}(s) \triangleq M \circ \alpha(s)$$

Then

$$\gamma(s_0) = \bar{\alpha}(s_0) \text{ and } \begin{cases} T_\gamma(s_0) = T_{\bar{\alpha}}(s_0) \\ N_\gamma(s_0) = N_{\bar{\alpha}}(s_0) \\ B_\gamma(s_0) = B_{\bar{\alpha}}(s_0) \end{cases}$$

We only wish to prove

$$T_\gamma(s) = T_{\bar{\alpha}}(s) \quad (s \in I)$$

Denote

$$T \triangleq T_\gamma \text{ and } \bar{T} \triangleq T_{\bar{\alpha}} \text{ and also similarly for } N, B$$

Compute

$$\begin{aligned} & \frac{d}{ds} \left( |T - \bar{T}|^2 + |N - \bar{N}|^2 + |B - \bar{B}|^2 \right) \\ &= 2 \left( \langle T' - \bar{T}', T - \bar{T} \rangle + \langle N' - \bar{N}', N - \bar{N} \rangle + \langle B' - \bar{B}', B - \bar{B} \rangle \right) \\ &= 2 \left( \kappa \langle N - \bar{N}, T - \bar{T} \rangle - \kappa \langle T - \bar{T}, N - \bar{N} \rangle - \tau \langle B - \bar{B}, N - \bar{N} \rangle + \tau \langle N - \bar{N}, B - \bar{B} \rangle \right) \\ &= 0 \end{aligned}$$

This then implies

$$|T - \overline{T}|^2 + |N - \overline{N}|^2 + |B - \overline{B}|^2 \text{ is a fixed constant on } I$$

Note that

$$T(s_0) = \overline{T}(s_0) \text{ and } N(s_0) = \overline{N}(s_0) \text{ and } B(s_0) = \overline{B}(s_0)$$

Then we know that fixed constant is exactly 0. This then let us deduce

$$T = \overline{T} \text{ on } I \text{ (done)}$$

■

## 1.3 Isoperimetric Inequality and Four-Vertex Theorem

In this section, we are given a smooth plane curve  $\alpha : [a, b] \rightarrow \mathbb{R}^2$  parametrized by arc-length. We say

- (a)  $\alpha$  is a **closed curve** if  $\alpha(a) = \alpha(b)$ .
- (b)  $\alpha$  is a **simple closed curve** if  $\alpha$  is closed and  $\alpha(t_1) \neq \alpha(t_2)$  for all  $t_1, t_2 \in [a, b]$ .
- (c)  $\alpha$  is **positively oriented** if  $\alpha' \times \alpha''$  is always positive.
- (d)  $\alpha$  is **convex** the trace  $\alpha([a, b])$  always entirely lies on the same side of the closed half-plane determined by  $T(s)$  for all  $s$
- (e)  $\alpha$  has **vertex**  $\alpha(s_0)$  if  $\kappa'(s_0) = 0$

The interior  $D$  of a piece-wise smooth, simple closed plane curve  $\alpha : [a, b] \rightarrow \mathbb{R}^2$  can be assigned a number to represent its area

$$A(D) = \iint_D 1 dx dy \quad (1.3)$$

that match with our geometric intuition, in the sense that if one compute the area of a rectangle or that of a circle, using Formula 1.3, then one obtain number same as the number obtained using elementary geometric way (height  $\times$  width, etc).

Note that by Green's Theorem, we know  $A(D)$  equals to

- (a)  $\int_a^b xy' dt$
- (b)  $-\int_a^b yx' dt$
- (c)  $\frac{1}{2} \int_a^b xy' - yx' dt = \frac{1}{2} \int_a^b (x, y) \times (x', y') dt$

**Theorem 1.3.1. (Isoperimetric Inequality)** Given a piece-wise  $C^1$  simple closed plane curve  $\alpha : [0, l] \rightarrow \mathbb{R}^2$ , where  $D$  is the interior of  $\alpha$  and  $A \triangleq A(D)$ , we have

- (a)  $4\pi A \leq l^2$
- (b)  $4\pi A = l^2 \iff \alpha$  is a parametrization of  $S^1$

*Proof.* We first show

$$4\pi A \leq l^2$$

Express  $\alpha = (x, y)$ . Define

$$r = \frac{1}{2} \left( \sup_{[0,l]} x - \inf_{[0,l]} x \right)$$

WOLG, suppose  $\sup_{[0,l]} x = r$ . Now, positively parametrize  $S^1$  by  $(\bar{x}, \bar{y})$  where

$$\bar{x} \triangleq x$$

Observe

$$\begin{aligned} A + \pi r^2 &= \oint_{\alpha} x dy - \oint_{S^1} y dx \\ &= \int_0^l (xy' - x'\bar{y}) dt \\ &= \int_0^l (x, -\bar{y}) \cdot (y', x') dt \\ &\leq \int_0^l |(x, -\bar{y})| \cdot |(y', x')| dt \quad (\text{Cauchy-Schwarz}) \\ &= \int_0^l \sqrt{x^2 + (-\bar{y})^2} \sqrt{(y')^2 + (x')^2} dt \\ &= \int_0^l \sqrt{x^2 + \bar{y}^2} dt \\ &= \int_0^l r dt = lr \end{aligned}$$

Using AM-GM inequality, we now have

$$\sqrt{A\pi r^2} \leq \frac{A + \pi r^2}{2} \leq \frac{lr}{2}$$

This then implies

$$4\pi A \leq l^2 \text{ (done)}$$

It is easy to see that the equality hold true when  $\alpha$  is a parametrization of  $S^1$ . We prove

$$4\pi A = l^2 \implies \alpha \text{ is a parametrization of } S^1 \text{ of radius } \frac{l}{2\pi}$$

We first prove

$$4\pi A = l^2 \implies x = \frac{l}{2\pi} y'$$

Note that  $4\pi A = l^2$  implies the Cauchy-Schwarz inequality

$$(x, -\bar{y}) \cdot (y', x') \leq |(x, -\bar{y})| \cdot |(y', x')|$$

must hold equal. This then give us

$$(x, -\bar{y}) \parallel (y', x')$$

Also, note that  $4\pi A = l^2$  implies the AM-GM inequality

$$\sqrt{A\pi r^2} \leq \frac{A + \pi r^2}{2}$$

must also hold equal. This then give us

$$A = \pi r^2 \text{ and } l = 2\pi r$$

Now, because

(a)  $(x, y)$  is parametrization by arc-length

(b)  $|(x, -\bar{y})| = |(\bar{x}, \bar{y})| = r$

(c)  $r = \frac{l}{2\pi}$

We have

$$x = \frac{l}{2\pi} y' \text{ (done)} \tag{1.4}$$

Similar argument now, WOLG, applies to

$$4\pi A = l^2 \implies y = \frac{l}{2\pi} x'$$

We now conclude

$$4\pi A = l^2 \implies |(x, y)| = \frac{l}{2\pi} |(y', x')| = \frac{l}{2\pi} \text{ (done)}$$

■

For next Theorem, we expand the definition of closed curve. We say

(a)  $\alpha$  is a **closed curve** if  $\alpha^k(a) = \alpha^k(b)$  for all  $k \in \mathbb{Z}_0^+$

**Lemma 1.3.2.** If  $\alpha : [0, l] \rightarrow \mathbb{R}^2$  is a smooth, convex, simple closed plane curve, then for all  $A, B, C \in \mathbb{R}$ , we have

$$\int_0^l (Ax + By + C) d\kappa = 0$$

*Proof.* Because  $\alpha$  is closed, it is clear that

$$\int_0^l C d\kappa = 0$$

Let  $\theta : [0, l] \rightarrow [0, 2\pi]$  satisfy

$$(x', y') = (\cos \theta, \sin \theta)$$

It is easy to check

$$(a) \quad \kappa = \theta'$$

$$(b) \quad (x'', y'') = \kappa(-y', x')$$

We now see

$$\begin{aligned} \int_0^l A x d\kappa &= A \int_0^l x \kappa' ds \\ &= -A \int_0^l x' \kappa ds \\ &= A \int_0^l y'' ds = 0 \end{aligned}$$

and

$$\begin{aligned} \int_0^l B y d\kappa &= B \int_0^l y \kappa' ds \\ &= - \int_0^l y' \kappa ds \\ &= -B \int_0^l x'' ds = 0 \end{aligned}$$

■

**Theorem 1.3.3. (Four-Vertex Theorem for Convex Curve)** If  $\alpha : [0, l] \rightarrow \mathbb{R}^2$  is a smooth, convex, simple closed plane curve, then

$\alpha$  has at least four distinct vertices

*Proof.* Because  $\kappa$  is continuous on  $[0, l]$ , by EVT, we know there exists  $p, q$  such that

$$\kappa(p) = \max_{[0, l]} \kappa \text{ and } \kappa(q) = \min_{[0, l]} \kappa$$

Because  $\kappa(p), \kappa(q)$  are local (global, in fact) extremum, we know

$$\kappa'(p) = \kappa'(q) = 0$$

Note that if  $p = q$ , then the proof become trivial. We have thus obtained two distinct vertices, namely,  $p$  and  $q$ .

WOLG, suppose  $p < q$ . Let  $L$  be the unique line containing  $\alpha(p)$  and  $\alpha(q)$ . We claim

$$\alpha[(p, q)] \text{ and } \alpha\left[[0, l] \setminus [p, q]\right] \text{ are on different side of } L$$

(done)

Note that

- (a)  $p < q$
- (b)  $\kappa(p)$  is a maximum
- (c)  $\kappa(q)$  is a minimum

Assume  $\kappa' \leq 0$  on  $(p, q)$  and  $\kappa' \geq 0$  on  $[p, q]^c$ . WOLG, suppose  $\alpha[(p, q)]$  is on the left side of  $L$ . Let  $A, B, C \in \mathbb{R}$  satisfy

- (a)  $L = \{(x, y) : Ax + By + C = 0\}$
- (b)  $A \in \mathbb{R}^+$

Now, because  $\alpha[(p, q)]$  is completely on the left side of  $L$ , we see

$$\int_p^q (Ax + By + C) d\kappa > 0 \quad (\because \kappa', Ax + By + C < 0)$$

and because  $\alpha[[p, q]^c]$  is completely on the right side of  $L$ , we see

$$\int_0^p (Ax + By + C) d\kappa + \int_q^l (Ax + By + C) d\kappa > 0 \quad (\because \kappa', Ax + By + C > 0)$$

This now let us deduce

$$\int_0^l (Ax + By + C) d\kappa > 0 \text{ CaC}$$

WOLG, suppose  $\kappa'(s) > 0$  for some  $s \in (p, q)$ . Because

- (a)  $\kappa(p)$  is a maximum



(b)  $\kappa(q)$  is a minimum

we know there exists  $\epsilon$  such that

$$\kappa(p + \epsilon) < 0 \text{ and } \kappa(q - \epsilon) < 0$$

Then by IVT, we see

$$\kappa'(s_1) = \kappa'(s_2) = 0 \text{ for some distinct } s_1, s_2 \in (p, q)$$

■

# Chapter 2

## HW

### 2.1 HW1

#### Question 1: 1-2: 2

Let  $\alpha(t)$  be a parametrized curve which does not pass through the origin. If  $\alpha(t_0)$  is the point of the trace of  $\alpha$  closest to the origin and  $\alpha'(t_0) \neq 0$ , show that the position vector  $\alpha(t_0)$  is orthogonal to  $\alpha'(t_0)$ .

*Proof.* Define  $g : I \rightarrow \mathbb{R}$  by

$$g(t) \triangleq |\alpha(t)|^2 = (\alpha \cdot \alpha)(t)$$

Notice that

$$g'(t) = (2\alpha' \cdot \alpha)(t) \text{ if exists}$$

From premise, we know  $g$  attains minimum at  $t_0$ . This tell us

$$0 = g'(t_0) = (2\alpha' \cdot \alpha)(t_0)$$

Then, we can deduce

$$\alpha'(t_0) \cdot \alpha(t_0) = 0$$

This implies  $\alpha(t_0) \perp \alpha'(t_0)$ . ■

#### Question 2: 1-2: 5

Let  $\alpha : I \rightarrow \mathbb{R}^3$  be a parametrized curve, with  $\alpha''(t) \neq 0$  for all  $t \in I$ . Show that  $|\alpha(t)|$  is a nonzero constant if and only if  $\alpha(t)$  is orthogonal to  $\alpha'(t)$  for all  $t \in I$ .

*Proof.* We wish to prove

$$\exists \beta \in \mathbb{R}^*, \forall t \in I, |\alpha(t)| = \beta \iff \forall t \in I, (\alpha \cdot \alpha')(t) = 0$$

Define  $g : I \rightarrow \mathbb{R}$  by

$$g(t) \triangleq |\alpha(t)|^2 = (\alpha \cdot \alpha)(t)$$

Notice that

$$g'(t) = (2\alpha' \cdot \alpha)(t) \tag{2.1}$$

( $\longrightarrow$ )

From premise,  $g$  is a constant on  $I$ . This implies  $g'(t) = 0$  for all  $t \in I$ . Then, from Equation 2.1, we see

$$(\alpha \cdot \alpha')(t) = 0 \text{ for all } t \in I$$

( $\longleftarrow$ )

Again, from Equation 2.1, we deduce

$$\forall t \in I, (\alpha \cdot \alpha')(t) = 0 \implies \forall t \in I, g'(t) = 0$$

This implies  $g$  is a constant, which implies  $|\alpha|$  is a constant, that is

$$\exists \beta \in \mathbb{R}, |\alpha(t)| = \beta$$

Lastly, we have to show

$$\beta \neq 0$$

Assume  $\beta = 0$ . Then, we see  $\alpha(t) = 0$  for all  $t \in I$ . This implies  $\alpha''(t) = 0$  for all  $t \in I$ , which **CaC** to the premise. (done) ■

### Question 3: 1-3:2

2. A circular disk of radius 1 in the plane  $xy$  rolls without slipping along the  $x$  axis. The figure described by a point of the circumference of the disk is called a *cycloid* (Fig. 1-7).

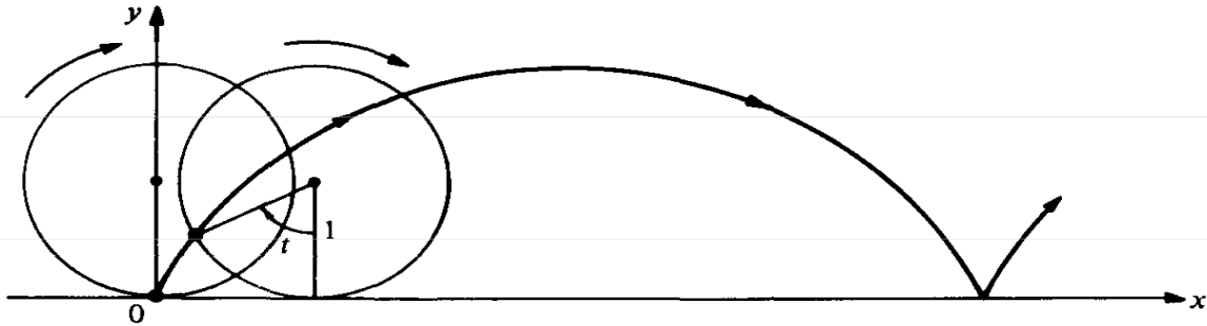


Figure 1-7. The cycloid.

- \*a. Obtain a parametrized curve  $\alpha: R \rightarrow R^2$  the trace of which is the cycloid, and determine its singular points.
- b. Compute the arc length of the cycloid corresponding to a complete rotation of the disk.

*Proof.* The solution of the question a is

$$\alpha(t) = (t - \sin t, 1 - \cos t)$$

Compute

$$\alpha'(t) = (1 - \cos t, \sin t)$$

and compute

$$|\alpha'(t)| = \sqrt{1 - 2\cos t + \cos^2 t + \sin^2 t} = \sqrt{2} \cdot \sqrt{1 - \cos t}$$

This implies the singular points are

$$\{2n\pi : n \in \mathbb{Z}\}$$

The solution of the question **b** is then

$$\begin{aligned}
 \int_0^{2\pi} |\alpha'(t)| dt &= \sqrt{2} \int_0^{2\pi} \sqrt{1 - \cos t} dt \\
 &= \sqrt{2} \int_0^{2\pi} \sqrt{2} \left| \sin \frac{t}{2} \right| dt \\
 &= 2 \int_0^{2\pi} \left| \sin \frac{t}{2} \right| dt \\
 &= 4 \int_0^{\pi} \sin\left(\frac{t}{2}\right) dt \\
 &= -8 \cos \frac{t}{2} \Big|_0^{\pi}
 \end{aligned}$$

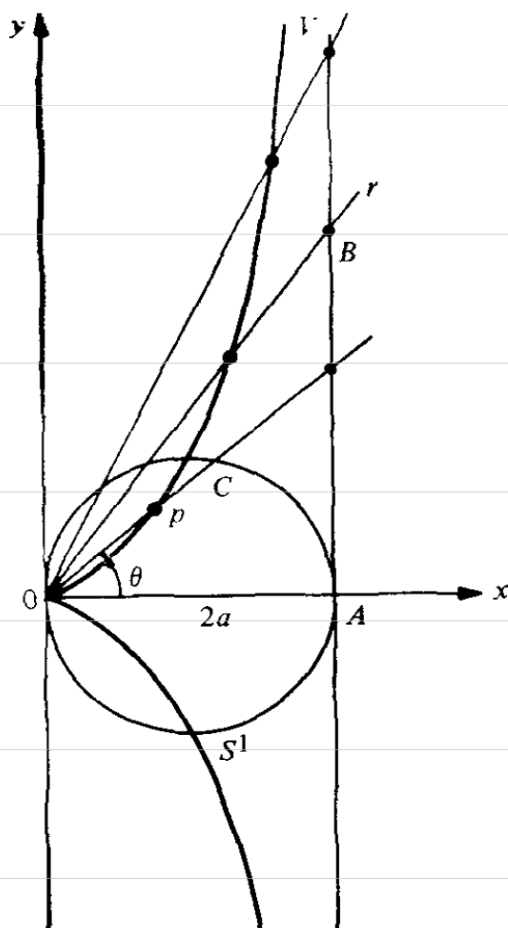
■

#### Question 4: 1-3:4

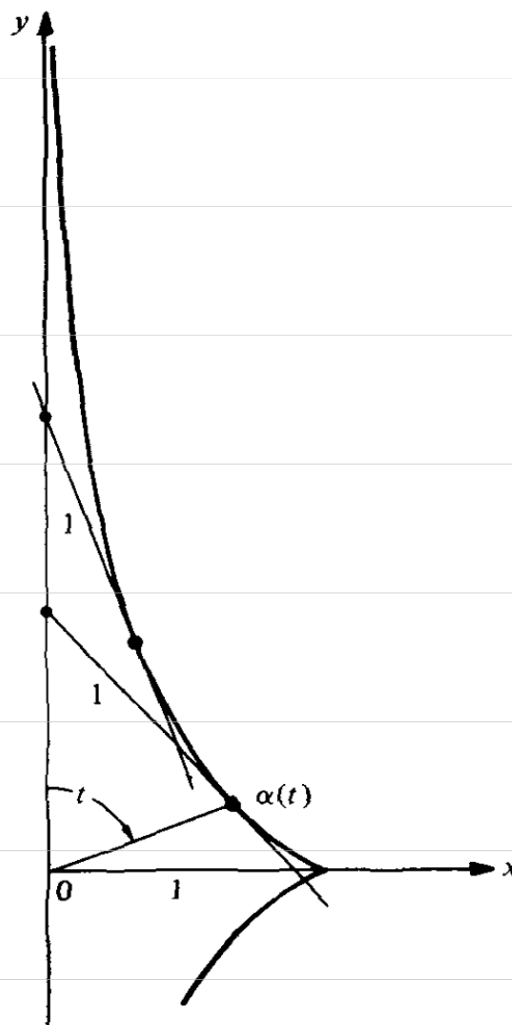
**4.** Let  $\alpha: (0, \pi) \rightarrow \mathbb{R}^2$  be given by

$$\alpha(t) = \left( \cos t, \cos t + \log \tan \frac{t}{2} \right),$$

where  $t$  is the angle that the  $y$  axis makes with the vector  $\alpha(t)$ . The trace of  $\alpha$  is called the *tractrix* (Fig. 1-9). Show that



**Figure 1-8.** The cissoid of Diocles.



**Figure 1-9.** The tractrix.

- a.  $\alpha$  is a differentiable parametrized curve, regular except at  $t = \pi/2$ .
- b. The length of the segment of the tangent of the tractrix between the point of tangency and the  $y$  axis is constantly equal to 1.

Typo correction:  $\alpha(t) = (\sin t, \cos t + \ln \tan \frac{t}{2})$

*Proof.* (a)

Notice that the interval  $I$  is  $(0, \pi)$ . It is clear that

- (a)  $\sin t$  is smooth on  $\mathbb{R}$
- (b)  $\cos t$  is smooth on  $\mathbb{R}$

(c)  $\ln t$  is smooth on  $\mathbb{R}$   $\tan \frac{t}{2}$  is smooth on  $I$

Then it follows that  $\alpha$  is a differentiable curve.

Compute

$$\alpha'(t) = (\cos t, -\sin t + \frac{1}{\tan \frac{t}{2}} \cdot \sec^2 \frac{t}{2} \cdot \frac{1}{2})$$

Because  $\cos t = \alpha'_1(t)$  is 0 on  $I$  only when  $t = \frac{\pi}{2}$ , we know  $\alpha$  is regular on  $I$  except possibly at  $t = \frac{\pi}{2}$ .

Compute

$$\alpha'(\frac{\pi}{2}) = (0, -1 + \frac{1}{1} \cdot 2 \cdot \frac{1}{2}) = (0, 0)$$

We now conclude  $\alpha$  is regular on  $I$  except  $\frac{\pi}{2}$ .

**(b)**

A useful Identity give us

$$\alpha'(t) = (\cos t, -\sin t + \csc t)$$

From the following facts

(a) the first argument of the segment is from 0 to  $\sin t = \alpha(t)$

(b)  $\alpha'_x(t) = \cos t$

(c)  $\frac{\sin t}{\cos t} = \tan t$

We conclude that the length of the segment is

$$\begin{aligned} |\tan t| \cdot |\alpha'(t)| &= |\tan t| \cdot \sqrt{\cos^2 t + \sin^2 t - 2 \sin t \csc t + \csc^2 t} \\ &= |\tan t| \cdot \sqrt{1 - 2 + \csc^2 t} \\ &= |\tan t| \cdot \sqrt{\csc^2 t - 1} = |\tan t| \cdot \sqrt{\cot^2 t} = 1 \end{aligned}$$

■

## Question 5

7. A map  $\alpha: I \rightarrow R^3$  is called a curve of class  $C^k$  if each of the coordinate functions in the expression  $\alpha(t) = (x(t), y(t), z(t))$  has continuous derivatives up to order  $k$ . If  $\alpha$  is merely continuous, we say that  $\alpha$  is of class  $C^0$ . A curve  $\alpha$  is called *simple* if the map  $\alpha$  is one-to-one. Thus, the curve in Example 3 of Sec. 1-2 is not simple.

Let  $\alpha: I \rightarrow R^3$  be a simple curve of class  $C^0$ . We say that  $\alpha$  has a *weak tangent* at  $t = t_0 \in I$  if the line determined by  $\alpha(t_0 + h)$  and  $\alpha(t_0)$  has a limit position when  $h \rightarrow 0$ . We say that  $\alpha$  has a *strong tangent* at  $t = t_0$  if the line determined by  $\alpha(t_0 + h)$  and  $\alpha(t_0 + k)$  has a limit position when  $h, k \rightarrow 0$ . Show that

a.  $\alpha(t) = (t^3, t^2)$ ,  $t \in R$ , has a weak tangent but not a strong tangent at  $t = 0$ .

\*b. If  $\alpha: I \rightarrow R^3$  is of class  $C^1$  and regular at  $t = t_0$ , then it has a strong tangent at  $t = t_0$ .

c. The curve given by

$$\alpha(t) = \begin{cases} (t^2, t^2), & t \geq 0, \\ (t^2, -t^2), & t \leq 0, \end{cases}$$

is of class  $C^1$  but not of class  $C^2$ . Draw a sketch of the curve and its tangent vectors.

*Proof.* (a) Let  $v = (0, 1)$ . Compute

$$\frac{\alpha(t) - \alpha(0)}{|\alpha(t) - \alpha(0)|} \cdot v = \frac{t^2}{\sqrt{t^6 + t^4}} = \frac{1}{\sqrt{t^2 + 1}} \rightarrow 1 \text{ as } t \rightarrow 1$$

This implies  $\alpha$  has a weak tangent at  $t = 0$ . Now, if  $\alpha$  has a strong tangent, we must have

$$\frac{\alpha(h) - \alpha(-h)}{2h} \cdot v \rightarrow 1 \text{ or } \rightarrow -1$$

But this is clearly not the case as

$$\frac{\alpha(h) - \alpha(-h)}{2h} \cdot v = 0 \text{ for all } h > 0$$



So we have the conclusion that  $\alpha$  has no strong tangent at 0.

(b) By MVT, for each  $h, k$  there exists a set of real numbers  $\{c_x, c_y, c_z\}$  between  $t + h$  and  $t + k$  such that

$$\frac{\alpha(t_0 + h) - \alpha(t_0 + k)}{h - k} = (x'(c_x), y'(c_y), z'(c_z))$$

Then because

$$h, k \rightarrow 0 \implies t_0 + h, t_0 + k \rightarrow t_0 \implies c_x, c_y, c_z \rightarrow t_0$$

Then from the fact  $\alpha$  is of class  $C^1$  ( $x', y', z'$  are all continuous), we can now deduce

$$\frac{\alpha(t_0 + h) - \alpha(t_0 + k)}{h - k} \rightarrow \alpha'(t_0) \text{ as } h, k \rightarrow 0 \quad (2.2)$$

Now, because  $\alpha'(t_0) \neq 0$  as  $\alpha$  is regular, we see

$$\lim_{h, k \rightarrow 0} \frac{\alpha(t_0 + h) - \alpha(t_0 + k)}{h - k} \cdot \alpha'(t_0) = |\alpha'(t_0)|^2$$

This then implies

$$\lim_{h, k \rightarrow 0} \frac{\alpha(t_0 + h) - \alpha(t_0 + k)}{|\alpha(t_0 + h) - \alpha(t_0 + k)|} \cdot \frac{\alpha'(t_0)}{|\alpha'(t_0)|} = 1$$

which implies the "strong tangent" must always converge to  $\alpha'(t_0)$ .

Notice that the last implication is backed by Equation 2.2

(c)

From

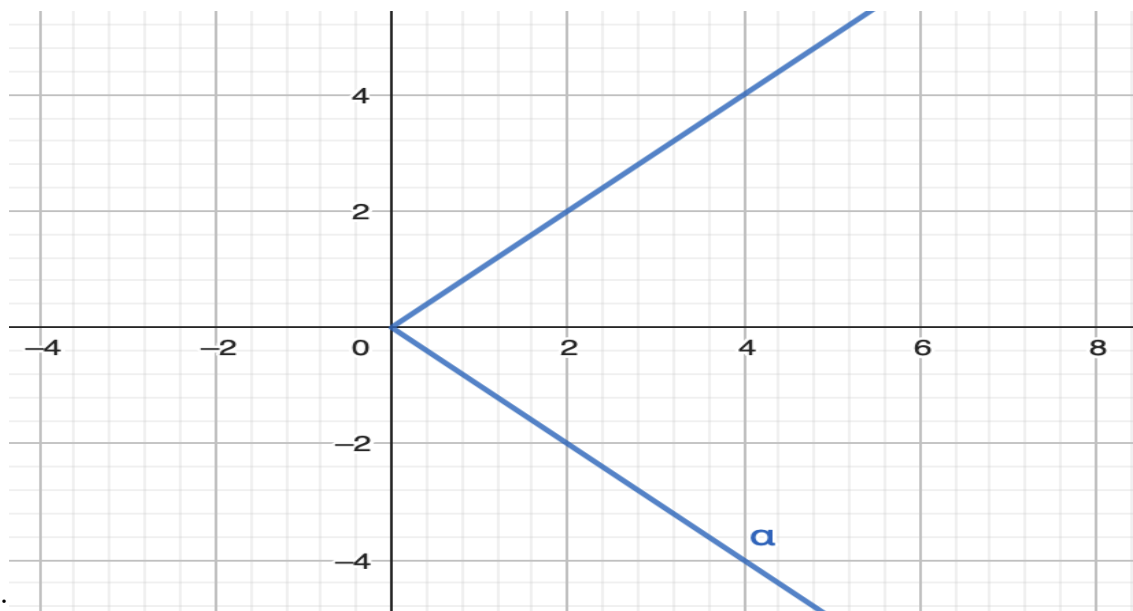
$$\alpha(t) = \left( t^2, \begin{cases} t^2 & \text{if } t \geq 0 \\ -t^2 & \text{if } t \leq 0 \end{cases} \right)$$

Compute

$$\alpha'(t) = \left( 2t, \begin{cases} 2t & \text{if } t \geq 0 \\ -2t & \text{if } t \leq 0 \end{cases} \right)$$

Notice that the derivative at  $t = 0$  is computed from definition instead of product rule.

Now, it is clear that  $x', y'$  are continuous. This implies  $\alpha \in C^1$ . Yet, we see  $y'$  is not differentiable at  $t = 0$ . This implies  $\alpha \notin C^2$ .



The sketch:



## Question 6

\*8. Let  $\alpha: I \rightarrow \mathbb{R}^3$  be a differentiable curve and let  $[a, b] \subset I$  be a closed interval. For every *partition*

$$a = t_0 < t_1 < \cdots < t_n = b$$

of  $[a, b]$ , consider the sum  $\sum_{i=1}^n |\alpha(t_i) - \alpha(t_{i-1})| = l(\alpha, P)$ , where  $P$  stands for the given partition. The norm  $|P|$  of a partition  $P$  is defined as

$$|P| = \max(t_i - t_{i-1}), i = 1, \dots, n.$$

Geometrically,  $l(\alpha, P)$  is the length of a polygon inscribed in  $\alpha([a, b])$  with vertices in  $\alpha(t_i)$  (see Fig. 1-12). The point of the exercise is to show that the arc length of  $\alpha([a, b])$  is, in some sense, a limit of lengths of inscribed polygons.

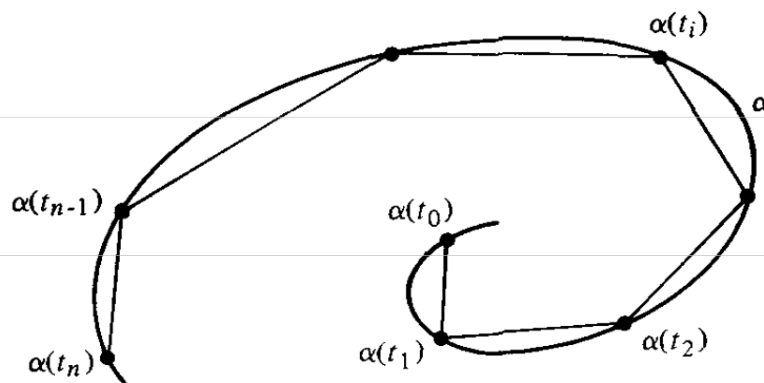


Figure 1-12

Prove that given  $\epsilon > 0$  there exists  $\delta > 0$  such that if  $|P| < \delta$  then

$$\left| \int_a^b |\alpha'(t)| dt - l(\alpha, P) \right| < \epsilon.$$

*Proof.* We first prove

$$\int_a^b |\alpha'(t)| dt \geq l(\alpha, P)$$

By FTC, we have

$$\begin{aligned} |\alpha(t_i) - \alpha(t_{i-1})| &= \left| \int_{t_{i-1}}^{t_i} \alpha'(t) dt \right| \\ &\leq \int_{t_{i-1}}^{t_i} |\alpha'(t)| dt \end{aligned}$$

This then implies

$$l(\alpha, P) = \sum |\alpha(t_i) - \alpha(t_{i-1})| \leq \sum \int_{t_{i-1}}^{t_i} |\alpha'(t)| dt = \int_a^b |\alpha'(t)| dt \text{ (done)}$$

We have reduced the problem into

$$\text{finding } \delta \text{ such that } \forall P : |P| < \delta, \int_a^b |\alpha'(t)| dt - l(\alpha, P) < \epsilon$$

Because  $\alpha'$  is uniformly continuous on  $[a, b]$  ( $\because$  continuous function on compact domain is uniformly continuous), we know there exists  $\delta'$  such that

$$|\alpha'(s) - \alpha'(t)| < \frac{\epsilon}{2(b-a)} \text{ if } |s - t| < \delta'$$

We claim

such  $\delta'$  works

Let  $|P| < \delta$ , and let  $s_i \in [t_{i-1}, t_i]$ . Because  $|s_i - t_i| < \delta$ , we have

$$|\alpha'(s_i) - \alpha'(t_i)| < \frac{\epsilon}{2(b-a)} \tag{2.3}$$

This give us

$$|\alpha'(s_i)| < |\alpha'(t_i)| + \frac{\epsilon}{2(b-a)}$$

Now, we can deduce

$$\begin{aligned}
\int_{t_{i-1}}^{t_i} |\alpha'(s)| ds &\leq |\alpha'(t_i)| \Delta t_i + \frac{\epsilon}{2(b-a)} \Delta t_i \\
&= \int_{t_{i-1}}^{t_i} |\alpha'(t_i)| dt + \frac{\epsilon}{2(b-a)} \Delta t_i \\
&= \left| \int_{t_{i-1}}^{t_i} \alpha'(t_i) dt \right| + \frac{\epsilon}{2(b-a)} \Delta t_i \\
&= \left| \int_{t_{i-1}}^{t_i} \alpha'(t_i) - \alpha'(t) dt + \int_{t_{i-1}}^{t_i} \alpha'(t) dt \right| + \frac{\epsilon}{2(b-a)} \Delta t_i \\
&\leq \left| \int_{t_{i-1}}^{t_i} \alpha'(t_i) - \alpha'(t) dt \right| + \left| \int_{t_{i-1}}^{t_i} \alpha'(t) dt \right| + \frac{\epsilon}{2(b-a)} \Delta t_i \\
&\leq \frac{\epsilon}{2(b-a)} \Delta t_i + |\alpha(t_i) - \alpha(t_{i-1})| + \frac{\epsilon}{2(b-a)} \Delta t_i \\
&= |\alpha(t_i) - \alpha(t_{i-1})| + \frac{\epsilon}{b-a} \Delta t_i
\end{aligned}$$

Notice that the last inequality follows from Equation 2.3. The long deduction above then give us

$$\begin{aligned}
\int_a^b |\alpha'(t)| dt &\leq \sum |\alpha(t_i) - \alpha(t_{i-1})| + \frac{\epsilon}{b-a} (b-a) \\
&= l(\alpha, P) + \epsilon
\end{aligned}$$

Then we have

$$\int_a^b |\alpha'(t)| dt - l(\alpha, P) \leq \epsilon \text{ (done)}$$

■

## Question 7

9. a. Let  $\alpha: I \rightarrow R^3$  be a curve of class  $C^0$  (cf. Exercise 7). Use the approximation by polygons described in Exercise 8 to give a reasonable definition of arc length of  $\alpha$ .
- b. (*A Nonrectifiable Curve.*) The following example shows that, with any reasonable definition, the arc length of a  $C^0$  curve in a closed interval may be unbounded. Let  $\alpha: [0, 1] \rightarrow R^2$  be given as  $\alpha(t) = (t, t \sin(\pi/t))$  if  $t \neq 0$ , and  $\alpha(0) = (0, 0)$ . Show, geometrically, that the arc length of the portion of the curve corresponding to  $1/(n+1) \leq t \leq 1/n$  is at least  $2/(n + \frac{1}{2})$ . Use this to show that the length of the curve in the interval  $1/N \leq t \leq 1$  is greater than  $2 \sum_{n=1}^N 1/(n+1)$ , and thus it tends to infinity as  $N \rightarrow \infty$ .

*Proof.* (a) Suppose  $I = [a, b]$ . Define arc length by

$$\sup_P l(P, \alpha) \text{ where } \sup \text{ runs over all partition } P \text{ of } [a, b]$$

(b)

Geometrically, we know the arc length of the portion of the curve corresponding to  $t \in [\frac{1}{n+1}, \frac{1}{n}]$  must be greater than

$$\left| \alpha\left(\frac{1}{n}\right) - \alpha\left(\frac{1}{n+\frac{1}{2}}\right) \right| + \left| \alpha\left(\frac{1}{n+\frac{1}{2}}\right) - \alpha\left(\frac{1}{n+1}\right) \right| \quad (2.4)$$

WOLG of  $n$  being odd or even, Compute

$$\begin{aligned}
\left| \alpha\left(\frac{1}{n}\right) - \alpha\left(\frac{1}{n+\frac{1}{2}}\right) \right| &= \left| \left(\frac{1}{n}, 0\right) - \left(\frac{1}{n+\frac{1}{2}}, \frac{1}{n+\frac{1}{2}}\right) \right| \\
&= \sqrt{\left(\frac{1}{n} - \frac{1}{n+\frac{1}{2}}\right)^2 + \left(\frac{1}{n+\frac{1}{2}}\right)^2} \\
&= \sqrt{\frac{1}{n^2} - \frac{4}{n(2n+1)} + \frac{8}{(2n+1)^2}} \\
&= \sqrt{\frac{(2n+1)^2 - 4n(2n+1) + 8n^2}{n^2(2n+1)^2}} \\
&= \sqrt{\frac{4n^2 + 1}{n^2(2n+1)^2}} \\
&= \frac{\sqrt{4n^2 + 1}}{n(2n+1)} \geq \frac{\sqrt{4n^2}}{n(2n+1)} = \frac{2}{2n+1}
\end{aligned}$$

and compute

$$\begin{aligned}
\left| \alpha\left(\frac{1}{n+\frac{1}{2}}\right) - \alpha\left(\frac{1}{n}\right) \right| &= \left| \left(\frac{1}{n+\frac{1}{2}}, \frac{1}{n+\frac{1}{2}}\right) - \left(\frac{1}{n}, 0\right) \right| \\
&= \sqrt{\left(\frac{1}{n+\frac{1}{2}} - \frac{1}{n}\right)^2 + \left(\frac{1}{n+\frac{1}{2}}\right)^2} \\
&= \sqrt{\frac{1}{(n+\frac{1}{2})^2} - \frac{4}{(n+\frac{1}{2})(2n+1)} + \frac{8}{(2n+1)^2}} \\
&= \sqrt{\frac{(2n+1)^2 - 4(n+\frac{1}{2})(2n+1) + 8(n+\frac{1}{2})^2}{(n+\frac{1}{2})^2(2n+1)^2}} \\
&= \sqrt{\frac{4n^2 + 8n + 5}{(n+\frac{1}{2})^2(2n+1)^2}} \\
&\geq \frac{\sqrt{4n^2 + 8n + 4}}{(n+\frac{1}{2})(2n+1)} = \frac{2}{2n+1}
\end{aligned}$$

From the computation and Equation 2.4, it is now clear that the arc length of the portion of the curve corresponding to  $t \in [\frac{1}{n+1}, \frac{1}{n}]$  is at least  $\frac{2}{n+\frac{1}{2}}$ . With simple addition, this then

implies the arc length of the curve in the interval  $[\frac{1}{N}, 1]$  is at least

$$\sum_{n=1}^{N-1} \frac{2}{2n+1} = 2 \sum_{n=1}^{N-1} \frac{1}{2n+1}$$

The number is clearly greater than

$$2 \sum_{n=1}^{N-1} \frac{1}{2n+2}$$

which equals to

$$\sum_{n=1}^{N-1} \frac{1}{n+1}$$

The series diverge to  $+\infty$  as  $N$  to  $\infty$ . ■

**Theorem 2.1.1. (Integrating the Dot Product)** Given a curve  $u : [a, b] \rightarrow \mathbb{R}^n$  and a vector  $v \in \mathbb{R}^n$ , suppose

- (a)  $u$  is differentiable on  $(a, b)$
- (b)  $u$  is continuous on  $[a, b]$

We have

$$\int_a^b u'(t) \cdot v dt = \left( \int_a^b u'(t) dt \right) \cdot v = (u(b) - u(a)) \cdot v$$

*Proof.*

$$\begin{aligned} \int_a^b u'(t) \cdot v dt &= \int_a^b \sum_{k=1}^n u'_k(t) \cdot v_k dt \\ &= \sum_{k=1}^n \int_a^b u'_k(t) \cdot v_k dt \\ &= \sum_{k=1}^n v_k \int_a^b u'_k(t) dt \\ &= v \cdot \left( \int_a^b u'(t) dt \right) \end{aligned}$$
■



## Question 8

**10. (Straight Lines as Shortest.)** Let  $\alpha: I \rightarrow \mathbb{R}^3$  be a parametrized curve. Let  $[a, b] \subset I$  and set  $\alpha(a) = p$ ,  $\alpha(b) = q$ .

a. Show that, for any constant vector  $v$ ,  $|v| = 1$ ,

$$(q - p) \cdot v = \int_a^b \alpha'(t) \cdot v \, dt \leq \int_a^b |\alpha'(t)| \, dt.$$

b. Set

$$v = \frac{q - p}{|q - p|}$$

and show that

$$|\alpha(b) - \alpha(a)| \leq \int_a^b |\alpha'(t)| \, dt;$$

that is, the curve of shortest length from  $\alpha(a)$  to  $\alpha(b)$  is the straight line joining these points.

*Proof. (a)*

The first equality

$$(q - p) \cdot v = \int_a^b \alpha'(t) \cdot v \, dt$$

follows directly from Theorem 2.1.1.

Now, by Cauchy-Schwarz inequality, we have

$$|\alpha'(t) \cdot v| \leq |\alpha'(t)| \cdot |v|$$

This then give us

$$\alpha'(t) \cdot v \leq |\alpha'(t) \cdot v| \leq |\alpha'(t)| \cdot |v| = |\alpha'(t)|$$

We now have

$$\int_a^b \alpha'(t) \cdot v \, dt \leq \int_a^b |\alpha'(t)| \, dt$$

as desired.

(b)

The first inequality tell us that if  $v$  is a constant and  $|v| = 1$ , we have

$$(q - p) \cdot v \leq \int_a^b |\alpha'(t)| dt$$

If  $v = \frac{q-p}{|q-p|}$ , it is clear that  $v$  is a constant and  $|v| = 1$ , and at the same time, we have

$$(q - p) \cdot v = \frac{(q - p) \cdot (q - p)}{|q - p|} = \frac{|q - p|^2}{|q - p|} = |q - p|$$

We now have

$$|q - p| = (q - p) \cdot v \leq \int_a^b |\alpha'(t)| dt$$

from the first inequality ■

### Question 9

**1. Check whether the following bases are positive:**

- a. The basis  $\{(1, 3), (4, 2)\}$  in  $R^2$ .**
- b. The basis  $\{(1, 3, 5), (2, 3, 7), (4, 8, 3)\}$  in  $R^3$ .**

*Proof.* Compute

$$\begin{vmatrix} 1 & 4 \\ 3 & 2 \end{vmatrix} = -10$$

and compute

$$\begin{vmatrix} 1 & 2 & 4 \\ 3 & 3 & 8 \\ 5 & 7 & 3 \end{vmatrix} = -9$$

Both bases are negatively oriented. ■

### Question 10

**\*2. A plane  $P$  contained in  $R^3$  is given by the equation  $ax + by + cz + d = 0$ . Show that the vector  $v = (a, b, c)$  is perpendicular to the plane and that  $|d|/\sqrt{a^2 + b^2 + c^2}$  measures the distance from the plane to the origin  $(0, 0, 0)$ .**

*Proof.* Arbitrarily pick two points  $u, w$  in  $P$ . We wish to show

$$v \cdot (u - w) = 0$$

Because  $v = (a, b, c)$  and

$$\begin{cases} au_1 + bu_2 + cu_3 = -daw_1 + bw_2 + cw_3 = -d \end{cases}$$

We see

$$\begin{aligned} v \cdot (u - w) &= a(u_1 - w_1) + b(u_2 - w_2) + c(u_3 - w_3) \\ &= (-d) - (-d) = 0 \text{ (done)} \end{aligned}$$

To measure the distance between  $P$  and the origin, we wish to find a vector  $u$  such that  $u \perp P$  and  $u \in P$ . We know that  $u$  must be linearly dependent with  $v = (a, b, c)$ , since the dimension of  $P^\perp$  is 1. Then, we can write

$$u = c_0(a, b, c) \text{ for some } c_0 \in \mathbb{R}$$

Because  $u \in P$ , we know

$$c_0a^2 + c_0b^2 + c_0c^2 + d = 0$$

This tell us

$$c_0 = \frac{-d}{a^2 + b^2 + c^2}$$

We now see that the distance  $|u|$  between  $P$  and origin is

$$|u| = |c_0| \cdot \sqrt{a^2 + b^2 + c^2} = \frac{|d|}{\sqrt{a^2 + b^2 + c^2}}$$

■

### Question 11

**\*3. Determine the angle of intersection of the two planes  $5x + 3y + 2z - 4 = 0$  and  $3x + 4y - 7z = 0$ .**

*Proof.* From last question, we know the two vectors  $u, v$  that are respectively perpendicular to  $P : 5x + 3y + 2z - 4 = 0$  and  $Q : 3x + 4y - 7z = 0$  respectively have the direction

$$(5, 3, 2) \text{ and } (3, 4, -7)$$

Then, we see the angle of the intersection are

$$\arccos \frac{5 \cdot 3 + 3 \cdot 4 + 2 \cdot (-7)}{\sqrt{5^2 + 3^2 + 2^2} \sqrt{3^2 + 4^2 + 7^2}} = \arccos \frac{13}{\sqrt{38} \sqrt{71}}$$

Notice that this angle is smaller than  $\frac{\pi}{2}$  as we intend it to be.

■

## Question 12

**\*6.** Given two nonparallel planes  $a_ix + b_iy + c_iz + d_i = 0$ ,  $i = 1, 2$ , show that their line of intersection may be parametrized as

$$x - x_0 = u_1t, \quad y - y_0 = u_2t, \quad z - z_0 = u_3t,$$

where  $(x_0, y_0, z_0)$  belongs to the intersection and  $u = (u_1, u_2, u_3)$  is the vector product  $u = v_1 \wedge v_2$ ,  $v_i = (a_i, b_i, c_i)$ ,  $i = 1, 2$ .

*Proof.* Let  $v = (x, y, z)$  be a point on the line of intersection. We see the vector  $v - (x_0, y_0, z_0)$  lies on both planes, and thus must be perpendicular to  $(a_1, b_1, c_1) = v_1$  and  $(a_2, b_2, c_2) = v_2$  thus satisfying

$$v - (x_0, y_0, z_0) = tv_1 \times v_2 = tu \text{ for some } t \in \mathbb{R}$$

since in  $\mathbb{R}^3$ , the only direction perpendicular to both  $v_1, v_2$  is  $v_1 \times v_2$ . We can rewrite the above equation of course into

$$x - x_0 = u_1t, y - y_0 = u_2t, z - z_0 = u_3t$$

■

## 2.2 HW2

### Question 13

#### 1. Given the parametrized curve (helix)

$$\alpha(s) = \left( a \cos \frac{s}{c}, a \sin \frac{s}{c}, b \frac{s}{c} \right), \quad s \in \mathbb{R},$$

where  $c^2 = a^2 + b^2$ ,

- a. Show that the parameter  $s$  is the arc length.
- b. Determine the curvature and the torsion of  $\alpha$ .
- c. Determine the osculating plane of  $\alpha$ .
- d. Show that the lines containing  $n(s)$  and passing through  $\alpha(s)$  meet the  $z$  axis under a constant angle equal to  $\pi/2$ .
- e. Show that the tangent lines to  $\alpha$  make a constant angle with the  $z$  axis.

*Proof.* (a) By computation

$$\alpha'(s) = \left( -\frac{a}{c} \sin \frac{s}{c}, \frac{a}{c} \cos \frac{s}{c}, \frac{b}{c} \right)$$

So

$$|\alpha'(s)| = \sqrt{\frac{a^2 + b^2}{c^2}} = 1 \quad (\because \sin^2 + \cos^2 = 1)$$

This shows  $\alpha$  is parametrized by arc-length.

(b) By computation

$$\alpha''(s) = \left( -\frac{a}{c^2} \cos \frac{s}{c}, -\frac{a}{c^2} \sin \frac{s}{c}, 0 \right)$$

Then because  $\alpha$  is parametrized by arc-length, we have

$$\begin{aligned} \kappa(s) &= |\alpha''(s)| = \sqrt{\frac{a^2}{c^4}} \\ &= \frac{|a|}{c^2} \end{aligned}$$

By computation

$$\alpha'''(s) = \left( \frac{a}{c^3} \sin \frac{s}{c}, \frac{-a}{c^3} \cos \frac{s}{c}, 0 \right)$$

Then using the identity of torsion, we have

$$\begin{aligned} \tau(s) &= -\frac{-(\alpha'(s) \times \alpha''(s)) \cdot \alpha'''(s)}{|\kappa(s)|^2} \\ &= -\frac{\frac{a^2 b}{c^6}}{\frac{a^2}{c^4}} \\ &= \frac{b}{-c^2} \end{aligned}$$

(c) Fix  $s$ . Define a set  $A$  by

$$A = \text{span}(\alpha'(s), \alpha''(s))$$

The osculating plane of  $\alpha$  at  $s$  is then exactly

$$\{a + \alpha(s) : a \in A\}$$

(d) Because  $\alpha''(s)$  by our computation is valued 0 in  $z$ -opponent, we know if the line containing  $N$  and passing through  $\alpha$  meet the  $z$  axis, it must be under a constant angle equal to  $\frac{\pi}{2}$ . (use dot product to check this fact.).

Now, we only have to prove that the line does meet the  $z$ -axis. See that

$$\alpha + c^2 \alpha'' = \left( 0, 0, b \frac{s}{c} \right)$$

and we are done.

(e) Observe that

$$\alpha' \cdot (0, 0, 1) = \frac{b}{c} \text{ is a constant}$$

This together with the fact  $|\alpha'|$  is a constant show that the angle between the tangent to  $\alpha$  and  $z$ -axis is a constant. ■

## Question 14

**\*2.** Show that the torsion  $\tau$  of  $\alpha$  is given by

$$\tau(s) = -\frac{\alpha'(s) \wedge \alpha''(s) \cdot \alpha'''(s)}{|k(s)|^2}.$$

**Theorem 2.2.1. (Identity of Torsion)** Given a parametrized by arc-length curve  $\alpha : I \rightarrow \mathbb{R}^3$ , we have

$$\tau(s) = -\frac{(\alpha'(s) \times \alpha''(s)) \cdot \alpha'''(s)}{\kappa^2(s)}$$

*Proof.* Because  $\alpha$  is parametrized by arc-length, we have

$$\alpha'(s) = T(s)$$

We first show

$$\alpha''(s) = \kappa(s)N(s) \quad (2.5)$$

Compute

$$\begin{aligned} N(s) &= \frac{T'(s)}{|T'(s)|} \\ &= \frac{\alpha''(s)}{|\alpha''(s)|} = \frac{\alpha''(s)}{\kappa(s)} \quad (\text{done}) \end{aligned}$$

We now show

$$\alpha'''(s) = \kappa(s)(-\tau B)(s) - (\kappa T)(s) + \kappa'(s)N(s)$$

By Equation 2.5 and Frenet Formula, we have

$$\begin{aligned} \alpha'''(s) &= \kappa'(s)N(s) + \kappa(s)N'(s) \\ &= \kappa'(s)N(s) + \kappa(s)(-\tau B)(s) - (\kappa T)(s) \quad (\text{done}) \end{aligned}$$

Lastly, we verify

$$\begin{aligned} -\frac{(\alpha'(s) \times \alpha''(s)) \cdot \alpha'''(s)}{\kappa^2(s)} &= -\frac{(T \times \kappa N) \cdot (\kappa(-\tau B - \kappa T) + \kappa' N)}{\kappa^2} \\ &= -\frac{-\kappa^2 \tau (T \times N) \cdot B}{\kappa^2} \quad (\because T \times N \cdot (T \text{ or } N) = 0) \\ &= \tau \end{aligned}$$

■

### Question 15

3. Assume that  $\alpha(I) \subset \mathbb{R}^2$  (i.e.,  $\alpha$  is a plane curve) and give  $k$  a sign as in the text. — Transport the vectors  $t(s)$  parallel to themselves in such a way that the origins of  $t(s)$  agree with the origin of  $\mathbb{R}^2$ ; the end points of  $t(s)$  then describe a parametrized curve  $s \rightarrow t(s)$  called the *indicatrix of tangents* of  $\alpha$ . Let  $\theta(s)$  be the angle from  $e_1$  to  $t(s)$  in the orientation of  $\mathbb{R}^2$ . Prove (a) and (b) (notice that we are assuming that  $k \neq 0$ ).

a. The indicatrix of tangents is a regular parametrized curve.

b.  $dt/ds = (d\theta/ds)n$ , that is,  $k = d\theta/ds$ .

*Proof.* (a)

The indicatrix of tangents  $\gamma : I \rightarrow \mathbb{R}^2$  is defined by

$$\gamma = \frac{\alpha'(s)}{|\alpha'(s)|}$$

Express  $\alpha'(s)$  by

$$\alpha' \triangleq (x, y)$$

To show  $\gamma$  is regular. We wish to show

$$\gamma'(s) \neq 0 \text{ for all } s \in I$$

Express  $\gamma$  by

$$\gamma = \frac{(x, y)}{\sqrt{x^2 + y^2}}$$

Then, we see the  $x$ -component of  $\gamma'(s)$  is

$$\gamma'(s) \Big|_x = \frac{x'y^2}{(x^2 + y^2)^{\frac{3}{2}}}$$

With similar computation on the  $y$ -component, we now arrive at

$$\gamma'(s) = \frac{(x'y^2, y'x^2)}{(x^2 + y^2)^{\frac{3}{2}}}$$

Now, for a contradiction, Assume  $\gamma'(s) = 0$  for some  $s$ . Then one of the three things below must happen



$$(a) \ x' = y' = 0$$

$$(b) \ y^2 = x^2 = 0$$

$$(c) \ x' = x^2 = 0 \text{ WLOG}$$

Because  $(x, y) = \alpha'$  and  $\alpha$  is parametrized by arc-length and curvature is non-zero by premise, we know it can not happen  $\alpha'' = (x', y') = 0$ .

Because  $(x, y) = \alpha'$  and  $\alpha$  is parametrized by arc-length, we also know it can not happen  $\alpha' = (x, y) = 0$ .

Now, we are given the hypothesis  $x' = x^2 = 0$ . Because  $\alpha$  is parametrized by arc-length, from  $x = 0$ , we know  $y = \pm 1$ . Then because  $|\alpha'|$  is constant, we can deduce

$$\begin{aligned} 0 &= (x', y') \cdot (x, y) \\ &= (0, y') \cdot (0, \pm 1) \end{aligned}$$

This show us  $y' = 0$ , which is impossible, since if  $(x', y') = 0$  then the curvature is 0 **CaC** (done)

**(b)** The functions  $\theta : [0, l] \rightarrow \mathbb{R}$ , is defined by

$$T = (x, y) \triangleq (\cos \theta, \sin \theta)$$

By Frenet Formula, we have

$$\kappa N = T' = \theta'(-\sin \theta, \cos \theta) \tag{2.6}$$

Because  $|(-\sin \theta, \cos \theta)| = 1$  and  $(-\sin \theta, \cos \theta) \cdot T = 0$  and

$$\begin{vmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{vmatrix} = 1$$

we can identify  $(-\sin \theta, \cos \theta) = N$ . Then from Equation 2.6, we now can deduce

$$\kappa = \theta'$$

■

## Question 16

- 6.** A *translation* by a vector  $v$  in  $R^3$  is the map  $A: R^3 \rightarrow R^3$  that is given by  $A(p) = p + v$ ,  $p \in R^3$ . A linear map  $\rho: R^3 \rightarrow R^3$  is an *orthogonal transformation* when  $\rho u \cdot \rho v = u \cdot v$  for all vectors  $u, v \in R^3$ . A *rigid motion* in  $R^3$  is the result of composing a translation with an orthogonal transformation with positive determinant (this last condition is included because we expect rigid motions to preserve orientation).
- Demonstrate that the norm of a vector and the angle  $\theta$  between two vectors,  $0 \leq \theta \leq \pi$ , are invariant under orthogonal transformations with positive determinant.
  - Show that the vector product of two vectors is invariant under orthogonal transformations with positive determinant. Is the assertion still true if we drop the condition on the determinant?
  - Show that the arc length, the curvature, and the torsion of a parametrized curve are (whenever defined) invariant under rigid motions.

*Proof.* Let  $A$  be a translation and  $\rho$  be an orthogonal transformation.

(a) Observe

$$\begin{aligned}\|v\| &= \sqrt{v \cdot v} \\ &= \sqrt{\rho v \cdot \rho v} \\ &= \|\rho v\|\end{aligned}$$

Because  $\theta$  is given by

$$\theta = \arccos \frac{v \cdot w}{|v| \cdot |w|}$$

and because norm is invariant under orthogonal transformation, from the definition of orthogonal transformation, we now see

$$\begin{aligned}\theta &= \arccos \frac{v \cdot w}{|v| \cdot |w|} \\ &= \arccos \frac{\rho v \cdot \rho w}{|v| \cdot |w|} \\ &= \arccos \frac{\rho v \cdot \rho w}{|\rho v| \cdot |\rho w|} = \theta_\rho\end{aligned}$$

where  $\theta_\rho$  is the angle between  $\rho v$  and  $\rho w$ .

(b) Fix  $v, w \in \mathbb{R}^3$  and a positive determinant orthogonal transformation  $\rho$ . We wish to show

$$\rho v \times \rho w = \rho(v \times w)$$

We can reduce the problem into proving

$$\rho v \times \rho w \cdot z = \rho(v \times w) \cdot z \text{ for all } z \in \mathbb{R}^3$$

Fix  $z \in \mathbb{R}^3$ . Because  $\rho$  has non-zero determinant, we know there exists  $z' \in \mathbb{R}^3$  such that

$$\rho z' = z$$

Now, because orthogonal transformation has determinant  $\pm 1$  and we have know  $\rho$  has positive determinant, we know

$$\begin{aligned} \rho v \times \rho w \cdot z &= \rho v \times \rho w \cdot \rho z' \\ &= \begin{vmatrix} \rho v \\ \rho w \\ \rho z' \end{vmatrix} \\ &= \begin{vmatrix} \rho v & \rho w & \rho z' \end{vmatrix} \quad (\because \det A = \det A^t) \\ &= |\rho| \cdot \begin{vmatrix} v & w & z' \end{vmatrix} \quad (\because \det A \det B = \det AB) \\ &= \begin{vmatrix} v \\ w \\ z' \end{vmatrix} \quad (\because \det \rho = 1) \\ &= v \times w \cdot z' \\ &= \rho(v \times w) \cdot \rho z' \\ &= \rho(v \times w) \cdot z \text{ (done)} \end{aligned}$$

The assertion is clearly false if the determinant is negative. One can check  $v = (1, 0, 0)$  and  $w = (0, 1, 0)$  and  $\rho(x, y, z) = (-x, y, z)$ .

(c) We first show arc length is invariant under rigid motion. We first show

$$\text{arc length is invariant under orthogonal transformation}$$

To show such, we only have to show

$$|(\rho \circ \gamma)'| = |\gamma'|$$

■

Fix  $y \in I$ . We have

$$|\gamma'(y)| = \left| \lim_{t \rightarrow y} \frac{\gamma(t) - \gamma(y)}{t - y} \right| = \lim_{t \rightarrow y} \left| \frac{\gamma(t) - \gamma(y)}{t - y} \right|$$

Notice that in above deduction, we exchange limit and norm. Such exchange hold true because the function inside is continuous.

Similarly, we have

$$|(\rho \circ \gamma)'(y)| = \lim_{t \rightarrow y} \left| \frac{\rho \circ \gamma(t) - \rho \circ \gamma(y)}{t - y} \right|$$

Then, we can reduce the problem into

$$\text{proving } |\gamma(t) - \gamma(y)| = |\rho \circ \gamma(t) - \rho \circ \gamma(y)|$$

Because  $\rho : \mathbb{R}^3 \rightarrow \mathbb{R}^3$  is an orthogonal transformation (a linear transformation too), we can deduce

$$\begin{aligned} |\rho \circ \gamma(t) - \rho \circ \gamma(y)| &= |\rho(\gamma(t) - \gamma(y))| \\ &= |\gamma(t) - \gamma(y)| \quad (\text{done}) \end{aligned}$$

We have proved arc-length is invariant under orthogonal transformation. With some simple computation, it is clear that arc-length is invariant under translation. This let us conclude arc length is invariant under rigid motion.

Now, to show curvature and torsion are also invariant under rigid motion. We first recall the following identities for curve parametrized by arc-length

$$\kappa = |\gamma''| \quad \text{and} \quad \tau = -\frac{\gamma' \times \gamma'' \cdot \gamma'''}{\kappa^2}$$

We now prove

$$\text{curvature is invariant under rigid motion}$$

Notice that  $\gamma'$  is invariant under translation, so in fact, we only have to prove

$$\text{curvature is invariant under orthogonal transformation}$$

Observe

$$|\gamma''(y)| = \left| \lim_{t \rightarrow y} \frac{\gamma'(t) - \gamma'(y)}{t - y} \right| = \lim_{t \rightarrow y} \left| \frac{\gamma'(t) - \gamma'(y)}{t - y} \right|$$

and

$$|(\rho \circ \gamma)''(y)| = \lim_{t \rightarrow y} \left| \frac{(\rho \circ \gamma)'(t) - (\rho \circ \gamma)'(y)}{t - y} \right|$$

We can now reduce the problem into proving

$$|\gamma'(t) - \gamma'(y)| = |(\rho \circ \gamma)'(t) - (\rho \circ \gamma)'(y)|$$

Because  $\rho$  is a linear transformation, we can compute

$$\begin{aligned} (\rho \circ \gamma)'(t) &= \lim_{u \rightarrow t} \frac{\rho \circ \gamma(u) - \rho \circ \gamma(t)}{u - t} \\ &= \lim_{u \rightarrow t} \rho \left( \frac{\gamma(u) - \gamma(t)}{u - t} \right) \\ &= \rho \lim_{u \rightarrow t} \left( \frac{\gamma(u) - \gamma(t)}{u - t} \right) = \rho \circ \gamma'(t) \end{aligned} \tag{2.7}$$

We now using the fact norm is invariant under orthogonal transformation to compute

$$\begin{aligned} |(\rho \circ \gamma)'(t) - (\rho \circ \gamma)'(y)| &= |\rho \circ \gamma'(t) - \rho \circ \gamma'(y)| \\ &= |\rho(\gamma'(t) - \gamma'(y))| \\ &= |\gamma'(t) - \gamma'(y)| \text{ (done)} \end{aligned}$$

Now, notice that in Equation 2.7, we just proved

$$(\rho\gamma)' = \rho\gamma'$$

Iterating the same argument, we can show

$$\begin{aligned} (\rho\gamma)'' &= ((\rho\gamma)')' \\ &= (\rho\gamma')' \\ &= \rho\gamma'' \end{aligned}$$

and also show

$$\begin{aligned} (\rho\gamma)''' &= ((\rho\gamma)'')' \\ &= (\rho\gamma'')' \\ &= \rho\gamma''' \end{aligned}$$

We now using the fact that  $|\rho| = 1$  to compute

$$\begin{aligned} (\rho\gamma)' \times (\rho\gamma)'' \cdot (\rho\gamma)''' &= |(\rho\gamma)' \ (\rho\gamma)'' \ (\rho\gamma)'''| \\ &= |\rho\gamma' \ \rho\gamma'' \ \rho\gamma'''| \\ &= |\rho [\gamma' \ \gamma'' \ \gamma''']| \\ &= |\rho| \cdot |\gamma' \ \gamma'' \ \gamma'''| \\ &= \gamma' \times \gamma'' \cdot \gamma''' \end{aligned}$$

Above computation with identity of torsion and the fact curvature is invariant under orthogonal transformation with positive determinant then show that torsion is also invariant under orthogonal transformation with positive determinant.

Because  $(\gamma + c)' = \gamma'$ , together with what we have proved, it is easy to check torsion is also invariant under rigid motion.

### Question 17

**9. Given a differentiable function  $k(s)$ ,  $s \in I$ , show that the parametrized plane curve having  $k(s) = k$  as curvature is given by**

$$\alpha(s) = \left( \int \cos \theta(s) ds + a, \int \sin \theta(s) ds + b \right),$$

where

$$\theta(s) = \int k(s) ds + \varphi,$$

and that the curve is determined up to a translation of the vector  $(a, b)$  and a rotation of the angle  $\varphi$ .

*Proof.* By Fundamental Theorem of Local Curves (you can think of our application as identifying  $\tau = 0$ ), we know if such curve exists then it is unique up to translation and rotation. This reduced our proof into showing

$\alpha$  has curvature  $\kappa$

Compute

$$\alpha' = (\cos \theta, \sin \theta)$$

This shows that  $\alpha$  is parametrized by arc-length, and shows that we can compute

$$\begin{aligned} |\alpha''| &= |\theta'(-\sin \theta, \cos \theta)| \\ &= |\theta'| = |\kappa| = \kappa \text{ (done)} \end{aligned}$$



## Question 18

**11.** One often gives a plane curve in polar coordinates by  $\rho = \rho(\theta)$ ,  $a \leq \theta \leq b$ .

**a.** Show that the arc length is

$$\int_a^b \sqrt{\rho^2 + (\rho')^2} d\theta,$$

where the prime denotes the derivative relative to  $\theta$ .

**b.** Show that the curvature is

$$k(\theta) = \frac{2(\rho')^2 - \rho\rho'' + \rho^2}{\{(\rho')^2 + \rho^2\}^{3/2}}.$$

*Proof.* (a)

Parametrize by

$$\alpha(\theta) \triangleq (x, y) \triangleq (r \cos \theta, r \sin \theta)$$

where  $r(\theta)$  is a function. With respect to  $\theta$ , we compute

$$\begin{aligned} (x')^2 + (y')^2 &= (r' \cos \theta - r \sin \theta)^2 + (r' \sin \theta + r \cos \theta)^2 \\ &= (r')^2 \cos^2 \theta + r^2 \sin^2 \theta + (r')^2 \sin^2 \theta + r^2 \cos^2 \theta \quad (\because \text{elimination}) \\ &= r^2 + (r')^2 \end{aligned}$$

We now see that the arc-length can be computed by

$$\begin{aligned} \int_a^b |\alpha'(\theta)| d\theta &= \int_a^b \sqrt{(x')^2 + (y')^2} d\theta \\ &= \int_a^b \sqrt{r^2 + (r')^2} d\theta \end{aligned}$$

(b)

Recall that

$$\kappa(t) = \frac{x'y'' - x''y'}{((x')^2 + (y')^2)^{\frac{3}{2}}}$$

plugin

$$\begin{aligned} (x', y') &= (r' \cos \theta - r \sin \theta, r' \sin \theta + r \cos \theta) \\ (x'', y'') &= (r'' \cos \theta - 2r' \sin \theta - r \cos \theta, r'' \sin \theta + 2r' \cos \theta - r \sin \theta) \end{aligned}$$

To compute

$$\begin{aligned} x'y'' &= r'r'' \cos \theta \sin \theta + 2(r')^2 \cos^2 \theta - rr' \cos \theta \sin \theta - rr'' \sin^2 \theta - 2rr' \cos \theta \sin \theta + r^2 \sin^2 \theta \\ x''y' &= r'r'' \sin \theta \cos \theta - 2(r')^2 \sin^2 \theta - rr' \cos \theta \sin \theta + rr'' \cos^2 \theta - 2rr' \cos \theta \sin \theta - r^2 \cos^2 \theta \end{aligned}$$

Eliminating the odd terms and using  $\cos^2 + \sin^2 = 1$ , we now compute

$$\begin{aligned} \kappa &= \frac{x'y'' - x''y'}{\left((x')^2 + (y')^2\right)^{\frac{3}{2}}} \\ &= \frac{2(r')^2 - 2rr'' + r^2}{\left(r^2 + (r')^2\right)^{\frac{3}{2}}} \end{aligned}$$

■

### Question 19

**17.** In general, a curve  $\alpha$  is called a *helix* if the tangent lines of  $\alpha$  make a constant angle with a fixed direction. Assume that  $\tau(s) \neq 0$ ,  $s \in I$ , and prove that:

- \*a.  $\alpha$  is a helix if and only if  $k/\tau = \text{const.}$
- \*b.  $\alpha$  is a helix if and only if the lines containing  $n(s)$  and passing through  $\alpha(s)$  are parallel to a fixed plane.
- \*c.  $\alpha$  is a helix if and only if the lines containing  $b(s)$  and passing through  $\alpha(s)$  make a constant angle with a fixed direction.
- d. The curve

$$\alpha(s) = \left( \frac{a}{c} \int \sin \theta(s) ds, \frac{a}{c} \int \cos \theta(s) ds, \frac{b}{c} s \right),$$

where  $a^2 = b^2 + c^2$ , is a helix, and that  $k/\tau = b/a$ .

*Proof.* (a) ( $\longrightarrow$ )

Because  $\alpha$  is a helix, we know there exists fixed unit  $a \in \mathbb{R}^3$  and  $b \in \mathbb{R}$  such that

$$\alpha' \cdot a = b \text{ for all } s$$

This then implies

$$\alpha'' \cdot a = 0 \text{ for all } s$$

which implies

$$N \cdot a = 0$$



since  $N$  is parallel with  $\alpha''$ . Because  $\{T, N, B\}$  is an orthonormal basis, this ( $N \cdot a = 0$ ) together with  $a$  being unit then tell us we can express  $a$  by

$$a = T \cos \theta + B \sin \theta \text{ for some fixed } \theta \in \mathbb{R}$$

We now have the information  $T \cos \theta + B \sin \theta$  is a constant function in  $s$ . Then, using Frenet Formula, we can deduce

$$0 = (T \cos \theta + B \sin \theta)' = \kappa N \cos \theta + \tau N \sin \theta$$

This then implies

$$\frac{\kappa}{\tau} = \frac{-\sin \theta}{\cos \theta} \text{ is a constant since } \theta \text{ is fixed.}$$

Notice that  $\cos \theta \neq 0$  because  $\tau \neq 0$  for all  $s$ .

( $\longleftarrow$ )

Define  $\theta \in \mathbb{R}$  by

$$\theta = \arctan \frac{-\kappa}{\tau}$$

We wish to show

$$a = T \cos \theta + B \sin \theta \text{ suffice}$$

Because we have

$$T \cdot a = \cos \theta$$

We only wish to show

$$a \text{ is a constant function in } s$$

Because  $\theta = \arctan \frac{-\kappa}{\tau}$ , we know

$$\frac{\sin \theta}{\cos \theta} = \tan \theta = \frac{-\kappa}{\tau}$$

This then tell us

$$\tau \sin \theta + \kappa \cos \theta = 0$$

and implies

$$\tau N \sin \theta + \kappa N \cos \theta = 0$$

Then

$$\begin{aligned}a' &= (T \cos \theta + N \sin \theta)' \\ &= \kappa N \cos \theta + \tau N \sin \theta = 0\end{aligned}$$

This implies  $a$  is indeed a constant. (done)

(b)

( $\longrightarrow$ )

Let  $a \in \mathbb{R}^3$  be the unit vector such that

$$T \cdot a \text{ is fixed}$$

We now see

$$N \cdot a = (T \cdot a)' = 0$$

This implies

the plane  $\{a\}^\perp$  suffice

( $\longleftarrow$ )

Observe that

$$\begin{aligned}0 &= N \cdot a = \frac{T'}{|T'|} \cdot a \\ &\implies T' \cdot a = 0 \\ &\implies T \cdot a \text{ is fixed}\end{aligned}$$

(c)

( $\longrightarrow$ )

Because  $T \cdot a$  is fixed, we can deduce

$$\kappa N \cdot a = T' \cdot a = 0$$

Now observe from Frenet Formula that

$$(B \cdot a)' = -\tau N \cdot a = 0$$

This implies  $B \cdot a$  is fixed.

( $\longleftarrow$ )

Because  $B \cdot a$  is fixed, we can deduce

$$\begin{aligned} 0 &= (B \cdot a)' = -\tau N \cdot a \\ \implies N \cdot a &= 0 \end{aligned}$$

The proof then now follows from the result of **(b)**.

**(d)**

First we have to notice the fucking typo correction  $\frac{\kappa}{\tau} = \frac{a}{b}$ .

Compute

$$\begin{aligned} \alpha'(s) &= \left( \frac{a}{c} \sin \theta, \frac{a}{c} \cos \theta, \frac{b}{c} \right) \\ \alpha''(s) &= \left( \theta' \frac{a}{c} \cos \theta, \theta' \frac{-a}{c} \sin \theta, 0 \right) \\ \alpha'''(s) &= \left( \theta'' \frac{a}{c} \cos \theta + (\theta')^2 \frac{-a}{c} \sin \theta, \theta'' \frac{-a}{c} \sin \theta + (\theta')^2 \frac{-a}{c} \cos \theta, 0 \right) \end{aligned}$$

This give us

$$\begin{aligned} &\alpha' \times \alpha'' \cdot \alpha''' \\ &= \frac{b}{c} \left[ \theta' \theta'' \frac{-a^2}{c^2} \cos \theta \sin \theta + (\theta')^3 \frac{-a^2}{c^2} \cos^2 \theta - \theta' \theta'' \frac{-a^2}{c} \sin \theta \cos \theta - (\theta')^3 \frac{a^2}{c^2} \sin^2 \theta \right] \\ &= \frac{b}{c} \left( (\theta')^3 \frac{-a^2}{c^2} \right) = \frac{-a^2 b}{c^3} (\theta')^3 \end{aligned}$$

And give us

$$\kappa = \theta' \frac{a}{c}$$

We now compute

$$\begin{aligned} \frac{\kappa}{\tau} &= \frac{\kappa}{-\frac{\alpha' \times \alpha'' \cdot \alpha'''}{\kappa^2}} \\ &= \frac{-\kappa^3}{\alpha' \times \alpha'' \cdot \alpha'''} \\ &= \frac{-(\theta')^3 \frac{a^3}{c^3}}{\frac{-a^2 b}{c^3} (\theta')^3} = \frac{a}{b} \end{aligned}$$



## Question 20

### 3. Compute the curvature of the ellipse

$$x = a \cos t, \quad y = b \sin t, \quad t \in [0, 2\pi], \quad a \neq b,$$

and show that it has exactly four vertices, namely, the points  $(a, 0)$ ,  $(-a, 0)$ ,  $(0, b)$ ,  $(0, -b)$ .

*Proof.* Compute

$$\begin{cases} x' = -a \sin t \text{ and } x'' = -a \cos t \\ y' = b \cos t \text{ and } y'' = -b \sin t \end{cases}$$

Plugging the curvature formula

$$\kappa = \frac{x'y'' - x''y'}{((x')^2 + (y')^2)^{\frac{3}{2}}}$$

We now have

$$\kappa = \frac{ab}{(a^2 \sin^2 t + b^2 \cos^2 t)^{\frac{3}{2}}}$$

Compute

$$\kappa' = (2a^2 \sin t \cos t - 2b^2 \sin t \cos t)(a^2 \sin^2 t + b^2 \cos^2 t)^{\frac{-5}{2}} \cdot (ab)$$

We see that

$$\kappa' = 0 \iff \sin 2t = 0$$

This only happens when  $t \in \{0, \frac{\pi}{2}, \pi, \frac{3\pi}{2}, 2\pi\}$  where  $2\pi$  is just 0 in the sense of parametrization of closed curve. We have shown there are exactly four vertices

$$(a, 0), (-a, 0), (0, b), (0, -b)$$



## Question 21

**\*4.** Let  $C$  be a plane curve and let  $T$  be the tangent line at a point  $p \in C$ . Draw a line  $L$  parallel to the normal line at  $p$  and at a distance  $d$  of  $p$  (Fig. 1-36). Let  $h$  be the length of the segment determined on  $L$  by  $C$  and  $T$  (thus,  $h$  is the “height” of  $C$  relative to  $T$ ). Prove that

$$|k(p)| = \lim_{d \rightarrow 0} \frac{2h}{d^2},$$

where  $k(p)$  is the curvature of  $C$  at  $p$ .

*Proof.* WOLG, let  $p = (0, 0)$ ,  $T$  be the  $x$ -axis and some neighborhood around  $p$  be above  $T$ . Positively oriented parametrize  $C$  by arc-length using  $(x, y)$  and  $(x, y)(0) = (0, 0)$ . Using Taylor Theorem about  $y(0)$ , we see

$$y(s) = y(0) + y'(0)s + \frac{y''(0)}{2}s^2 + R_y \text{ where } \frac{R_y}{s^2} \rightarrow 0 \text{ as } s \rightarrow 0$$

Because  $T$  the tangent is the  $x$ -axis, we know  $x''(0) = 0$  ( $\because N = (0, 1)$ ). This tell us

$$\begin{aligned} |\kappa(0)| &= \sqrt{(x'')^2(0) + (y'')^2(0)} \\ &= y''(0) \quad (\because N = (0, 1)) \end{aligned}$$

■

By our setting  $(x, y)(0) = (0, 0)$ , we see

$$y(0) = y'(0) = 0 \quad (\because (x', y') = (1, 0))$$

We now see

$$y''(0) = \lim_{s \rightarrow 0} \frac{2(y(s) - R_y)}{s^2} \text{ for all } s \neq 0$$

This tell us

$$y''(0) = \lim_{s \rightarrow 0} \frac{2(y(s) - R_y)}{s^2} = \lim_{s \rightarrow 0} \frac{2y(s)}{s^2}$$

Using Taylor Theorem about  $x(0)$ , we see

$$x(s) = x(0) + x'(0)s + R_x \text{ where } \frac{R_x}{s} \rightarrow 0 \text{ as } s \rightarrow 0$$

Because  $x(0) = 0$  and  $x'(0) = 1$ , we see

$$\lim_{s \rightarrow 0} \frac{x(s)}{s} = \lim_{s \rightarrow 0} \frac{s + R_x}{s} = 1$$

This now give us

$$|\kappa(0)| = y''(0) = \lim_{s \rightarrow 0} \frac{2y(s)}{s^2} = \lim_{s \rightarrow 0} \frac{2y(s)}{x^2(s)} = \lim_{d \rightarrow 0} \frac{2h}{d^2}$$

## Question 22

**6.** Let  $\alpha(s)$ ,  $s \in [0, l]$  be a closed convex plane curve positively oriented. The curve

$$\beta(s) = \alpha(s) - rn(s),$$

where  $r$  is a positive constant and  $n$  is the normal vector, is called a *parallel curve* to  $\alpha$  (Fig. 1-37). Show that

**a.** Length of  $\beta$  = length of  $\alpha$  +  $2\pi r$ .

**b.**  $A(\beta) = A(\alpha) + rl + \pi r^2$ .

**c.**  $k_\beta(s) = k_\alpha(s)/(1 + r)$ .

*Proof.* (a)

Using Frenet Formula to compute

$$\beta'(s) = \alpha'(s) + r\kappa T(s)$$

Because  $\alpha$  is parametrized by arc-length, we now know

$$|\beta'| = |(1 + r\kappa)\alpha'| = |1 + r\kappa| = 1 + r\kappa$$

This now give us

$$\int_0^l |\beta'| ds = l + r \int_0^l \kappa ds$$

Because a closed convex curve must also be simple (Sec. 5-7, Prop. 1), we now can deduce

$$\begin{aligned} \text{Length of } \beta &= l + r \int_0^l \kappa ds \\ &= \text{Length of } \alpha + r(2\pi) \end{aligned}$$

(b)

Set

$$\alpha = (x, y) \text{ and } \beta = (x - rN_1, y - rN_2)$$

Because

$$\beta' = (1 + r\kappa)\alpha'$$

We know

$$\beta' = \left( (1 + r\kappa)x', (1 + r\kappa)y' \right)$$

Now, we use Green's Theorem to compute the Area

$$\begin{aligned} A(\beta) &= \frac{1}{2} \int_0^l (x - rN_1)(1 + r\kappa)y' - (y - rN_2)(1 + r\kappa)x' ds \\ &= \frac{1}{2} \int_0^l (xy' - yx') ds + \frac{r}{2} \int_0^l (\kappa xy' + \kappa x'y) ds \\ &\quad + \frac{r}{2} \int_0^l -(N_1y' + N_2x') ds + \frac{r^2}{2} \int_0^l (-N_1y'\kappa + N_2x'\kappa) ds \end{aligned}$$

Notice that by Frenet Formula, we have

$$N' = -\kappa(x', y')$$

so in fact we know

$$\kappa xy' + \kappa x'y = N' \cdot (-y, x)$$

Now using integral by part and the fact  $\alpha = (x, y)$  is closed, we know

$$\begin{aligned} \int_0^l (\kappa xy' + \kappa x'y) ds &= \int_0^l N' \cdot (-y, x) ds \\ &= \int_0^l N \cdot (-y', x') ds \end{aligned}$$

Then now we have

$$\frac{r}{2} \int_0^l (\kappa xy' + \kappa x'y) ds + \frac{r}{2} \int_0^l -N_1y' + N_2x' ds = \frac{r}{2} \int_0^l 2N \cdot (-y', x') ds$$

Using positive orientation and the fact  $|N| = 1 = |(-y', x')|$  to identify that  $N = (-y', x')$ , we now have

$$\frac{r}{2} \int_0^l 2N \cdot (-y', x') ds = rl$$

and have

$$\frac{r^2}{2} \int_0^l (-N_1 y' \kappa + N_2 x' \kappa) ds = \frac{r^2}{2} \int_0^l \kappa ds = r^2 \pi$$

since  $(x, y)$  is simple closed. This finishes the proof.

(c)

Recall that

$$\kappa(a, b) = \frac{a'b'' - a''b'}{((a')^2 + (b')^2)^{\frac{3}{2}}}$$

We use this formula on  $\beta$  to compute

$$\begin{aligned} \kappa_\beta &= \frac{(1 + r\kappa)x'((1 + r\kappa)y')' - ((1 + r\kappa)x')'(1 + r\kappa)y'}{(1 + r\kappa)^3} \\ &= \frac{(1 + r\kappa)^2(x'y'' - x''y')}{(1 + r\kappa)^3} \\ &= \frac{x'y'' - x''y'}{1 + r\kappa} = \frac{\kappa}{1 + r\kappa} \quad (\because (x')^2 + (y')^2 = 1) \end{aligned}$$

■



## Question 23

**8. \*a.** Let  $\alpha(s)$ ,  $s \in [0, l]$ , be a plane simple closed curve. Assume that the curvature  $k(s)$  satisfies  $0 < k(s) \leq c$ , where  $c$  is a constant (thus,  $\alpha$  is less curved than a circle of radius  $1/c$ ). Prove that

$$\text{length of } \alpha \geq \frac{2\pi}{c}.$$

**b.** In part a replace the assumption of being simple by “ $\alpha$  has rotation index  $N$ .” Prove that

$$\text{length of } \alpha \geq \frac{2\pi N}{c}.$$

*Proof.* (a)

Because  $\alpha$  is simple closed and  $\kappa \leq c$ , we know

$$cl = \int_0^l cds \geq \int_0^l \kappa ds = 2\pi$$

This then implies

$$\text{Length of } \alpha = l \geq \frac{2\pi}{c}$$

(b)

Because  $\alpha$  has rotation index  $N$  and  $\kappa \leq c$ , we know

$$cl = \int_0^l cds \geq \int_0^l \kappa ds = N2\pi$$

This then implies

$$\text{Length of } \alpha = l \geq \frac{2\pi N}{c}$$



## Question 24

- \*11.** Given a nonconvex simple closed plane curve  $C$ , we can consider its *convex hull*  $H$  (Fig. 1-39), that is, the boundary of the smallest convex set containing the interior of  $C$ . The curve  $H$  is formed by arcs of  $C$  and by the segments of the tangents to  $C$  that bridge “the nonconvex gaps” (Fig. 1-39). It can be proved that  $H$  is a  $C^1$  closed convex curve. Use this to show that, in the isoperimetric problem, we can restrict ourselves to convex curves.



Figure 1-39

*Proof.* Suppose we have proved that a convex closed curve must satisfy the isoperimetric inequality. Let  $C$  be an arbitrary closed plane curve, and let  $H$  be its convex hull. Now, because straight line is the shortest curve between two point and because we know  $H$ , a convex curve, must satisfy isoperimetric inequality, we now see

$$4\pi A(C) \leq 4\pi A(H) \leq l_H^2 \leq l_C^2$$

If the equality hold true, we can deduce from  $l_H = l_C$  that  $H = C$  and use the argument for isoperimetric inequality of convex curve to argue that  $C = H$  must be a circle. ■

## Question 25

- 3.** Show that the two-sheeted cone, with its vertex at the origin, that is, the set  $\{(x, y, z) \in \mathbb{R}^3; x^2 + y^2 - z^2 = 0\}$ , is not a regular surface.

*Proof.* Let  $S = \{(x, y, z) \in \mathbb{R}^3 : x^2 + y^2 - z^2 = 0\}$ . It is clear  $S$  contain  $(0, 0, 0)$ . To show  $S$  is not regular, we only wish to find a neighborhood  $V$  around  $(0, 0, 0)$  in  $S$  such that  $V$  can not expressed as graph of differentiable functions from  $\mathbb{R}^2$  to  $\mathbb{R}$ . This is trivially true, as all neighborhood ought to contain some open ball  $B_\epsilon(0)$ , and in this open ball, if we fix, say  $(x, y) \in B_\epsilon(0)$  such that  $(x, y, \sqrt{x^2 + y^2}) \in B_\epsilon(0)$ , we see that  $z = -\sqrt{x^2 + y^2}$  is also in  $B_\epsilon(0)$  and  $S$ . The same argument applies to when  $(x, z)$  and  $(y, z)$  are fixed. ■

## Question 26

**6. Give another proof of Prop. 1 by applying Prop. 2 to  $h(x, y, z) = f(x, y) - z$ .**

*Proof.* Because  $f$  is differentiable, we see  $f_x, f_y$  are all continuous on  $U$ . This then implies

$$h_x(x, y, z) = f_x(x, y), h_y(x, y, z) = f_y(x, y), h_z = -1 \text{ are all continuous on } U$$

We have shown  $h$  is differentiable. Now that observe

$$h(x, y, z) = 0 \implies (x, y, z) = (x, y, f(x, y))$$

The converse of course hold true. This then implies

$$f[U] = h^{-1}[0]$$

Fix arbitrary  $(x, y) \in U$ . We see

$$dh(x, y, f(x, y)) = \begin{bmatrix} h_x & h_y & h_z \end{bmatrix} \Big|_{(x, y, f(x, y))} = \begin{bmatrix} f_x(x, y) & f_y(x, y) & -1 \end{bmatrix}$$

which is clearly not onto. This show

$$(x, y, f(x, y)) \text{ is not a critical point}$$

Because  $(x, y) \in U$  is arbitrary, we have shown  $f[U]$  contain no critical point. Now it follows 0 is a regular value and  $f[U] = h^{-1}[0]$  is a regular surface. ■

## Question 27

**7. Let  $f(x, y, z) = (x + y + z - 1)^2$ .**

- a. Locate the critical points and critical values of  $f$ .**
- b. For what values of  $c$  is the set  $f(x, y, z) = c$  a regular surface?**
- c. Answer the questions of parts a and b for the function  $f(x, y, z) = xyz^2$ .**

*Proof.* (a)

Compute

$$f_x = f_y = f_z = 2(x + y + z - 1)$$

This implies the set of critical points are

$$\{(x, y, z) \in \mathbb{R}^3 : x + y + z = 1\}$$

Then it follows from simple computation the set of critical values is exactly

$$\{0\}$$

(b)

For all  $c > 0$ , the set  $f^{-1}[c]$  is a regular surface, and for all  $c < 0$ , the set  $f^{-1}[c]$  is empty (thus trivially regular).

(c)

Compute

$$f_x = yz^2 \text{ and } f_y = xz^2 \text{ and } f_z = 2xyz$$

This implies the set of critical points is

$$\{(x, y, z) : z = 0 \text{ or } x = y = 0\}$$

With simple computation, we see the set of critical values is exactly

$$\{0\}$$

The set of regular values are exactly  $\mathbb{R}^*$ , so all  $c \neq 0$  suffice. ■

### Question 28

**8. Let  $\mathbf{x}(u, v)$  be as in Def. 1. Verify that  $d\mathbf{x}_q: \mathbb{R}^2 \rightarrow \mathbb{R}^3$  is one-to-one if and only if**

$$\frac{\partial \mathbf{x}}{\partial u} \wedge \frac{\partial \mathbf{x}}{\partial v} \neq 0.$$

*Proof.* Note that

$$dx_q = [\partial_u x \quad \partial_v x]$$

This give us

$$dx_q: \mathbb{R}^2 \rightarrow \mathbb{R}^3 \text{ is one-to-one} \iff \partial_u x, \partial_v x \in \mathbb{R}^3 \text{ is linearly independent everywhere}$$

Then we can reduce the problem into proving

$$\partial_u x, \partial_v x \in \mathbb{R}^3 \text{ is linearly independent everywhere} \iff \partial_u x \times \partial_v x \neq 0 \text{ everywhere}$$

This then follows from Theorem 2.2.2 at the next page, as one can see that each component of the output of cross product is exactly the three determinant. ■

**Theorem 2.2.2. (Computation to check Linearly Independence)**

$$\begin{bmatrix} v_1 & w_1 \\ v_2 & w_2 \\ v_3 & w_3 \end{bmatrix} \text{ is linearly independent} \iff \begin{vmatrix} v_1 & w_1 \\ v_2 & w_2 \end{vmatrix} \neq 0 \text{ or } \begin{vmatrix} v_2 & w_2 \\ v_3 & w_3 \end{vmatrix} \neq 0 \text{ or } \begin{vmatrix} v_1 & w_1 \\ v_3 & w_3 \end{vmatrix} \neq 0$$

*Proof.* ( $\leftarrow$ )

Assume  $v, w$  are linearly dependent. Fix  $w_k = cv_k$ . We see

$$\begin{vmatrix} v_1 & w_1 \\ v_2 & w_2 \end{vmatrix} = cv_1v_2 - cv_1v_2 = 0 \text{ CaC}$$

( $\rightarrow$ )

Assume all determinant are 0. Pick  $k$  such that  $v_k$  is non-zero. Define

$$c \triangleq \frac{w_k}{v_k}$$

WOLG, suppose

$$w_1 = cv_1 \text{ and } v_1 \neq 0$$

We then can deduce

$$\begin{vmatrix} v_1 & w_1 \\ v_2 & w_2 \end{vmatrix} \implies cv_1v_2 = v_1w_2 \implies w_2 = cv_2$$

The same argument implies  $w_3 = cv_3$  CaC

■

## 2.3 HW3

### Question 29

**12.** Show that  $\mathbf{x}: U \subset \mathbb{R}^2 \rightarrow \mathbb{R}^3$  given by

$$\mathbf{x}(u, v) = (a \sin u \cos v, b \sin u \sin v, c \cos u), \quad a, b, c \neq 0,$$

where  $0 < u < \pi$ ,  $0 < v < 2\pi$ , is a parametrization for the ellipsoid

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} = 1.$$

Describe geometrically the curves  $u = \text{const.}$  on the ellipsoid.

*Proof.* We are required to show

- (a) range of  $\mathbf{x}$  lies in the ellipsoid
- (b)  $\mathbf{x}$  is smooth
- (c)  $d\mathbf{x}$  is one-to-one everywhere on  $U \triangleq (0, \pi) \times (0, 2\pi)$
- (d)  $\mathbf{x}$  is a homeomorphism

Compute

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} = \sin^2 u \cos^2 v + \sin^2 u \sin^2 v + \cos^2 u = 1$$

This shows that the range of  $\mathbf{x}$  indeed lies in the ellipsoid.

It is clear that  $\mathbf{x}$  is smooth.

Compute

$$d\mathbf{x} = \begin{bmatrix} a \cos u \cos v & -a \sin u \sin v \\ b \cos u \sin v & b \sin u \cos v \\ -c \sin u & 0 \end{bmatrix}$$

Then compute

$$\frac{\partial(y, z)}{\partial(u, v)} = bc \sin^2 u \cos v \text{ and } \frac{\partial(x, z)}{\partial(u, v)} = -ac \sin^2 u \sin v$$

Because  $u \in (0, \pi)$  and  $v \in (0, 2\pi)$ , and  $b, c \neq 0$ , we now can deduce

$$\begin{aligned}\frac{\partial(y, z)}{\partial(u, v)} = 0 &\iff v \in \left\{\frac{\pi}{2}, \frac{3}{2}\pi\right\} \\ \frac{\partial(y, z)}{\partial(u, v)} = 0 &\iff v = \pi\end{aligned}$$

This then let us deduce

$d\mathbf{x}$  is one-to-one everywhere on  $(0, \pi) \times (0, 2\pi)$

Traditionally, the function  $\arctan$  is defined on  $\mathbb{R}$  and have codomain  $(-\frac{\pi}{2}, \frac{\pi}{2})$ .

Deduce first from the  $z$ -component of  $\mathbf{x}$ . We see

$$\mathbf{x}^{-1}(x, y, z) = \left( \arccos \frac{z}{c}, \begin{cases} \arctan \frac{ay}{bx} & \text{if } x, y \in \mathbb{R}^+ \text{ (first quadrant)} \\ \frac{\pi}{2} & \text{if } x = 0, y \in \mathbb{R}^+ \\ \frac{3\pi}{2} + \arctan \frac{ay}{bx} & \text{if } x \in \mathbb{R}^-, y \in \mathbb{R}^+ \text{ (second quadrant)} \\ \pi + \arctan \frac{ay}{bx} & \text{if } x \in \mathbb{R}^-, y \in \mathbb{R}_0^- \text{ (third quadrant)} \\ \frac{3\pi}{2} & \text{if } x = 0, y \in \mathbb{R}^- \\ \frac{4\pi}{2} + \arctan \frac{ay}{bx} & \text{if } x \in \mathbb{R}^+, y \in \mathbb{R}^- \text{ (forth quadrant)} \end{cases} \right)$$

Now it follows that  $\mathbf{x}$  is indeed a homeomorphism.

When  $u$  is fixed, the image is an oval missing a point  $(a \sin u, 0, c \cos u)$  floating in air (contained by  $\{(x, y, c_0) \in \mathbb{R}^3 : (x, y) \in \mathbb{R}^2\}$  where  $c_0 = c \cos u$  is fixed) ■

**Definition 2.3.1. (Definition of regular plane curve)** We say  $C \subseteq \mathbb{R}^2$  is a regular plane curve if for all  $p \in C$  there exists

- (a) an open neighborhood  $p \in V \subseteq \mathbb{R}^2$
- (b) an open set  $U \subseteq \mathbb{R}$
- (c) a function  $\mathbf{x} : U \rightarrow V \cap C$

such that  $\mathbf{x}$  satisfy

- (a)  $\mathbf{x}$  is smooth
- (b)  $\mathbf{x}$  is a homoeomorphism between  $U$  and  $V \cap C$
- (c)  $d\mathbf{x}_q \in L(\mathbb{R}, \mathbb{R}^2)$  is one-to-one for all  $q \in U$

**Definition 2.3.2. (Definition of regular space curve)** We say  $C \subseteq \mathbb{R}^3$  is a regular space curve if for all  $p \in C$  there exists

- (a) an open neighborhood  $p \in V \subseteq \mathbb{R}^3$
- (b) an open set  $U \subseteq \mathbb{R}$
- (c) a function  $\mathbf{x} : U \rightarrow V \cap C$

such that  $\mathbf{x}$  satisfy

- (a)  $\mathbf{x}$  is smooth
- (b)  $\mathbf{x}$  is a homeomorphism between  $U$  and  $V \cap C$
- (c)  $d\mathbf{x}_q \in L(\mathbb{R}, \mathbb{R}^3)$  is one-to-one for all  $q \in U$

### Question 30

**17. Define a regular curve in analogy with a regular surface. Prove that**

**a. The inverse image of a regular value of a differentiable function**

$$f: U \subset \mathbb{R}^2 \rightarrow \mathbb{R}$$

**is a regular plane curve. Give an example of such a curve which is not connected.**

**b. The inverse image of a regular value of a differentiable map**

$$F: U \subset \mathbb{R}^3 \rightarrow \mathbb{R}^2$$

**is a regular curve in  $\mathbb{R}^3$ . Show the relationship between this proposition and the classical way of defining a curve in  $\mathbb{R}^3$  as the intersection of two surfaces.**

**\*c. The set  $C = \{(x, y) \in \mathbb{R}^2; x^2 = y^3\}$  is not a regular curve.**

*Proof. (a)*

Suppose  $f : U \subseteq \mathbb{R}^2 \rightarrow \mathbb{R}$  is a smooth function and  $c$  is a regular value. We wish to prove

$$C \triangleq f^{-1}[c] \text{ is a regular plane curve}$$

Fix  $p \in f^{-1}[c]$ . We wish

to find a local parametrization  $\mathbf{x} : I \subseteq \mathbb{R} \rightarrow C$  around  $p$



Because  $c$  is a regular value, we know  $df_p$  is one-to-one. Then, WOLG, we can let  $\partial_y F(p) \neq c$ . Define  $F : U \rightarrow \mathbb{R}^2$  by

$$F(x, y) \triangleq (x, f(x, y))$$

Compute

$$dF = \begin{bmatrix} 1 & 0 \\ \partial_x f & \partial_y f \end{bmatrix}$$

It is now clear that  $\det(dF_p) \neq 0$ . Now, because  $f$  is smooth, we can use inverse function Theorem and obtain a diffeomorphism  $F$  between open neighborhood around  $p$  and open neighborhood around  $f(p)$ . Now, note that  $f[C] = \{c\}$ . This tell us

$$F[C] \subseteq \{(x, c) \in \mathbb{R}^2 : x \in \mathbb{R}\}$$

we now claim

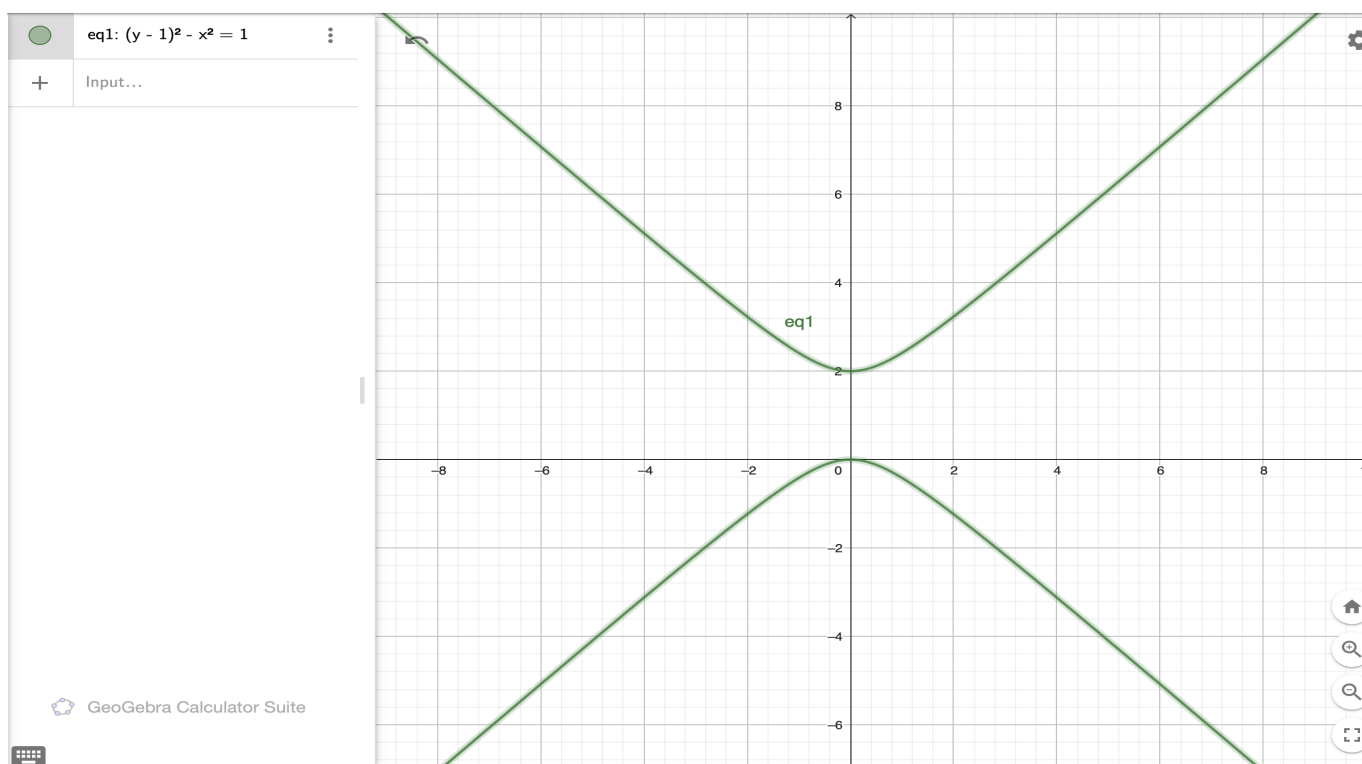
$\mathbf{x}(u) \triangleq F^{-1}(u, c)$  is the desired local parametrization around  $p$

The fact that  $\mathbf{x}$  is smooth and homeomorphism follows from

- (a)  $F$  is a diffeomorphism around  $p$
- (b)  $\mathbf{x}$  can be identified as restriction of  $F^{-1}$

Note that  $d(F^{-1})_p = (dF_{F^{-1}(p)})^{-1} \neq 0$ . Now, because  $\mathbf{x}$  is restriction of  $F^{-1}$ , we see  $d\mathbf{x}$  must not be 0 around  $p$ . (done)

An example is  $f(x, y) = (y - 1)^2 - x^2$ .



(b)

Suppose  $F : U \subseteq \mathbb{R}^3 \rightarrow \mathbb{R}^2$  is a smooth function and  $(c_0, c_1)$  is a regular value. We wish to prove

$C \triangleq F^{-1}[(c_0, c_1)]$  is a regular space curve

Fix  $p \in F^{-1}[(c_0, c_1)]$ . We wish

to find a local parametrization  $\mathbf{x} : I \subseteq \mathbb{R} \rightarrow C$  around  $p$

Define  $G : U \rightarrow \mathbb{R}^3$  by

$$G(x, y, z) \triangleq (x, F(x, y, z))$$

Compute

$$dG = \begin{bmatrix} 1 & 0 & 0 \\ \partial_x F_1 & \partial_y F_1 & \partial_z F_1 \\ \partial_x F_2 & \partial_y F_2 & \partial_z F_2 \end{bmatrix}$$

Because  $p$  is a regular point of  $F$ , we can WOLG, suppose

$$\det(dG_p) = \det\left(\frac{\partial(F_1, F_2)}{\partial(y, z)}\bigg|_p\right) \neq 0$$

This Then, by Inverse function Theorem,  $G$  is locally a diffeomorphism around  $p$ . We now see

$\mathbf{x}(t) \triangleq G^{-1}(t, c_0, c_1)$  is the desired local parametrization around  $p$  (done)

Suppose we are given two function  $A, B : \mathbb{R}^3 \rightarrow \mathbb{R}$ , and suppose  $A^{-1}[c_0], B^{-1}[c_1]$  are two surfaces. Define  $F : \mathbb{R}^3 \rightarrow \mathbb{R}^2$  by

$$F(p) \triangleq (A(p), B(p))$$

We see that

the intersection  $A^{-1}[c_0] \cap B^{-1}[c_1]$  is exactly  $F^{-1}[(c_0, c_1)]$

(c)

Assume for a contradiction,  $C$  is a regular curve. Note that  $(0, 0) \in C$ . We know there exists an open-neighborhood  $N \subseteq \mathbb{R}^2$  around  $(0, 0)$  such that  $N \cap C$  is the graph of some differentiable function in  $x$  or  $y$ . However, this is impossible, since if one view  $N \cap C$  as a function in  $x$ , the function  $y = x^{\frac{2}{3}}$  is not differentiable at  $x = 0$ , and one can not even view  $N \cap C$  as a function in  $y$  as each  $y$  correspond to two  $x$ , namely  $x = \pm y^{\frac{3}{2}}$ . CaC

■

### Question 31

**2.** Let  $S \subset \mathbb{R}^3$  be a regular surface and  $\pi : S \rightarrow \mathbb{R}^2$  be the map which takes each  $p \in S$  into its orthogonal projection over  $\mathbb{R}^2 = \{(x, y, z) \in \mathbb{R}^3; z = 0\}$ . Is  $\pi$  differentiable?

*Proof.* Yes. Fix  $p$  in  $S$ . We wish to prove

$\pi$  is differentiable at  $p$  in the sense of manifold

Let  $\mathbf{x}_1 : U_1 \subseteq \mathbb{R}^2 \rightarrow V_1 \cap S \subseteq \mathbb{R}^3$  be a local parametrization around  $p$ . Define a local parametrization  $\mathbf{x}_2 : U_2 \subseteq \mathbb{R}^2 \rightarrow \mathbb{R}^2$  around  $\pi(p)$  by

$$\mathbf{x}_2 \triangleq \text{id}_{U_2}$$

We are require to prove

$\mathbf{x}_2^{-1} \circ \pi \circ \mathbf{x}_1$  is differentiable at  $\mathbf{x}_1^{-1}(p)$

Notice that

(a)  $\mathbf{x}_1 : U_1 \rightarrow \mathbb{R}^3$  is differentiable at  $p$  by definition

(b)  $\pi : \mathbb{R}^3 \rightarrow \mathbb{R}^2$  is clearly differentiable, with derivative  $\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix}$

(c)  $\mathbf{x}_2^{-1} = \text{id}_{U_2} : U_2 \rightarrow \mathbb{R}^2$  is clearly differentiable.

This shows that  $\mathbf{x}_2^{-1} \circ \pi \circ \mathbf{x}_1$  is differentiable at  $p$ . (done) ■

### Question 32

**3. Show that the paraboloid  $z = x^2 + y^2$  is diffeomorphic to a plane.**

*Proof.* Let  $S$  be the paraboloid. We show

$S$  is diffeomorphic to  $\{(x, y, 0) : x, y \in \mathbb{R}\}$

Define

$$\pi : S \rightarrow \{(x, y, 0) : x, y \in \mathbb{R}\} \text{ by } \pi(x, y, z) \triangleq (x, y, 0)$$

We wish to show

$\pi$  and  $\pi^{-1}$  is differentiable everywhere in the sense of manifold

Define global parametrizations  $\mathbf{x}_1$  of  $S$  and global parametrization  $\mathbf{x}_2$  of  $\{(x, y, 0) : x, y \in \mathbb{R}\}$  by

(a)  $\mathbf{x}_1 : \mathbb{R}^2 \rightarrow S$  and  $\mathbf{x}_1(x, y) \triangleq (x, y, x^2 + y^2)$

(b)  $\mathbf{x}_2 : \mathbb{R}^2 \rightarrow \{(x, y, 0) : x, y \in \mathbb{R}\}$  and  $\mathbf{x}_2 \triangleq \text{id}_{\mathbb{R}^2}$

We now reword the problem into proving

$\mathbf{x}_2^{-1} \circ \pi \circ \mathbf{x}_1 : \mathbb{R}^2 \rightarrow \mathbb{R}^2$  and  $\mathbf{x}_1^{-1} \circ \pi^{-1} \circ \mathbf{x}_2 : \mathbb{R}^2 \rightarrow \mathbb{R}^2$  both are differentiable

Because  $\pi, \mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_2^{-1}$  are clearly differentiable, we only have to prove

$\pi^{-1} : \{(x, y, 0) : x, y \in \mathbb{R}\} \rightarrow \mathbb{R}^3$  is differentiable and  $\mathbf{x}_1^{-1} : \mathbb{R}^3 \cap S \rightarrow \mathbb{R}^2$  is differentiable on  $S$

Observe

$$\pi^{-1}(x, y, 0) \equiv (x, y, x^2 + y^2) \text{ and } \mathbf{x}_1(x, y, z) \equiv (x, y)$$

It is now clear that  $\pi^{-1}$  and  $\mathbf{x}_1^{-1}$  are both differentiable. (done) ■

### Question 33

## 6. Prove that the definition of a differentiable map between surfaces does not depend on the parametrizations chosen.

*Proof.* Suppose we are given a map  $\pi : S_1 \rightarrow S_2$  differentiable in the sense of manifold. We know for arbitrary  $p$  in  $S_1$ , there exists

- (a)  $\mathbf{x}_1 : U_1 \rightarrow S_1$  (a local parametrization around  $p$ )
- (b)  $\mathbf{x}_2 : U_2 \rightarrow S_2$  (a local parametrization around  $\pi(p)$ )

such that

$$\left( \mathbf{x}_2^{-1} \circ \pi \circ \mathbf{x}_1 \right) : U_1 \subseteq \mathbb{R}^2 \rightarrow U_2 \subseteq \mathbb{R}^2 \text{ is a diffeomorphism} \quad (2.8)$$

Now, fix two arbitrary

- (a)  $\mathbf{x}'_1 : U'_1 \rightarrow S_1$  (a local parametrization around  $p$ )
- (b)  $\mathbf{x}'_2 : U'_2 \rightarrow S_2$  (a local parametrization around  $\pi(p)$ )

We are required to prove (Note that the domain of each composited function may be smaller, but this does not undermine the validity of our argument, since we only care about the differentiability at  $p$ )

$$\left( (\mathbf{x}'_2)^{-1} \circ \pi \circ \mathbf{x}'_1 \right) : U'_1 \subseteq \mathbb{R}^2 \rightarrow U'_2 \subseteq \mathbb{R}^2 \text{ is a diffeomorphism}$$

Note that

$$\begin{aligned} (\mathbf{x}'_2)^{-1} \circ \pi \circ \mathbf{x}'_1 &= (\mathbf{x}'_2)^{-1} \circ (\mathbf{x}_2 \circ \mathbf{x}_2^{-1}) \circ \pi \circ (\mathbf{x}_1 \circ \mathbf{x}_1^{-1}) \circ \mathbf{x}'_1 \\ &= (\mathbf{x}'_2)^{-1} \circ \mathbf{x}_2 \circ \mathbf{x}_2^{-1} \circ \pi \circ \mathbf{x}_1 \circ \mathbf{x}_1^{-1} \circ \mathbf{x}'_1 \\ &= h_2 \circ \mathbf{x}_2^{-1} \circ \pi \circ \mathbf{x}_1 \circ h_1 \end{aligned}$$

where

$$\begin{cases} h_1 \equiv \mathbf{x}_1^{-1} \circ \mathbf{x}'_1 : U'_1 \rightarrow U_1 \\ h_2 \equiv (\mathbf{x}'_2)^{-1} \circ \mathbf{x}_2 : U_2 \rightarrow U'_2 \end{cases} \quad \text{are changes of coordinate}$$

Now, because changes of coordinates are diffeomorphism, and  $\mathbf{x}_2^{-1} \circ \pi \circ \mathbf{x}_1$  is diffeomorphism by Equation 2.8 (definition), we see that

$$(\mathbf{x}'_2)^{-1} \circ \pi \circ \mathbf{x}'_1 = h_2 \circ (\mathbf{x}_2^{-1} \circ \pi \circ \mathbf{x}_1) \circ h_1 \text{ is a diffeomorphism at } (\mathbf{x}'_1)^{-1}(p)$$

This then conclude the proof, since  $p$  is arbitrary picked from  $S_1$ . (done) ■

**Definition 2.3.3. (Definition of Differentiable function on a regular curve)** Given two regular curve  $C_1, C_2$ , we say the function  $f : C_1 \rightarrow C_2$  is differentiable at  $p$  if for all local parametrizations  $\mathbf{x}_1 : I \rightarrow C_1 \ni p, \mathbf{x}_2 : I \rightarrow C_2 \ni f(p)$ , we have

$$\mathbf{x}_2^{-1} \circ f \circ \mathbf{x}_1 \text{ is differentiable as a real to real function}$$

### Question 34

- 9. a.** Define the notion of differentiable function on a regular curve. What does one need to prove for the definition to make sense? Do not prove it now. If you have not omitted the proofs in this section, you will be asked to do it in Exercise 15.
- b.** Show that the map  $E: \mathbb{R} \rightarrow S^1 = \{(x, y) \in \mathbb{R}^2; x^2 + y^2 = 1\}$  given by

$$E(t) = (\cos t, \sin t), \quad t \in \mathbb{R},$$

is differentiable (geometrically,  $E$  “wraps”  $\mathbb{R}$  around  $S^1$ ).

*Proof.* Fix  $t_0 \in \mathbb{R}$ . We wish to prove

$E$  is differentiable at  $t_0$  in the sense of manifold

Locally parametrize  $t_0$  and  $E(t_0)$  by

$$\mathbf{x}_1(t) \triangleq t \text{ and } \mathbf{x}_2(t) \triangleq (\cos t, \sin t)$$

Now, see that

$$\mathbf{x}_2^{-1} \circ E \circ \mathbf{x}_1(t) = t \text{ is clearly differentiable (done)}$$

■

### Question 35

- 14.** Let  $A \subset S$  be a subset of a regular surface  $S$ . Prove that  $A$  is itself a regular surface if and only if  $A$  is open in  $S$ ; that is,  $A = U \cap S$ , where  $U$  is an open set in  $\mathbb{R}^3$ .

*Proof.* ( $\longleftarrow$ )

Fix  $a \in A$ . Because  $a \in S$ , we know there exists a local parametrization  $\mathbf{x}_1 : E \rightarrow V \cap S$  around  $a$  where  $V$  is open in  $\mathbb{R}^3$ . Suppose

$$E' \triangleq \mathbf{x}_1^{-1}[U \cap V \cap S]$$

Now, from

- (a)  $U \cap V \cap S$  is open in  $V \cap S$  ( $\because U$  is open in  $\mathbb{R}^3$ )
- (b)  $\mathbf{x}_1$  is a homeomorphism between  $E$  and  $V \cap S$
- (c)  $\mathbf{x}_1$  is smooth
- (d)  $d\mathbf{x}_1$  is one-to-one for all  $p \in E$
- (e)  $E' \subseteq E$

We see

- (a)  $E'$  is open in  $\mathbb{R}^2$
- (b) the restriction  $\mathbf{x}_1|_{E'}$  is a local parametrization around  $a$  contained by  $A$

Because  $a$  is arbitrary, this established that  $A$  is a regular surface.

( $\longrightarrow$ )

Suppose  $A$  is a regular surface. Fix arbitrary  $a \in A$ . Using Proposition 2.2.3 in Do Carmo, WOLG, we can suppose there exists a chart  $\mathbf{x} : U \rightarrow \bar{V} \cap S$  around  $a$  where  $\bar{V}$  is open in  $\mathbb{R}^3$  such that

$$\mathbf{x}(x, y) = (x, y, f(x, y)) \text{ for some smooth } f$$

Because each curve in  $A$  lies in  $S$  and  $A$  is itself a regular surface, we see that

$$T_a(A) = T_a(S)$$

This tell us the restriction

$$\mathbf{x}|_A \text{ is one-to-one}$$

Note that  $\mathbf{x}$  is smooth. Now by inverse function theorem, it follows that there exists  $V$  open in  $\mathbb{R}^3$  such that

$$\mathbf{x}|_{A \cap V} \text{ is a chart around } a$$

Now, define  $W \triangleq V \cap \overline{V}$ . Now, identify

$$\mathbf{x}|_{A \cap W} \text{ is a chart in both } A \text{ and } S$$

We now see

$A \cap W$  is an open neighborhood around  $a$  in topology of  $S$

This shows that  $a \in A^\circ$  in topology of  $S$ . Because  $a$  is arbitrary, it follows that  $A$  is open in  $S$ . ■

### Question 36

**\*16.** Let  $R^2 = \{(x, y, z) \in R^3; z = -1\}$  be identified with the complex plane  $\mathbb{C}$  by setting  $(x, y, -1) = x + iy = \zeta \in \mathbb{C}$ . Let  $P: \mathbb{C} \rightarrow \mathbb{C}$  be the complex polynomial

$$P(\zeta) = a_0 \zeta^n + a_1 \zeta^{n-1} + \cdots + a_n, \quad a_0 \neq 0, a_i \in \mathbb{C}, i = 0, \dots, n.$$

Denote by  $\pi_N$  the stereographic projection of  $S^2 = \{(x, y, z) \in R^3; x^2 + y^2 + z^2 = 1\}$  from the north pole  $N = (0, 0, 1)$  onto  $R^2$ . Prove that the map  $F: S^2 \rightarrow S^2$  given by

$$\begin{aligned} F(p) &= \pi_N^{-1} \circ P \circ \pi_N(p), \quad \text{if } p \in S^2 - \{N\}, \\ F(N) &= N \end{aligned}$$

is differentiable.

*Proof.* Note that

$$\pi_N(x, y, z) = \left( \frac{2x}{1-z}, \frac{2y}{1-z} \right) \text{ and } \pi_N^{-1}(u, v) = \left( \frac{4u}{u^2 + v^2 + 4}, \frac{4v}{u^2 + v^2 + 4}, \frac{u^2 + v^2 - 4}{u^2 + v^2 + 4} \right)$$

and that

$$P(x, y, -1) = (Q(x, y), T(x, y), -1) \text{ for some } Q, T \in \mathbb{R}[x, y]$$

It is then now clear that

$$F \text{ is differentiable on } S^2 \setminus N$$



Note that

$$\pi_S(x, y, z) = \left(\frac{2x}{1+z}, \frac{2y}{1+z}\right) \text{ and } \pi_S^{-1}(u, v) = \left(\frac{4u}{u^2+v^2+4}, \frac{4v}{u^2+v^2+4}, \frac{-u^2-v^2+4}{u^2+v^2+4}\right)$$

Note that

$$\pi_S^{-1} \circ \pi_S \circ F \circ \pi_S^{-1} \circ \pi_S \text{ coincide with } F \text{ on } S^2 \setminus S$$

Then, we can reduce proving  $F$  is differentiable at  $N$  into

$$\text{proving } \pi_S^{-1} \circ \pi_S \circ F \circ \pi_S^{-1} \circ \pi_S \text{ is differentiable at } N$$

Compute

$$\begin{aligned} \pi_N \circ \pi_S^{-1}(u, v) &= \pi_N\left(\frac{4u}{u^2+v^2+4}, \frac{4v}{u^2+v^2+4}, \frac{-u^2-v^2+4}{u^2+v^2+4}\right) \\ &= \left(\frac{4u}{u^2+v^2}, \frac{4v}{u^2+v^2}\right) \end{aligned}$$

Compute

$$\pi_S \circ \pi_N^{-1}(u, v) = \left(\frac{4u}{u^2+v^2}, \frac{4v}{u^2+v^2}\right)$$

Note that if we identify  $\mathbb{R}^2 \setminus 0$  by  $\mathbb{C}^*$ , we see

$$\pi_S \circ \pi_N^{-1}(z) = \pi_N \circ \pi_S^{-1}(z) = \frac{4z}{|z|^2} = \frac{4z}{z\bar{z}} = \frac{4}{\bar{z}} \quad (z \in \mathbb{C}^*)$$

Fix  $z \in \mathbb{C}^*$ . Compute

$$\begin{aligned} \pi_S \circ F \circ \pi_S^{-1}(z) &= \pi_S \circ \pi_N^{-1} \circ P \circ \pi_N \circ \pi_S^{-1}(z) \\ &= \pi_S \circ \pi_N^{-1} \circ P\left(\frac{4}{\bar{z}}\right) \\ &= \pi_S \circ \pi_N^{-1}\left(a_0\left(\frac{4}{\bar{z}}\right)^n + \cdots + a_n\right) \\ &= \frac{4}{a_0\left(\frac{4}{\bar{z}}\right)^n + \cdots + a_n} \\ &= \frac{4}{\overline{a_0\left(\frac{4}{z}\right)^n + \cdots + a_n}} \\ &= \frac{4z^n}{\overline{a_n z^n + \cdots + a_0 4^n}} \end{aligned}$$

Compute

$$\pi_S \circ F \circ \pi_S^{-1}(0) = \pi_S \circ F(N) = \pi_S(N) = 0$$

Then because  $a_0 \neq 0$ . It is now clear that

$$\pi_S \circ F \circ \pi_S^{-1}(z) = \frac{4z^n}{\overline{a_n}z^n + \cdots + \overline{a_0}4^n} \quad (z \in \mathbb{C})$$

which is differentiable at 0. Now, we have

- (a)  $\pi_S : S^2 \setminus S \rightarrow \mathbb{C}$  is differentiable on  $S^2 \setminus S$
- (b)  $\pi_S \circ F \circ \pi_S^{-1} : \mathbb{C} \rightarrow \mathbb{C}$  is differentiable on  $\mathbb{C}$
- (c)  $\pi_S^{-1} : \mathbb{C} \rightarrow S^2 \setminus S$  is differentiable on  $\mathbb{C}$

We can deduce

$$\pi_S^{-1} \circ (\pi_S \circ F \circ \pi_S^{-1}) \circ \pi_S \text{ is differentiable on } S^2 \setminus S \text{ (done)}$$

Note that we used Theorem 2.3.4 in our proof. ■

**Theorem 2.3.4. (Composition of Differentiable functions is differentiable)** Given three regular surfaces  $\{S_1, S_2, S_3\}$ , two differentiable functions  $f_1 : S_1 \rightarrow S_2$  and  $f_2 : S_2 \rightarrow S_3$ , we see

$$f_2 \circ f_1 \text{ is differentiable on } S_1$$

*Proof.* Fix  $p_1 \in S_1$ . We wish to prove

$$f_2 \circ f_1 \text{ is differentiable at } p_1$$

Set

- (a)  $p_2 \triangleq f_1(p_1)$
- (b)  $p_3 \triangleq f_2(p_2)$

Let

- (a)  $\mathbf{x}_1 : U_1 \rightarrow V_1 \cap S_1 \ni p_1$  be a local parametrization
- (b)  $\mathbf{x}_2 : U_2 \rightarrow V_2 \cap S_2 \ni p_2$  be a local parametrization
- (c)  $\mathbf{x}_3 : U_3 \rightarrow V_3 \cap S_3 \ni p_3$  be a local parametrization

We wish to prove

$$\mathbf{x}_3^{-1} \circ f_2 \circ f_1 \circ \mathbf{x}_1 \text{ is differentiable at } p_1$$

Observe that

$$\begin{aligned} \mathbf{x}_3^{-1} \circ f_2 \circ f_1 \circ \mathbf{x}_1 &= \mathbf{x}_3^{-1} \circ f_2 \circ \mathbf{x}_2 \circ \mathbf{x}_2^{-1} \circ f_1 \circ \mathbf{x}_1 \\ &= \left( \mathbf{x}_3^{-1} \circ f_2 \circ \mathbf{x}_2 \right) \circ \left( \mathbf{x}_2^{-1} \circ f_1 \circ \mathbf{x}_1 \right) \text{ is differentiable (done)} \end{aligned}$$

■

# Chapter 3

## Surface

### 3.1 Prerequisite

**Theorem 3.1.1. (Inverse function Theorem)** Given a map  $f$  from  $E$  open in  $\mathbb{R}^n$  to  $\mathbb{R}^n$ , if

- (a)  $f$  is continuously differentiable on  $E$
- (b)  $df_a$  is one-to-one
- (c)  $a \in E$

Then there exists

- (a)  $U \subseteq E$  open in  $E$  where  $a \in U$
- (b)  $V \subseteq \mathbb{R}^n$  open in  $\mathbb{R}^n$

Such that

$$f|_U : U \rightarrow V \text{ is a diffeomorphism}$$

**Theorem 3.1.2. (Implicit function Theorem)** Given a map  $f$  from an open neighborhood around  $(a, b) \in E \subseteq \mathbb{R}^{n+m} \rightarrow \mathbb{R}^n$  such that

- (a)  $f$  is continuously differentiable on  $E$
- (b) the linear transformation  $df_{(a,b)}|_{\mathbb{R}^n} : \mathbb{R}^n \rightarrow \mathbb{R}^n$  is one-to-one
- (c)  $f(a, b) = 0$

Then there exists open neighborhood  $U$  around  $(a, b) \in U \subseteq \mathbb{R}^{n+m}$  and open neighborhood  $V$  around  $b \in V \subseteq \mathbb{R}^m$  such that we can uniquely define a function  $g : V \rightarrow U$  by

$$f(g(y), y) = 0 \text{ for all } y \in V$$

$$\text{and } g \text{ is continuously differentiable with } dg_b = -(df_{(a,b)}|_{\mathbb{R}^n})^{-1} \circ df_{(a,b)}|_{\mathbb{R}^m}$$

## 3.2 Equivalent Definition of Regular Surface

**Definition 3.2.1. (Definition of Regular Surface: Local Parametrization)** We say a set  $S \subseteq \mathbb{R}^3$  is a regular surface if for all  $p \in S$  there exists

- (a) an open neighborhood  $p \in V \subseteq \mathbb{R}^3$
- (b) an open set  $U \subseteq \mathbb{R}^2$
- (c) a function  $\mathbf{x} : U \rightarrow V \cap S$

such that  $\mathbf{x}$  satisfy

- (a)  $\mathbf{x}$  is smooth
- (b)  $\mathbf{x}$  is a homomorphism between  $U$  and  $V \cap S$
- (c)  $d\mathbf{x}_q \in L(\mathbb{R}^2, \mathbb{R}^3)$  is one-to-one for all  $q \in U$

**Definition 3.2.2. (Definition of Regular Surface: Implicit function)** We say a set  $S \subseteq \mathbb{R}^3$  is a regular surface if for all  $p \in S$  there exists

- (a) an open neighborhood  $p \in V \subseteq \mathbb{R}^3$
- (b) a function  $F : V \rightarrow \mathbb{R}$

such that  $F$  satisfy

- (a)  $dF_q$  is onto for all  $q \in V \cap S$
- (b)  $F$  is smooth on  $V$
- (c)  $\exists c_0 \in \mathbb{R}, V \cap S = \{(x, y, z) \in V : F(x, y, z) = c_0\}$

We now verify the equivalency between the two definitions.

**Theorem 3.2.3. (Implicit function definition  $\longrightarrow$  Local parametrization definition)**

*Proof.* Fix  $p \in S$ . We are given an open neighborhood  $p \in V \subseteq \mathbb{R}^3$  and a function  $F : V \rightarrow \mathbb{R}$  such that, WOLG,

- (a)  $dF_q$  is onto for all  $q \in V \cap S$
- (b)  $F$  is smooth on  $V$
- (c)  $V \cap S = \{(x, y, z) \in V : F(x, y, z) = 0\}$

We wish to find

a local parametrization  $\mathbf{x}$  around  $p$

Define  $f : V \rightarrow \mathbb{R}^3$  by

$$f(x, y, z) = (x, y, F(x, y, z))$$

Because  $dF_p \neq 0$ , WOLG, we can suppose  $\partial_z F(p) \neq 0$ . Now, see

$$\det(df) = \begin{vmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ \partial_x F & \partial_y F & \partial_z F \end{vmatrix} \neq 0$$

Now, note that

(a)  $f$  is smooth on  $V$  ( $\because F$  is smooth on  $V$ )

(b)  $df_p$  is one-to-one ( $\because \partial_z F(p) \neq 0$ )

Then, by inverse function Theorem, we know

$f|_{V'} \rightarrow U'$  is a local diffeomorphism around  $V' \ni p$  and around  $U' \ni f(p)$

Let  $U \subseteq \{(x, y, 0) : (x, y) \in \mathbb{R}^2\}$  be an open-neighborhood around  $f(p)$  contained by  $U'$ .  
We claim

$\mathbf{x} \triangleq f^{-1}|_U$  suffices

Note that  $\mathbf{x}$  is well-defined since  $U \subseteq U'$  and  $f$  is a bijective between  $V'$  and  $U'$ .

Also, note that  $\mathbf{x}$  do maps points in  $U$  to points in  $V \cap S$ , since  $V \cap S = \{(x, y, z) \in V : F(x, y, z) = 0\}$ .

Suppose that

$$\begin{bmatrix} \alpha_{1,1} & \alpha_{1,2} & \alpha_{1,3} \\ \alpha_{2,1} & \alpha_{2,2} & \alpha_{2,3} \\ \alpha_{3,1} & \alpha_{3,2} & \alpha_{3,3} \end{bmatrix} \triangleq df_\alpha^{-1} = (df_{f^{-1}(\alpha)})^{-1} \text{ for all } \alpha \in U$$

We clearly have

$$d\mathbf{x} = \begin{bmatrix} \alpha_{1,1} & \alpha_{1,2} \\ \alpha_{2,1} & \alpha_{2,2} \\ \alpha_{3,1} & \alpha_{3,2} \end{bmatrix}$$

Now, one can use the premise

$dF_q$  is onto for all  $q \in V \cap S$

to check  $\mathbf{x}$  do satisfy the regular condition. (Compute  $\det(df_\alpha^{-1})$  using co-factor formula on the third column) (done) ■

---

**Definition 3.2.4. (Definition of Regular surface: Monge Patches)** We say a set  $S \subseteq \mathbb{R}^3$  is a regular surface if for all  $p \in S$  there exists some open neighborhood  $p \in V \subseteq \mathbb{R}^3$  such that

$V \cap S$  can be expressed as the graph of some smooth function  $f : O \subseteq \mathbb{R}^2 \rightarrow \mathbb{R}$  in the sense that one of the followings hold

- (a)  $V \cap S = \{(x, y, f) : (x, y) \in O\}$  for some smooth  $f : O \subseteq \mathbb{R}^2 \rightarrow \mathbb{R}$
- (b)  $V \cap S = \{(x, f, z) : (x, z) \in O\}$  for some smooth  $f : O \subseteq \mathbb{R}^2 \rightarrow \mathbb{R}$
- (c)  $V \cap S = \{(f, y, z) : (y, z) \in O\}$  for some smooth  $f : O \subseteq \mathbb{R}^2 \rightarrow \mathbb{R}$

### 3.3 Change of Parameter

Given two regular surfaces  $S_1, S_2$ , an open neighborhood  $V_1 \subseteq \mathbb{R}^3$  around  $p$ , and a continuous function  $f : V_1 \cap S_1 \rightarrow S_2$ , we say  $f$  is differentiable at  $p \in V_1$  if there exists local parametrizations

(a)  $\mathbf{x}_1 : U_1 \subseteq \mathbb{R}^2 \rightarrow V_1' \cap S_1$  around  $p$

(b)  $\mathbf{x}_2 : U_2 \subseteq \mathbb{R}^2 \rightarrow V_2 \cap S_2$  around  $f(p)$

such that

$$\mathbf{x}_2^{-1} \circ f \circ \mathbf{x}_1 \text{ is differentiable at } \mathbf{x}_1^{-1}(p)$$

Note that our definition of differentiability of function between regular surface is well-defined, in the sense that if  $f$  is differentiable, all local parametrizations suffice to check. This fact is backed by Theorem 3.3.1

**Theorem 3.3.1. (Change of Parameter is a diffeomorphism)** Let  $p$  be a point of a regular surface  $S$ , and let  $\mathbf{x} : U_1 \rightarrow V_1 \cap S$  and  $\mathbf{y} : U_2 \rightarrow V_2 \cap S$  be two local parametrizations around  $p$ . Define  $W \triangleq V_1 \cap V_2 \cap S$ . Then

The **change of coordinate**  $h = \mathbf{x}^{-1} \circ \mathbf{y} : \mathbf{y}^{-1}(W) \rightarrow \mathbf{x}^{-1}(W)$  is a diffeomorphism

*Proof.* It is clear that  $h$  is a homeomorphism, since  $\mathbf{x}, \mathbf{y}$  both are.

Note the symmetry  $h^{-1} = \mathbf{y}^{-1} \circ \mathbf{x}$ . WOLOG, we only have to prove

$$h : \mathbf{y}^{-1}(W) \subseteq U_2 \rightarrow \mathbf{x}^{-1}(W) \subseteq U_1 \text{ is differentiable}$$

Fix  $r \in \mathbf{y}^{-1}(W)$ . We prove

$$h \text{ is differentiable at } r$$

Define  $q \triangleq h(r) \in \mathbf{x}^{-1}(W) \subseteq \mathbb{R}^2$ . Let's write  $\mathbf{x}$  by

$$\mathbf{x}(u, v) = (x, y, z)$$

By definition, we know  $d\mathbf{x}_q$  is one-to-one. This, WOLOG, let us have

$$\begin{vmatrix} \partial_u x & \partial_v x \\ \partial_u y & \partial_v y \end{vmatrix}(q) \neq 0$$

Now, define  $F : \mathbf{x}^{-1}(W) \times \mathbb{R} \rightarrow \mathbb{R}^3$  by

$$F(u, v, t) \triangleq (x(u, v), y(u, v), z(u, v) + t) \tag{3.1}$$



Compute

$$\det(dF_{(q,0)}) = \begin{vmatrix} \partial_u x & \partial_v x & 0 \\ \partial_u y & \partial_v y & 0 \\ \partial_u z & \partial_v z & 1 \end{vmatrix} (q, 0) \neq 0$$

Then by Inverse function Theorem, we see that there exists an open neighborhood  $M \subseteq \mathbb{R}^3$  around  $F(q, 0)$  such that  $F^{-1}$  exists and is differentiable on  $M$ .

Now, from Equation 3.1, note that

$$F(u, v, 0) = \mathbf{x}(u, v)$$

Recall the definition  $h$ , we now have

$$h \equiv \mathbf{x}^{-1} \circ \mathbf{y} = F^{-1} \circ \mathbf{y}$$

Then because

- (a)  $\mathbf{y}$  is differentiable at  $r$
- (b)  $F^{-1}$  is differentiable at  $F(q, 0) = \mathbf{x}(q) = \mathbf{y}(r)$

We see  $h$  is indeed differentiable at  $r$  (done) ■

---

**Theorem 3.3.2. (Composition of Differentiable functions is differentiable)** Given three regular surfaces  $\{S_1, S_2, S_3\}$ , two differentiable functions  $f_1 : S_1 \rightarrow S_2$  and  $f_2 : S_2 \rightarrow S_3$ , we see

$$f_2 \circ f_1 \text{ is differentiable on } S_1$$

*Proof.* Fix  $p_1 \in S_1$ . We wish to prove

$$f_2 \circ f_1 \text{ is differentiable at } p_1$$

Set

- (a)  $p_2 \triangleq f_1(p_1)$
- (b)  $p_3 \triangleq f_2(p_2)$

Let

- (a)  $\mathbf{x}_1 : U_1 \rightarrow V_1 \cap S_1 \ni p_1$  be a local parametrization
- (b)  $\mathbf{x}_2 : U_2 \rightarrow V_2 \cap S_2 \ni p_2$  be a local parametrization

(c)  $\mathbf{x}_3 : U_3 \rightarrow V_3 \cap S_3 \ni p_3$  be a local parametrization

We wish to prove

$\mathbf{x}_3^{-1} \circ f_2 \circ f_1 \circ \mathbf{x}_1$  is differentiable at  $p_1$

Observe that

$$\begin{aligned}\mathbf{x}_3^{-1} \circ f_2 \circ f_1 \circ \mathbf{x}_1 &= \mathbf{x}_3^{-1} \circ f_2 \circ \mathbf{x}_2 \circ \mathbf{x}_2^{-1} \circ f_1 \circ \mathbf{x}_1 \\ &= \left( \mathbf{x}_3^{-1} \circ f_2 \circ \mathbf{x}_2 \right) \circ \left( \mathbf{x}_2^{-1} \circ f_1 \circ \mathbf{x}_1 \right) \text{ is differentiable (done)}\end{aligned}$$

■

## 3.4 Equivalent Definition of Tangent Plane

**Definition 3.4.1. (Definition of Tangent Plane: Space of Tangent Vectors)** Given a regular surface  $S$  and  $p \in S$ , we define **tangent plane**  $T_p S$  to  $S$  at  $p$  by

$$T_p S = \{ \alpha'(0) \in \mathbb{R}^3 \mid \alpha : I \rightarrow S \text{ is a smooth curve passing through } p \text{ at } \alpha(0) \}$$

**Definition 3.4.2. (Definition of Tangent Plane: Local Parametrization)** Given a regular surface  $S$ , that  $p \in S$  and a local parametrization  $\mathbf{x} : (u, v) \mapsto (x, y, z)$  around  $p$  such that  $\mathbf{x}(q) = p$ , we define **tangent plane**  $T_p S$  to  $S$  at  $p$  by

$$T_p S = d\mathbf{x}(\mathbb{R}^2)$$

**Theorem 3.4.3. (Equivalence of Definitions)** Given a regular surface  $S$ , that  $p \in S$  and a local parametrization  $\mathbf{x} : (u, v) \mapsto (x, y, z)$  around  $p$  such that  $\mathbf{x}(q) = p$ . we have

$$d\mathbf{x}(\mathbb{R}^2) = \{ \alpha'(0) \in \mathbb{R}^3 \mid \alpha : I \rightarrow S \text{ is a smooth curve passing through } p \text{ at } \alpha(0) \}$$

*Proof.* We first prove

$$d\mathbf{x}_q(\mathbb{R}^2) \subseteq \{ \alpha'(0) \in \mathbb{R}^3 \mid \alpha : I \rightarrow S \text{ is a smooth curve passing through } p \text{ at } \alpha(0) \}$$

Fix  $w \in d\mathbf{x}_q(\mathbb{R}^2)$ . We wish

$$\text{to find smooth } \alpha : I \rightarrow S \text{ such that } \alpha(0) = p \text{ and } \alpha'(0) = w$$

We know there exists  $v \in \mathbb{R}^2$  such that  $d\mathbf{x}_q(v) = w$ . Define  $\gamma : I \rightarrow \mathbb{R}^2$  by

$$\gamma(t) = tv + q$$

We claim

$$\mathbf{x} \circ \gamma : I \rightarrow S \text{ suffices}$$

Note that  $\mathbf{x} \circ \gamma(0) = \mathbf{x}(q) = p$  and

$$(\mathbf{x} \circ \gamma)'(0) = d\mathbf{x}_q(\gamma'(0)) = d\mathbf{x}_q(v) = w \text{ (done)}$$

We now prove

$$\{ \alpha'(0) \in \mathbb{R}^3 \mid \alpha : I \rightarrow S \text{ is a smooth curve passing through } p \text{ at } \alpha(0) \} \subseteq d\mathbf{x}_q(\mathbb{R}^2)$$

Fix a smooth curve  $\alpha : I \rightarrow S$  passing through  $p$  at  $\alpha(0)$ . We wish

$$\text{to show } \alpha'(0) \in d\mathbf{x}_q(\mathbb{R}^2)$$

Define  $\beta : I \rightarrow U$  by

$$\beta(t) = \mathbf{x}^{-1} \circ \alpha(t)$$

We claim

$$\alpha'(0) = d\mathbf{x}_q(\beta'(0))$$

Compute using Chain Rule

$$\beta'(0) = (d\mathbf{x}_q)^{-1} \circ \alpha'(0)$$

This now give us

$$d\mathbf{x}_q(\beta'(0)) = \alpha'(0) \text{ (done)}$$

■

Now, given a differentiable function  $f$  between two regular surface  $S_1, S_2$ , we can define the differential  $df$  of  $f$  in the sense of differentiable manifold.

Question: Isn't the derivative  $df_p$  exactly the same as  $df_p$  when  $f$  has domain  $\mathbb{R}^3$ ? Then why bother? just to avoid the definition of derivative on a non-interior point?

**Definition 3.4.4. (Derivative of Differentiable mapping between regular surface)**

Given a differentiable mapping  $f : S_1 \rightarrow S_2$ , we define  $df_p : T_p(S_1) \rightarrow T_{f(p)}(S_2)$  by

$$df_p(\alpha'(0)) \triangleq \frac{d}{dt} f(\alpha(t))|_{t=0}$$

**Theorem 3.4.5. (Derivative is well-defined and linear)**

*Proof.* Note that

$$df_p(\alpha'(0)) \stackrel{\text{def}}{=} \frac{d}{dt} f(\alpha(t))|_{t=0} = (f \circ \alpha)'(0)$$

Note that

■

### 3.5 First Fundamental Form

**Definition 3.5.1. (First Fundamental Form)** Given a regular surface  $S$  and  $p \in S$ , by the first fundamental form of  $S$  at  $p$ , we mean a function  $I_p : T_p(S) \rightarrow \mathbb{R}$  defined by

$$I_p(w) \triangleq w \cdot w$$

Given a local chart  $\mathbf{x}(u, v) : U \rightarrow S$ , we can define three real valued- function  $E, F, G : U \rightarrow \mathbb{R}$  by

$$\begin{aligned} E(u, v) &\triangleq |\partial_u \mathbf{x}(u, v)|^2 \\ F(u, v) &\triangleq \partial_u \mathbf{x}(u, v) \cdot \partial_v \mathbf{x}(u, v) \\ G(u, v) &\triangleq |\partial_v \mathbf{x}(u, v)|^2 \end{aligned}$$

These three functions help us compute the arc-length of a smooth curve that lies in  $\mathbf{x}(U)$ . Suppose  $\alpha(t)$  lies in  $\mathbf{x}(U)$ , and express

$$\alpha(t) = \mathbf{x}(u(t), v(t))$$

Note that the expression give us

$$\alpha'(t) = d\mathbf{x}(u'(t), v'(t)) = u'(t)\partial_u \mathbf{x}(u(t), v(t)) + v'(t)\partial_v \mathbf{x}(u(t), v(t)) \text{ where } q = \alpha(t)$$

We see that

$$\begin{aligned} \int_0^r |\alpha'(t)| dt &= \int_0^r \sqrt{\alpha'(t) \cdot \alpha'(t)} dt \\ &= \int_0^r \sqrt{(u'(t)\partial_u \mathbf{x}(q) + v'(t)\partial_v \mathbf{x}(q)) \cdot (u'(t)\partial_u \mathbf{x}(q) + v'(t)\partial_v \mathbf{x}(q))} dt \\ &= \int_0^r \sqrt{E(q)(u'(t))^2 + 2F(q)u'(t)v'(t) + G(q)(v'(t))^2} dt \end{aligned}$$

!!!! Show that given a stereographical projection  $\mathbf{x} : \mathbb{R}^2 \times 0 \rightarrow S^2 \setminus N$  preserve angle. Prove that given  $v, w \in \mathbb{R}^2$  starting at  $p \in \mathbb{R}^2$ , we have

$$\frac{d\mathbf{x}_q(v) \cdot d\mathbf{x}_q(w)}{|d\mathbf{x}_q(v)| |d\mathbf{x}_q(w)|} = v \cdot w$$

So, we can show that  $\mathbf{x} : \mathbb{R}^2 \rightarrow S^2 \setminus N$  satisfy

$$d\mathbf{x}(v) \cdot d\mathbf{x}(w) = C(v \cdot w) \text{ where } C \text{ is a constant}$$

is conformal (preserving angle).

## 3.6 HW4

### Question 37

3. Show that the equation of the tangent plane of a surface which is the graph of a differentiable function  $z = f(x, y)$ , at the point  $p_0 = (x_0, y_0)$ , is given by

$$z = f(x_0, y_0) + f_x(x_0, y_0)(x - x_0) + f_y(x_0, y_0)(y - y_0).$$

Recall the definition of the differential  $df$  of a function  $f: \mathbb{R}^2 \rightarrow \mathbb{R}$  and show that the tangent plane is the graph of the differential  $df_p$ .

*Proof.* The question first ask us to prove

$$T_{p_0}(S) = \{(x, y, z) \in \mathbb{R}^3 : z = f(x_0, y_0) + (x - x_0)\partial_x f(p_0) + (y - y_0)\partial_y f(p_0)\}$$

By premise of the question, we know there exists a global chart  $\mathbf{x}$

$$\mathbf{x}(x, y) \triangleq (x, y, f(x, y))$$

Compute

$$d\mathbf{x} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ \partial_x f & \partial_y f \end{bmatrix}$$

This tell us

$$\begin{aligned} T_{p_0}(S) &= (x_0, y_0, f(x_0, y_0)) + \text{span}\left(\begin{bmatrix} 1 \\ 0 \\ \partial_x f(p_0) \end{bmatrix}, \begin{bmatrix} 0 \\ 1 \\ \partial_y f(p_0) \end{bmatrix}\right) \\ &= \{(x, y, z) \in \mathbb{R}^3 : z = f(x_0, y_0) + (x - x_0)\partial_x f(p_0) + (y - y_0)\partial_y f(p_0)\} \text{ (done)} \end{aligned}$$

Compute

$$df_{p_0} = [\partial_x f(p_0) \quad \partial_y f(p_0)]$$

Then we see

$$T_{p_0}(S) = (x_0, y_0, f(x_0, y_0)) + \{(x, y, df_{p_0}(x, y)) \in \mathbb{R}^3 : (x, y) \in \mathbb{R}^2\}$$

where the right hand side is the graph of  $df_{p_0}$  when the origin is set to be  $(p_0, f(p_0))$

■

### Question 38

5. If a coordinate neighborhood of a regular surface can be parametrized in the form

$$\mathbf{x}(u, v) = \alpha_1(u) + \alpha_2(v),$$

where  $\alpha_1$  and  $\alpha_2$  are regular parametrized curves, show that the tangent planes along a fixed coordinate curve of this neighborhood are all parallel to a line.

*Proof.* WOLG, suppose the coordinate curve  $\gamma : I \rightarrow S$  is

$$\gamma(t) = \mathbf{x}(u_0, t)$$

Compute

$$d\mathbf{x} = [\alpha'_1(u) \quad \alpha'_2(v)] \quad \text{and} \quad d\mathbf{x}_{\gamma(t)} = [\alpha'_1(u_0) \quad \alpha'_2(v)]$$

Then see that

$$T_{\gamma(t)}(S) = \text{span}(\alpha'_1(u_0), \alpha'_2(t))$$

Since  $\alpha'_1(u_0)$  is fixed, we see  $T_{\gamma(t)}(S)$  are all parallel to  $\alpha'_1(u_0)$ . ■



## Question 39

**10. (Tubular Surfaces.)** Let  $\alpha: I \rightarrow \mathbb{R}^3$  be a regular parametrized curve with nonzero curvature everywhere and arc length as parameter. Let

$$\mathbf{x}(s, v) = \alpha(s) + r(n(s) \cos v + b(s) \sin v), \quad r = \text{const.} \neq 0, s \in I,$$

be a parametrized surface (the *tube* of radius  $r$  around  $\alpha$ ), where  $n$  is the normal vector and  $b$  is the binormal vector of  $\alpha$ . Show that, when  $\mathbf{x}$  is regular, its unit normal vector is

### 2. Regular Surfaces

$$N(s, v) = -(n(s) \cos v + b(s) \sin v).$$

*Proof.* Use Frenet-Serret Formula to compute

$$d\mathbf{x} = [\alpha' + r((- \kappa T - \tau B) \cos v + \tau N \sin v) \quad r(-N \sin v + B \cos v)]$$

We wish to show

$$-(N \cos v + B \sin v) \perp d\mathbf{x}(\mathbb{R}^2)$$

We then only have to prove

$$\begin{aligned} & (N \cos v + B \sin v) \perp -N \sin v + B \cos v \\ & \text{and } (N \cos v + B \sin v) \perp \alpha' + r((- \kappa T - \tau B) \cos v + \tau N \sin v) \end{aligned}$$

Because  $\{T, N, B\}$  form an orthonormal basis and  $\alpha'$  is just  $T$ , we have

$$(N \cos v + B \sin v) \cdot (-N \sin v + B \cos v) = -(\cos v \sin v) + \sin v \cos v = 0$$

and have

$$\begin{aligned} & (N \cos v + B \sin v) \cdot \left( \alpha' + r((- \kappa T - \tau B) \cos v + \tau N \sin v) \right) \\ &= r\tau \cos v \sin v - r\tau \sin v \cos v = 0 \text{ (done)} \end{aligned}$$

■

### Question 40

**13.** A *critical point* of a differentiable function  $f: S \rightarrow R$  defined on a regular surface  $S$  is a point  $p \in S$  such that  $df_p = 0$ .

**\*a.** Let  $f: S \rightarrow R$  be given by  $f(p) = |p - p_0|$ ,  $p \in S$ ,  $p_0 \notin S$  (cf. Exercise 5, Sec. 2-3). Show that  $p \in S$  is a critical point of  $f$  if and only if the line joining  $p$  to  $p_0$  is normal to  $S$  at  $p$ .

**b.** Let  $h: S \rightarrow R$  be given by  $h(p) = p \cdot v$ , where  $v \in R^3$  is a unit vector (cf. Example 1, Sec. 2-3). Show that  $p \in S$  is a critical point of  $f$  if and only if  $v$  is a normal vector of  $S$  at  $p$ .

*Proof.* Compute

$$dh_p(\alpha'(0)) = \frac{d}{dt} h(\alpha(t))|_{t=0} = v \cdot \alpha'(0)$$

In other words,

$$dh_p(w) = v \cdot w$$

This implies

$$dh_p(l) = 0, \forall l \in T_p(S) \iff v \perp T_p(S) \iff v \text{ is a normal vector of } S \text{ at } p$$

■

## Question 41

**15.** Show that if all normals to a connected surface pass through a fixed point, the surface is contained in a sphere.

*Proof.* WOLOG, suppose the fixed point is the origin. Let  $S$  be the regular surface. We are given the fact that any local chart  $\mathbf{x}(u, v)$  satisfy the equation

$$\mathbf{x}(u, v) = f_{\mathbf{x}}(u, v)N(u, v) \quad (3.2)$$

where  $f_{\mathbf{x}}(u, v)$  is a scalar-valued function and  $N(u, v)$  is the unit normal vector of  $S$  at  $\mathbf{x}(u, v)$ . We first show that

the distance of the surface to the origin is locally a constant

In other words, we wish to prove that any local chart  $\mathbf{x}(u, v)$  satisfy

$f_{\mathbf{x}}$  is constant on domain of  $\mathbf{x}$

Doing partial derivative on  $N \cdot N = 1$ , we see that

$$\partial_u N \perp N \text{ and } \partial_v N \perp N$$

This implies

$$\partial_u N, \partial_v N \in T_p(S)$$

We know

$$\partial_u \mathbf{x}, \partial_v \mathbf{x} \in T_p(S)$$

Now, doing partial derivative on both side of ( 3.2), we see

$$\partial_u \mathbf{x} = (\partial_u f_{\mathbf{x}})N + f_{\mathbf{x}}(\partial_u N) \text{ and } \partial_v \mathbf{x} = (\partial_v f_{\mathbf{x}})N + f_{\mathbf{x}}(\partial_v N)$$

and see

$$(\partial_u f_{\mathbf{x}})N = \partial_u \mathbf{x} - f_{\mathbf{x}}(\partial_u N) \in T_p(S) \text{ and } (\partial_v f_{\mathbf{x}})N = \partial_v \mathbf{x} - f_{\mathbf{x}}(\partial_v N) \in T_p(S)$$

Then because  $N \notin T_p(S)$ , we can conclude  $\partial_u f_{\mathbf{x}} = \partial_v f_{\mathbf{x}} = 0$ . This establish that  $f_{\mathbf{x}}$  is a constant. (done)

Note that the surface is connected, this implies that the distance of the surface to the origin is globally a constant, which implies the surface is contained in a sphere. ■

## Question 42

**18.** Prove that if a regular surface  $S$  meets a plane  $P$  in a single point  $p$ , then this plane coincides with the tangent plane of  $S$  at  $p$ .

*Proof.* WOLOG, suppose  $P$  is the  $x, y$ -plane,  $p$  is the origin and  $S \subseteq \{(x, y, z) \in \mathbb{R}^3 : z \geq 0\}$  (This can be achieved by a rigid motion). We wish to show

$$T_p(S) = P$$

Because  $\dim(T_p S) = \dim(P) = 2$ , we can reduce the problem into proving

$$T_p(S) \subseteq P$$

Fix  $w \in T_p(S)$ . We reduce the problem into

$$\text{proving } w \in P$$

Let  $\alpha : (-\epsilon, \epsilon) \rightarrow S$  satisfy

$$\alpha(0) = 0 \text{ and } \alpha'(0) = w$$

Express

$$\alpha(t) \triangleq (x, y, z)$$

Because  $S$  is above  $P$ , the  $x, y$ -plane, we know  $z$  attain minimum at 0. This implies  $z'(0) = 0$ , and implies  $\alpha'(0) = (x'(0), y'(0), 0) \in P$  (the  $x, y$ -plane) (done) ■

### Question 43

**\*20.** Show that the perpendicular projections of the center  $(0, 0, 0)$  of the ellipsoid

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} = 1$$

onto its tangent planes constitute a regular surface given by

$$\{(x, y, z) \in \mathbb{R}^3; (x^2 + y^2 + z^2)^2 = a^2x^2 + b^2y^2 + c^2z^2\} - \{(0, 0, 0)\}.$$

*Proof.* Let  $S$  be the ellipsoid. Let

$$E \triangleq \{(x, y, z) \in \mathbb{R}^3 : (x^2 + y^2 + z^2)^2 = a^2x^2 + b^2y^2 + c^2z^2\} \setminus O$$

Let  $E'$  be the perpendicular projections of  $O$  of  $S$  onto the tangent planes of  $S$ . We are required to prove

$$E' = E$$

We first prove

$$E' \subseteq E$$

Fix  $p_0 = (x_0, y_0, z_0) \in S$ . We first prove

$$T_{p_0}(S) = \{(x, y, z) \in \mathbb{R}^3 : \frac{xx_0}{a^2} + \frac{yy_0}{b^2} + \frac{zz_0}{c^2} = 1\} \quad (3.3)$$

Fix

$$f(x, y, z) = \frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2}$$

We have  $S = f^{-1}(1)$ . Compute

$$\nabla f(x, y, z) = \left( \frac{2x}{a^2}, \frac{2y}{b^2}, \frac{2z}{c^2} \right)$$

Then because  $T_{p_0}(S) \perp \nabla f(p_0)$ , we have

$$T_{p_0}(S) = \left\{ (x, y, z) \in \mathbb{R}^3 : \frac{xx_0}{a^2} + \frac{yy_0}{b^2} + \frac{zz_0}{c^2} = \frac{x_0^2}{a^2} + \frac{y_0^2}{b^2} + \frac{z_0^2}{c^2} = 1 \right\} \text{ (done)}$$

We know that the line  $L$  passing through  $O$  and perpendicular to  $T_{p_0}(S)$  can be parametrized by

$$L(t) = t \nabla f(p_0) \equiv t \left( \frac{x_0}{a^2}, \frac{y_0}{b^2}, \frac{z_0}{c^2} \right)$$

Compute

$$L(t) \in T_{p_0}(S) \implies t \left( \frac{x_0^2}{a^4} + \frac{y_0^2}{b^4} + \frac{z_0^2}{c^4} \right) = 1$$

This implies

$$t = \left( \frac{x_0^2}{a^4} + \frac{y_0^2}{b^4} + \frac{z_0^2}{c^4} \right)^{-1} \text{ and } q = t \left( \frac{x_0}{a^2}, \frac{y_0}{b^2}, \frac{z_0}{c^2} \right)$$

where  $q \in T_{p_0}(S)$  is the point to which  $O$  is perpendicular projected.

Express  $q = (x, y, z)$ . Now, we can reduce the problem into proving

$$(x^2 + y^2 + z^2)^2 = a^2 x^2 + b^2 y^2 + c^2 z^2$$

Compute

$$(x^2 + y^2 + z^2)^2 = \left( t^2 \left( \frac{x_0^2}{a^4} + \frac{y_0^2}{b^4} + \frac{z_0^2}{c^4} \right) \right)^2$$

Compute

$$a^2 x^2 + b^2 y^2 + c^2 z^2 = t^2 \left( \frac{x_0^2}{a^2} + \frac{y_0^2}{b^2} + \frac{z_0^2}{c^2} \right) = t^2 \quad \left( \because \frac{x_0^2}{a^2} + \frac{y_0^2}{b^2} + \frac{z_0^2}{c^2} = 1 \right)$$

We reduce the problem into proving

$$t^2 \left( \frac{x_0^2}{a^4} + \frac{y_0^2}{b^4} + \frac{z_0^2}{c^4} \right)^2 = 1$$

Note that  $t = (\frac{x_0^2}{a^4} + \frac{y_0^2}{b^4} + \frac{z_0^2}{c^4})^{-1}$  and we are done. (done)

It remains to prove

$$E \subseteq E'$$

Fix  $(x_1, y_1, z_1) \in S_1$ . Let

$$r \triangleq \sqrt{a^2 x_1^2 + b^2 y_1^2 + c^2 z_1^2}$$

We claim

$(x_1, y_1, z_1)$  is the projection of  $O$  onto the tangent plane of  $S$  at  $(\frac{a^2 x_1}{r}, \frac{b^2 y_1}{r}, \frac{c^2 z_1}{r})$

It is easily checked that  $(\frac{a^2 x_1}{r}, \frac{b^2 y_1}{r}, \frac{c^2 z_1}{r}) \in S$ . Let  $p = (\frac{a^2 x_1}{r}, \frac{b^2 y_1}{r}, \frac{c^2 z_1}{r})$ . Using (3.3), we have

$$T_p(S) = \{(x, y, z) \in \mathbb{R}^3 : \frac{xx_1 + yy_1 + zz_1}{r} = 1\}$$

It is now very clear that

$(x_1, y_1, z_1)$  as a vector is perpendicular to  $T_p(S)$

and we can use the fact  $(x_1, y_1, z_1) \in E$  to compute

$$\frac{x_1^2 + y_1^2 + z_1^2}{r} = \frac{\sqrt{a^2 x_1^2 + b^2 y_1^2 + c^2 z_1^2}}{r} = 1$$

This conclude  $(x_1, y_1, z_1) \in T_p(S)$ . (done) ■

## Question 44

1. Compute the first fundamental forms of the following parametrized surfaces where they are regular:
  - a.  $\mathbf{x}(u, v) = (a \sin u \cos v, b \sin u \sin v, c \cos u)$ ; ellipsoid.
  - b.  $\mathbf{x}(u, v) = (au \cos v, bu \sin v, u^2)$ ; elliptic paraboloid.
  - c.  $\mathbf{x}(u, v) = (au \cosh v, bu \sinh v, u^2)$ ; hyperbolic paraboloid.
  - d.  $\mathbf{x}(u, v) = (a \sinh u \cos v, b \sinh u \sin v, c \cosh u)$ ; hyperboloid of two sheets.

*Proof.* Let  $\alpha'(0) \in T_p(S)$  and express  $\alpha(t) = \mathbf{x}(u(t), v(t))$ . We have

$$\begin{aligned}
 I_p(\alpha'(0)) &= \alpha'(0) \cdot \alpha'(0) \\
 &= \left( u'(0) \partial_u \mathbf{x}(p) + v'(0) \partial_v \mathbf{x}(p) \right) \cdot \left( u'(0) \partial_u \mathbf{x}(p) + v'(0) \partial_v \mathbf{x}(p) \right) \\
 &= |\mathbf{x}_u(p)|^2 (u'(0))^2 + 2(\partial_u \mathbf{x}(p) \cdot \partial_v \mathbf{x}(p)) u'(0) v'(0) + |\mathbf{x}_v(p)|^2 (v'(0))^2 \\
 &\triangleq E(u'(0))^2 + 2F u'(0) v'(0) + G(v'(0))^2
 \end{aligned}$$

From now on, we compute only  $E, F, G$ .

(a) Compute

$$\begin{aligned}
 \partial_u \mathbf{x} &= (a \cos u \cos v, b \cos u \sin v, -c \sin u) \\
 \text{and } \partial_v \mathbf{x} &= (-a \sin u \sin v, b \sin u \cos v, 0)
 \end{aligned}$$

This give us

$$\begin{aligned}
 E &= |\partial_u \mathbf{x}|^2 = \cos^2 u (a^2 \cos^2 v + b^2 \sin^2 v) + c^2 \sin^2 u \\
 F &= \partial_u \mathbf{x} \cdot \partial_v \mathbf{x} = (-a^2 + b^2) \cos u \sin u \cos v \sin v \\
 G &= |\partial_v \mathbf{x}|^2 = \sin^2 u (a^2 \sin^2 v + b^2 \cos^2 v)
 \end{aligned}$$



(b) Compute

$$\partial_u \mathbf{x} = (a \cos v, b \sin v, 2u) \text{ and } \partial_v \mathbf{x} = (-a \sin v, b \cos v, 0)$$

This give us

$$E = |\partial_u \mathbf{x}|^2 = a^2 \cos^2 v + b^2 \sin^2 v + 4u^2$$

$$F = \partial_u \mathbf{x} \cdot \partial_v \mathbf{x} = \cos v \sin v (-a^2 + b^2)u$$

$$G = |\partial_v \mathbf{x}|^2 = u^2(a^2 \sin^2 v + b^2 \cos^2 v)$$

(c) Compute

$$\partial_u \mathbf{x} = (a \cosh v, b \sinh v, 2u) \text{ and } \partial_v \mathbf{x} = (a \sinh v, b \cosh v, 0)$$

This give us

$$E = |\partial_u \mathbf{x}|^2 = a^2 \cosh^2 v + b^2 \sinh^2 v + 4u^2$$

$$F = \partial_u \mathbf{x} \cdot \partial_v \mathbf{x} = (a^2 + b^2)u \cosh v \sinh v$$

$$G = |\partial_v \mathbf{x}|^2 = u^2(a^2 \sinh^2 v + b^2 \cosh^2 v)$$

(d) Compute

$$\partial_u \mathbf{x} = (a \cosh u \cos v, b \cosh u \sin v, c \sinh u) \text{ and } \partial_v \mathbf{x} = (-a \sinh u \sin v, b \sinh u \cos v, 0)$$

This give us

$$E = |\partial_u \mathbf{x}|^2 = \cosh^2 u (a^2 \cos^2 v + b^2 \sin^2 v) + c^2 \sinh^2 u$$

$$F = \partial_u \mathbf{x} \cdot \partial_v \mathbf{x} = \cosh u \sinh u \cos v \sin v (b^2 - a^2)$$

$$G = |\partial_v \mathbf{x}|^2 = \sinh^2 u (a^2 \sin^2 v + b^2 \cos^2 v)$$

■

### Question 45

3. Obtain the first fundamental form of the sphere in the parametrization given by stereographic projection (cf. Exercise 16, Sec. 2-2).

*Proof.* We are given

$$\mathbf{x}(u, v) = \left( \frac{4u}{u^2 + v^2 + 4}, \frac{4v}{u^2 + v^2 + 4}, \frac{2(u^2 + v^2)}{u^2 + v^2 + 4} \right)$$

Note that in Question 2.5.1, we have already given the complete formula of  $I_p(\alpha'(0))$ . We only have to compute  $E, F, G$ .

$$\begin{aligned}\partial_u \mathbf{x} &= \left( \frac{4(-u^2 + v^2 + 4)}{(u^2 + v^2 + 4)^2}, \frac{-8vu}{(u^2 + v^2 + 4)^2}, \frac{16u}{(u^2 + v^2 + 4)^2} \right) \\ \partial_v \mathbf{x} &= \left( \frac{-8uv}{(u^2 + v^2 + 4)^2}, \frac{4(-v^2 + u^2 + 4)}{(u^2 + v^2 + 4)^2}, \frac{16v}{(u^2 + v^2 + 4)^2} \right)\end{aligned}$$

Then compute

$$\begin{aligned}E &= \frac{16u^4 + 32u^2v^2 + 128u^2 + 16v^4 + 128v^2 + 256}{(u^2 + v^2 + 4)^4} \\ F &= 0 \\ G &= \frac{16v^4 + 32u^2v^2 + 128v^2 + 16u^4 + 128u^2 + 256}{(u^2 + v^2 + 4)^4}\end{aligned}$$

■

#### Question 46

**7.** The coordinate curves of a parametrization  $\mathbf{x}(u, v)$  constitute a *Tchebyshef net* if the lengths of the opposite sides of any quadrilateral formed by them are equal. Show that a necessary and sufficient condition for this is

$$\frac{\partial E}{\partial v} = \frac{\partial G}{\partial u} = 0.$$

*Proof.* For each  $v$ , define

$$\alpha_v(t) = \mathbf{x}(t, v)$$

WOLG, we are require to show

$$\forall r \in \mathbb{R}^+, \int_0^r |\alpha'_v(t)| dt \text{ is a constant in } v \iff \frac{\partial E}{\partial v} = 0$$

( $\longleftarrow$ )

Note that we have

$$u'(t) = 1 \text{ and } v'(t) = 0 \text{ if we write } \alpha_v(t) = \mathbf{x}(u(t), v(t))$$

Then, we have

$$\int_0^C |\alpha'_v(t)| dt = \int_0^C \sqrt{E(t, v)} dt$$

If  $\frac{\partial E}{\partial v} = 0$ , then for each  $v_1, v_2$ , we clearly have

$$\int_0^r |\alpha'_{v_1}(t)| dt = \int_0^r \sqrt{E(t, v_1)} dt = \int_0^r \sqrt{E(t, v_2)} dt = \int_0^r |\alpha'_{v_2}(t)| dt$$

( $\longrightarrow$ )

Suppose for all  $r \in \mathbb{R}^+$ , the function  $\int_0^r |\alpha'_v(t)| dt$  is a constant in  $v$ . We then can define  $f : \mathbb{R}^+ \rightarrow \mathbb{R}^+$  by

$$f(r) = \int_0^r |\alpha'_v(t)| dt \text{ for all } v$$

Differentiating  $f$ , we see

$$f'(r) = \sqrt{E(r, v)} \text{ for all } v$$

This tell us

$$E(r, v) \text{ is a constant in } v \text{ for all } r$$

which implies

$$\frac{\partial E}{\partial v} = 0 \text{ (done)}$$

■

### Question 47

**\*8.** Prove that whenever the coordinate curves constitute a Tchebyshef net (see Exercise 7) it is possible to reparametrize the coordinate neighborhood in such a way that the new coefficients of the first fundamental form are

$$E = 1, \quad F = \cos \theta, \quad G = 1,$$

where  $\theta$  is the angle of the coordinate curves.

*Proof.* Note that  $\frac{\partial E}{\partial v} = \frac{\partial G}{\partial u} = 0$  implies

$E$  stay constant in  $v$  and  $G$  stay constant in  $u$

In other words,  $E$  can be treated as a function of  $u$  and  $G$  can be treated as a function of  $v$ . Let

$$\bar{u}(u) = \int_0^u \sqrt{E(t)} dt \text{ and } \bar{v}(v) = \int_0^v \sqrt{G(t)} dt$$

Reparametrize by

$$\mathbf{x}(u(\bar{u}), v(\bar{v}))$$

By Chain Rule and Single-Variable Inverse Function Theorem, we have

$$\partial_{\bar{u}} \mathbf{x} = \frac{1}{\sqrt{E(u)}} \partial_u \mathbf{x} \text{ and } \partial_{\bar{v}} \mathbf{x} = \frac{1}{\sqrt{G(v)}} \partial_v \mathbf{x}$$

This give us

$$\bar{E} = \partial_{\bar{u}} \mathbf{x} \cdot \partial_{\bar{u}} \mathbf{x} = \frac{E(u)}{E(u)} = 1 \text{ and } \bar{G} = \partial_{\bar{v}} \mathbf{x} \cdot \partial_{\bar{v}} \mathbf{x} = \frac{G(v)}{G(v)} = 1$$

Now, by CS-inequality, we know  $\bar{F} = \partial_{\bar{u}} \mathbf{x} \cdot \partial_{\bar{v}} \mathbf{x} \in (-1, 1)$ . Then there must exists  $\theta$  such that  $\bar{F} = \cos \theta$ . ■

## Question 48

**11.** Let  $S$  be a surface of revolution and  $C$  its generating curve (cf. Example 4, Sec. 2-3). Let  $s$  be the arc length of  $C$  and denote by  $\rho = \rho(s)$  the distance to the rotation axis of the point of  $C$  corresponding to  $s$ .

**a.** (*Pappus' Theorem.*) Show that the area of  $S$  is

$$2\pi \int_0^l \rho(s) ds,$$

where  $l$  is the length of  $C$ .

**b.** Apply part a to compute the area of a torus of revolution.

*Proof.* (a)

Because  $S$  is a surface of revolution, we have an almost global chart

$$\mathbf{x}(\theta, s) = (\cos \theta f(s), \sin \theta f(s), g(s))$$

where

$$f(s) = \rho(s) \text{ and } (f'(s))^2 + (g'(s))^2 = 1$$

Compute

$$\partial_\theta \mathbf{x} = (-\sin \theta f(s), \cos \theta f(s), 0) \text{ and } \partial_s \mathbf{x} = (\cos \theta f'(s), \sin \theta f'(s), g'(s))$$

This let us compute

$$E = |\partial_\theta \mathbf{x}|^2 = |f(s)|^2 = \rho(s)^2$$

$$F = \partial_\theta \mathbf{x} \cdot \partial_s \mathbf{x} = 0$$

$$G = |\partial_s \mathbf{x}|^2 = (f'(s))^2 + (g'(s))^2 = 1$$

Now we see that the area  $A(S)$  of  $S$  is exactly

$$A(S) = \int_0^{2\pi} \int_0^l \sqrt{EG - F^2} ds d\theta = 2\pi \int_0^l \rho(s) ds$$

(b)

Note that

$$(f(s), g(s)) \triangleq (a + r \cos \frac{s}{r}, a + r \sin \frac{s}{r}) \text{ where } f(s) \equiv \rho(s)$$

satisfy all the condition. Then we can compute the surface area of the torus by

$$2\pi \int_0^{2\pi r} (a + r \cos(\frac{s}{r})) ds = 4\pi^2 r a$$



### Question 49

- 14. (Gradient on Surfaces.)** The *gradient* of a differentiable function  $f: S \rightarrow R$  is a differentiable map  $\text{grad } f: S \rightarrow R^3$  which assigns to each point  $p \in S$  a vector  $\text{grad } f(p) \in T_p(S) \subset R^3$  such that

$$\langle \text{grad } f(p), v \rangle_p = df_p(v) \quad \text{for all } v \in T_p(S).$$

Show that

- a.** If  $E, F, G$  are the coefficients of the first fundamental form in a parametrization  $\mathbf{x}: U \subset R^2 \rightarrow S$ , then  $\text{grad } f$  on  $\mathbf{x}(U)$  is given by

$$\text{grad } f = \frac{f_u G - f_v F}{EG - F^2} \mathbf{x}_u + \frac{f_v E - f_u F}{EG - F^2} \mathbf{x}_v.$$

In particular, if  $S = R^2$  with coordinates  $x, y$ ,

$$\text{grad } f = f_x e_1 + f_y e_2,$$

where  $\{e_1, e_2\}$  is the canonical basis of  $R_2$  (thus, the definition agrees with the usual definition of gradient in the plane).

- b.** If you let  $p \in S$  be fixed and  $v$  vary in the unit circle  $|v| = 1$  in  $T_p(s)$ , then  $df_p(v)$  is maximum if and only if  $v = \text{grad } f / |\text{grad } f|$  (thus,  $\text{grad } f(p)$  gives the direction of maximum variation of  $f$  at  $p$ ).
- c.** If  $\text{grad } f \neq 0$  at all points of the level curve  $C = \{q \in S; f(q) = \text{const.}\}$ , then  $C$  is a regular curve on  $S$  and  $\text{grad } f$  is normal to  $C$  at all points of  $C$ .

*Proof.* (a)

Suppose  $\nabla f = \frac{f_u G - f_v F}{EG - F^2} \mathbf{x}_u + \frac{f_v E - f_u F}{EG - F^2}$ . First observe

$$\begin{aligned} \langle \nabla f, \mathbf{x}_u \rangle &= \frac{f_u G - f_v F}{EG - F^2} E + \frac{f_v E - f_u F}{EG - F^2} F \\ &= \frac{f_u (GE - F^2)}{EG - F^2} \\ &= f_u = \frac{\partial}{\partial u} (f \circ \mathbf{x}) = df(\mathbf{x}_u) \end{aligned}$$

The justification of the last inequality is as followed. Define

$$\alpha(t) = \mathbf{x}(u_0 + t, v_0)$$

We have

$$\alpha(0) = \mathbf{x}(u_0, v_0) \text{ and } \alpha'(0) = d\mathbf{x}_{(u_0, v_0)}(1, 0) = \mathbf{x}_u(u_0, v_0)$$

Now

$$df_{\mathbf{x}(u_0, v_0)}(\mathbf{x}_u(u_0, v_0)) \stackrel{\text{def}}{=} \left. \frac{d}{dt} (f \circ \alpha(t)) \right|_{t=0} = \frac{d}{dt} ((f \circ \mathbf{x})(u_0 + t, v_0)) = \frac{\partial}{\partial u} (f \circ \mathbf{x})(u_0, v_0)$$

This justified the  $\langle \nabla f, \mathbf{x}_u \rangle = df(\mathbf{x}_u)$ .

Similarly, we have

$$\langle \nabla f, \mathbf{x}_v \rangle = df(\mathbf{x}_v)$$

Now, for all  $w \in T_p(S)$ , we see that

$$\begin{aligned} \langle \nabla f(p), w \rangle &= \langle \nabla f(p), c_u \mathbf{x}_u(p) + c_v \mathbf{x}_v(p) \rangle \quad (\text{ for a unique pair } c_u, c_v \in \mathbb{R} ) \\ &= c_u \langle \nabla f(p), \mathbf{x}_u(p) \rangle + c_v \langle \nabla f(p), \mathbf{x}_v(p) \rangle \\ &= c_u df_p(\mathbf{x}_u(p)) + c_v df_p(\mathbf{x}_v(p)) \\ &= df_p(c_u \mathbf{x}_u(p) + c_v \mathbf{x}_v(p)) = df_p(w) \end{aligned}$$

If  $S = \mathbb{R}^2$  with coordinates  $x, y$ , we can easily compute

$$\mathbf{x}_x = (1, 0) \text{ and } \mathbf{x}_y = (0, 1)$$

and

$$E = 1 \text{ and } F = 0 \text{ and } G = 1$$

Then from the formula of  $\nabla f$  we just derived, we have

$$\nabla f = f_x(1, 0) + f_y(0, 1) \equiv f_x e_1 + f_y e_2$$

(b)

By C-S inequality, we see that

$$df_p(v) \equiv \langle \nabla f(p), v \rangle \text{ reach maximum if and only if } v = c_0 \nabla f(p) \text{ for some positive } c_0$$

It then come very clear, under the constraint  $|v| = 1$ , that  $c_0$  must be  $\frac{1}{|\nabla f(p)|}$ .

(c)

Let that constant be  $c_0$ , and let  $p = \mathbf{x}(q) \in C$ . Define  $g : \mathbb{R}^{2+1} \rightarrow \mathbb{R}$  by

$$g(u, v, t) = f(\mathbf{x}(u, v)) - t$$

Check that

$$\partial_t g = -1 \neq 0$$

Then by Implicit function theorem, there exists a function  $h : U \subseteq \mathbb{R}^2 \rightarrow \mathbb{R}$  such that

$$h(q) = c_0 \text{ and } g(u, v, h(u, v)) = 0 \text{ for all } (u, v) \in U$$

We now see

$$C = (h \circ \mathbf{x}^{-1})^{-1}(c_0) \text{ which is a regular preimage}$$

This established that  $C$  is a regular curve.

Locally parametrize  $\gamma(t) \subseteq C$ . Because  $f \circ \gamma$  stay constant, we see

$$0 = df_{\gamma(t)}(\gamma'(t)) = \langle \nabla f(\gamma(t)), \gamma'(t) \rangle$$

This then implies  $\nabla f(\gamma(t))$  is perpendicular to  $\gamma'(t)$ , thus perpendicular to  $C$ . ■