

Differential Geometry Lecture Notes



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Preface

Textbook Reference

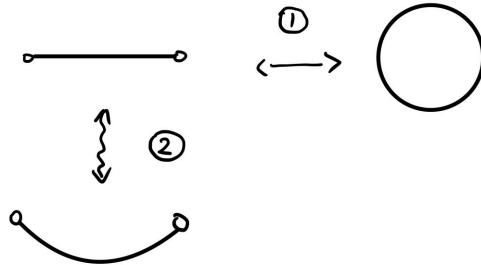
- (1) Do Carmo: Differential Geometry of Curves and Surfaces.
- (2) Sebastián Montiel, Antonio Ros: Curves and Surfaces.
- (3) Chinese Title, add later

Course Introduction

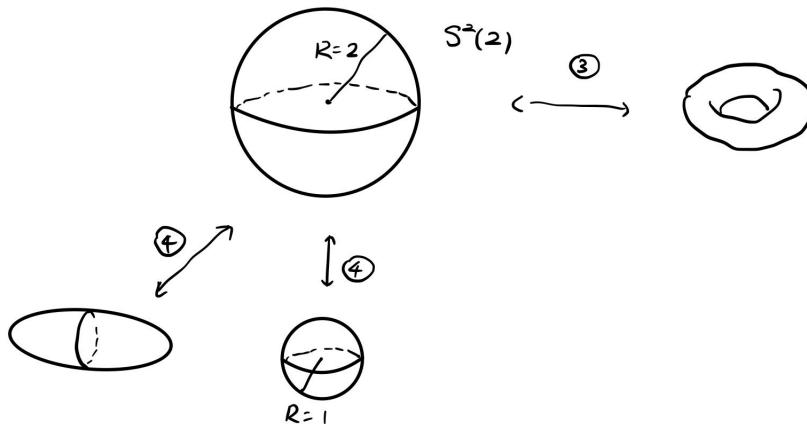
The Goal of this course is to study the “differential geometry of curves and surfaces”.

- **Geometry:** How is a geometric object curved / How to measure the curvedness of a geometric object?

Example. In the illustration below, (1) differs by “topology”. In (2), they are topologically the same, while the lower curve is “more curved” than the upper curve.



Example. (3) differs by “topology”, but in (4) $\mathbb{S}^2(1)$ is more curve than $\mathbb{S}^2(2)$, even topologically they are the same.(either homeomorphically or diffeomorphically).



The “Curved property” also affects geometric quantities, like length, area, volume, angle between the curves, etc.

Local Geometry: How does a “curved” space look like in a neighborhood of a point?

Global Geometry: If we know how a “curved space” is look like at each point, can we observe how such space looks like globally? This is usually related to topological problems.

• **Differential:** In this course, by “smoothness” we mean the geometric objects we’ll study are “nice” enough so we can apply “calculus” tools to study them.

Main tool: Calculus! We’ll see how powerful calculus is in this course, especially, like the maximal principle, integration by parts(stoke’s theorem), Taylor’s expansion, implicit function theory, etc.



Queastion: How to tell the “smoothness”? (Need to find good parametrization) Finding a good “gauge”(that is “coordinate”) to work with is also an important question in geometry.

• Curves: 1-d geometric object.

Surfaces: 2-d geometric object.

Remark. In this course, we only focus on curves and surfaces in \mathbb{R}^3 . However, as a training on preparing for later geometry course, I suggest you also try to think about the ambient space is \mathbb{S}^3 or \mathbb{H}^3 .

• **Intrinsic geometry:** Study the geometric object without considering the ambient space. This begins from the Gauss's elegant theorem and was developed by Riemann.

Example. Consider the unit sphere \mathbb{S}^2

Extrinsic geometry: view it as $x^2 + y^2 + z^2 = 1$ in \mathbb{R}^3 .

Intrinsic geometry: (θ, φ) or (φ, θ) are “essential” coordinates on \mathbb{S}^2 .

$$ds^2 = d\varphi^2 + (\sin \varphi)^2 d\theta^2$$

(Caution: (θ, φ) is outer normal, while (φ, θ) is inner normal.)

- Useful / Common techniques:

1) Comparison: compare the studied geometric object with “model space”. It’s very important to study examples in geometry. As a suggestion you are expected to spend time to play with \mathbb{S}^2 . For example: How is \mathbb{S}^2 curved? What’s the shortest line in \mathbb{S}^2 ? How many symmetries are there on \mathbb{S}^2 ? Can you add “extra structure” on \mathbb{S}^2 to make it a complex object? Is this “extra structure” “rigid”? What/s the “moment map” on \mathbb{S}^2 ? Does there exist a “holomorphic” map from \mathbb{S}^2 to a torus, or a surface of arbitrary genus?

If we consider an “Energy minimizing map” from \mathbb{S}^2 to \mathbb{S}^2 , what can we say about such map?(It is holomorphic/antiholomorphic.)

After you have learned Riemann Geometry, you’ll see an energy minimizing map from \mathbb{S}^2 to a Riemannian manifold must be an angle-preserving map(conformal map).

What kinds of 2-d geometric space could be \mathbb{S}^2 ?(this is a global geometry problem.)(i.e. what kinds of geometric conditions can characterize \mathbb{S}^2 ?)

- 2) To study higher dimensional objects,it’s also important to understand lower dimensional objects, and it’s also important to understand lower dimensional objects contained in the studied objects.
- 3) Study “functions” (more generally sections, including functions, vector fields, differential forms, etc.) on a given geometric object.

Example. On a closed surface ($\mathbb{S}^2, \mathbb{T}^2, \Sigma_g$)(compact without boundary) there is no non-constant harmonic function.(i.e. $\Delta u = 0$)(Analysis will get involved.)

We usually care about those functions related to geometry, such as distance functions, curvature-related functions, etc.

Example (More trivial than the last one). Consider $f''(x) = 0$, what can you say of the solution of it when x lies on a line and when x lies on a circle?

Chapter 1

Differential Geometry of Curves

1.1 Linear algebra convention and its geometric explanation

- We use “ROW VECTOR” in this course, *i.e.*

$$v \in \mathbb{R}^n, v = (v_1, v_2, \dots, v_n)$$

- let $e_1 = (1, 0, \dots, 0), \dots, e_n = (0, \dots, 1)$ be the standard basis, then

$$v = \sum_{i=1}^n v^i e_i = \begin{bmatrix} v^1 & v^2 & \cdots & v^n \end{bmatrix} \begin{bmatrix} e_1 \\ e_2 \\ \vdots \\ e_n \end{bmatrix}$$

- $\varphi: \mathbb{R}^n \rightarrow \mathbb{R}^n$ (non-degenerate) linear map

$$v \mapsto \varphi(v) = v \cdot A.$$

This corresponds to the right action of $GL(n, \mathbb{R})$ on \mathbb{R}^n .

$$\Rightarrow \varphi(e_i) = e_j \cdot A = \sum_{i=1}^n A_j^i e_i \text{ (taking the j-th row of } A\text{)}$$

$$A_j^i \left\{ \begin{array}{l} \text{upper index: column index} \\ \text{lower index: row index} \end{array} \right.$$

$$\Rightarrow \varphi \begin{bmatrix} e_1 \\ e_2 \\ \vdots \\ e_n \end{bmatrix} = \begin{bmatrix} \varphi(e_1) \\ \varphi(e_2) \\ \vdots \\ \varphi(e_n) \end{bmatrix} = \begin{bmatrix} e_1 \cdot A \\ e_2 \cdot A \\ \vdots \\ e_n \cdot A \end{bmatrix} = A \begin{bmatrix} e_1 \\ e_2 \\ \vdots \\ e_n \end{bmatrix}$$

Remark (Important!). In row vector convention, a non-degenerate linear map corresponds to the right action of $GL(n, \mathbb{R})$ on \mathbb{R}^n . But this induces left action of $GL(n, \mathbb{R})$ on the orthonormal basis (frame) $\{e_1, e_2, \dots, e_n\}$. This phenomenon provides an important example in differential geometry, which will be explained later in the theory of principle bundle. (*i.e.* let G be a lie group, $G \curvearrowright M$ being a right action, where M is a differentiable manifold, then this right action induces a left action of G on the frame bundle of M .)



Let $\{\tilde{e}_1, \dots, \tilde{e}_n\}$ be another basis of \mathbb{R}^n . Let f be the corresponding linear map, i.e.

$$f \begin{bmatrix} e_1 \\ e_2 \\ \vdots \\ e_n \end{bmatrix} = \begin{bmatrix} \tilde{e}_1 \\ \tilde{e}_2 \\ \vdots \\ \tilde{e}_n \end{bmatrix} = B \cdot \begin{bmatrix} e_1 \\ e_2 \\ \vdots \\ e_n \end{bmatrix}$$

$$\Rightarrow \tilde{e}_k = \sum_{j=1}^n B_k^j e_j$$

We compare the matrix of φ in terms of $\{\tilde{e}_1, \dots, \tilde{e}_n\}$

$$\varphi \begin{bmatrix} \tilde{e}_1 \\ \vdots \\ \tilde{e}_n \end{bmatrix} = \varphi \left[B \begin{bmatrix} \tilde{e}_1 \\ \vdots \\ e_n \end{bmatrix} \right] = B \cdot \varphi \begin{bmatrix} e_1 \\ \vdots \\ e_n \end{bmatrix} \quad (\text{linearity of } \varphi)$$

$$= BA \begin{bmatrix} e_1 \\ \vdots \\ e_n \end{bmatrix} = BAB^{-1} \begin{bmatrix} \tilde{e}_1 \\ \vdots \\ e_n \end{bmatrix}$$

Note in this case,

$$(\varphi \circ f) \begin{bmatrix} e_1 \\ \vdots \\ e_n \end{bmatrix} = BA \begin{bmatrix} e_1 \\ \vdots \\ e_n \end{bmatrix}$$

In terms of entries,

$$\varphi(\tilde{e}_k) = \varphi \left(\sum_{j=1}^n B_k^j e_j \right) = \sum_{j=1}^n B_k^j \varphi(e_j) \quad (\text{linearity})$$

$$= \sum_{i,j=1}^n B_k^j A_j^i e_i = \sum_{i,j,p=1}^n B_k^j A_j^i (B^{-1})_i^p \tilde{e}_p$$

Remark. This computation tells that the row vector convention yields to the fact that $GL(n, \mathbb{R})$ acting on itself from the right when we consider the action of $GL(n, \mathbb{R})$ on \mathbb{R}^n . In modern Geometry, it's more common to use column vector as convention. This row vector convention was adopted by S.S. Chern and also Do Cormo's book.

1.2 Parametrized Curves

Definition 1.2.1. Let $I = (a, b)$, if $\alpha: I \rightarrow \mathbb{R}^3$ is a C^∞ map,

$$t \mapsto (x(t), y(t), z(t))$$

then $\alpha(t)$ is a parametrized differentiable curve in \mathbb{R}^3 . The image of α is called the trace of the curve.

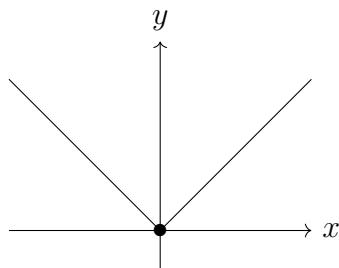
Remark.



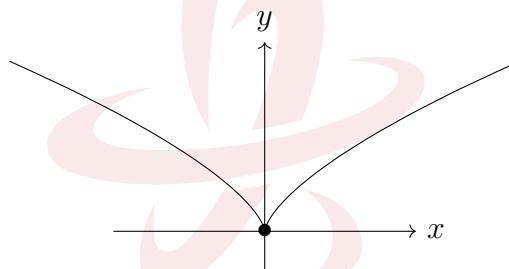
- 1) a, b could be finite number or infinity.
- 2) Same curve may have different parametrizations.
- 3) The parametrization automatically gives the direction of the motion on the curve.
- 4) “Differentiable” just means $\alpha(t)$ is a C^∞ map, it does not say the (trace of) curve can not have singularities.

Example.

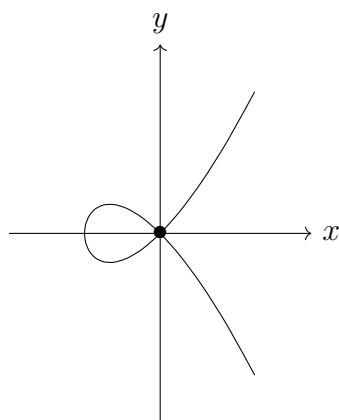
(1) $\alpha(t) = (t, |t|)$ is not a differentiable curve.



(2) $\alpha = (t^3, t^2)$ is a differentiable curve. It can be also given by a equation $y^3 = x^2$, which is a cuspidal cubic curve.



(3) $\alpha(t) = (t^2 - 1, t^3 - t)$. This parametrization appears in the “blow-up” process of $y^2 = x^3 + x^2$. Here “blow-up” is introducing tangents to separate points.



Remark. (2) and (3) above may be the first examples you'll see in an algebraic geometry course.



Question: At the origin, what can you observe on (2) and (3)?

Answer: (2) $\alpha'(0) = 0$. (3) α is not one to one, but $\alpha'(0) \neq 0$.

Question: Define a differentiable curve in \mathbb{R}^3 and \mathbb{S}^n .

Remark. Among above differentiable parametrizations, (2) and (3) are differentiable curves. However, if we take $\beta(t) = (t, t^{2/3})$, this also parametrizes (2), but it's not a differentiable curve!

Definition 1.2.2. Let $\alpha(t): I \rightarrow \mathbb{R}^3$ be a parametrized differentiable curve, then at $t_0 \in I$.

$$\alpha'(t_0) = (x'(t_0), y'(t_0), z'(t_0))$$

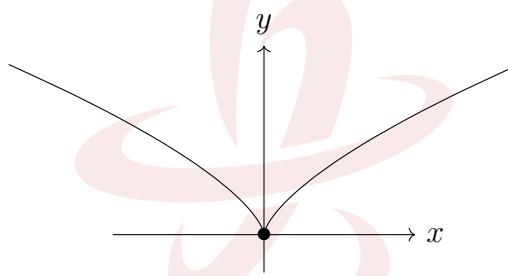
is the velocity of $\alpha(t)$ at t_0 .

- (1) If $\alpha'(t_0) \neq 0$, we call $\alpha(t_0)$ a regular point.
- (2) If $\alpha'(t_0) = 0$, we call $\alpha(t_0)$ a singular point.
- (3) If for all $t \in I$, $\alpha'(t) \neq 0$, we call $\alpha(t)$ a regular curve.

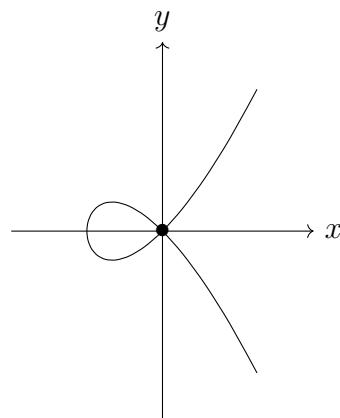
Question: What can you say about C^∞ parametrization for a regular curve?

Regular curve \iff at each point, there is a unique tangent line.

Example. $\alpha(t) = (t^3, t^2)$ is not a regular curve. (Since $\alpha'(0) = 0$)

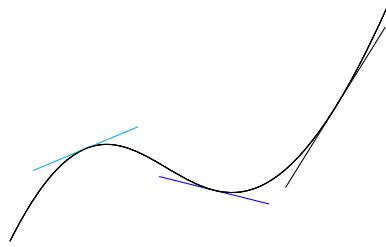


Example. $\alpha(t) = (t^2 - 1, t^3, t)$ is a regular curve.



Definition 1.2.3. Let $\alpha(t)$ be a regular curve, then the tangent line at t_0 is

$$l(t) = \alpha(t_0) + \alpha'(t_0)(t - t_0)$$



Definition 1.2.4. Let $\alpha(t)$ be a regular curve, the arc-length of $\alpha(t)$ is

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

Then $s'(t) = |\alpha'(t)|$

Question What's $|\alpha'(t)|$?

$\alpha(t): I \rightarrow \mathbb{R}^3$ is a curve in \mathbb{R}^3 . Here on \mathbb{R}^3 , as the Euclidean space, we always assume the standard Euclidean inner product on it, i.e. $\forall u = (u_1, u_2, u_3), v = (v_1, v_2, v_3)$

$$\langle u, v \rangle = u_1 v_1 + u_2 v_2 + u_3 v_3 = \sum_{i,j=1}^3 \delta_{ij} u_i v_j$$

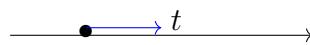
Let $\alpha(t) = (x(t), y(t), z(t))$, $\alpha'(t) = (x'(t), y'(t), z'(t))$, then $|\alpha'(t)| = \sqrt{\langle \alpha'(t), \alpha'(t) \rangle}$

Exercise. Review vector Calculations, such as dot product, cross product and their properties, especially geometric meaning of these calculation, such as length, area, volume, angle, orientation, etc.

Question: Can you define the arclength of a regular curve in \mathbb{R}^n ? How about on \mathbb{S}^n ?

- Arclength parameter(an intrinsic parametrization of a curve)

Example. On a straight line, $x=t$ describes the distance of the point away from the origin.



On a general curve, we also want “some” parameter, which describes the arclength of point away from the initial point. This can happen iff $|\alpha'(t)| = 1$, i.e. a point on the curve moves in a unit speed.

$$\Rightarrow s(t) = \int_0^t dt = t.$$

Question: For a given regular curve $\alpha(t): I \rightarrow \mathbb{R}^3$, how to find such parameter?

Answer: $s(t) = \int_{t_0}^t |\alpha'(t)| dt$ is a function in t , and $s'(t) = |\alpha'(t)| \neq 0$ (because the curve is regular). By the implicit function theorem, there is a function

$$t = t(s), t'(s) = \frac{1}{|\alpha'(t)|}.$$

This implies that

$$\begin{aligned}\alpha(t) &= \alpha(t(s)) = (x(t(s)), y(t(s)), z(t(s))) \\ |\alpha'(s)| &= |\alpha'(t)t'(s)| = |\alpha'(t)| |t'(s)| = 1\end{aligned}$$

Convention In this course, we only consider differentiable regular curves, which are parametrized by the arclength (for convenience).

Remark. In this course, we only consider the curve without self-intersecting points, i.e. curves “embedded into” \mathbb{R}^3 . Here “embedded” means $d\alpha$ is a linear isomorphism and α is homeomorphic to its image.

1.3 Local theory of a regular space curve

Goal. Describe a space curve by using geometric quantities.

Question. How to make a space curve?

Starting with a straight line, we can bend it and twist it in a given way to produce a space curve.

- Bending the line \rightarrow “curvature”.
- Twisting \rightarrow “torsion”.
- Their relations are contained in Frenet formula.
- Conversely, fundamental theorem of the local theory of curves tells, once we’re given two functions, $\kappa(s), \tau(s)$, we can describe a unique curve in \mathbb{R}^3 up to a rigid motion, s.t. $\kappa(s)$ is its curvature and $\tau(s)$ is its torsion.

Recall: In Calculus, if $y = f(x)$ represents a curve, then $f''(x)$ tells the convexity of the curve. It measures how fast the velocity changes. It’s also related to how straight line is bent.

Let $\alpha: I \rightarrow \mathbb{R}^2$ be a regular plane curve, parametrized by arc length, i.e. $|\alpha'(s)| = 1$. Then $\langle \alpha'(s), \alpha''(s) \rangle = 0$, and hence $\alpha''(s) \perp \alpha'(s)$. For a plane curve, we take normal of the curve to be counterclockwise 90° rotation of the tangent vector.

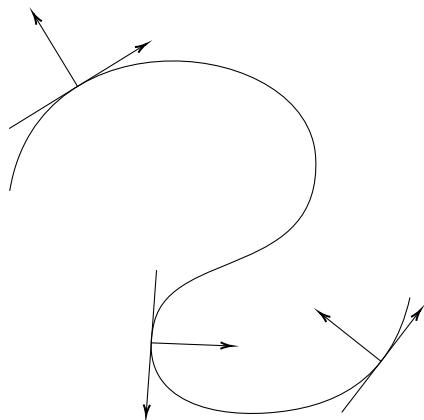


Figure 1.3.1: Example of a plane curve and its tangent and normal

Let N be the unit normal vector along $\alpha(s)$, we have

$$\langle \alpha''(s), N(s) \rangle = \pm |\alpha''(s)|.$$



Definition 1.3.1. The curvature of a plane curve $\alpha(s)$ is defined as

$$\kappa(s) = \langle \alpha''(s), N(s) \rangle.$$

Definition 1.3.2. Further we denote T be the unit tangent vector, then the Frenet equation of $\alpha(s)$ is

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

Note that

$$\langle T', N \rangle = \kappa \implies \langle T, N' \rangle = -\kappa.$$

- $\kappa > 0 \implies$ the point on the curve moves counterclockwise direction or say “to its left”.
- $\kappa < 0 \implies$ the point on the curve moves clockwise direction or say “to its right”.

Question. For the curve in fig. 1.3.1, can you tell where $\kappa > 0$ and where $\kappa < 0$ without doing calculation?

Remark. The sign of the curvature of the plane curve is caused by the direction convention of the unit normal vector. This could change according to the orientation of a curve.

Next, we take a look at the geometric meaning of $|\alpha''(s)|$ at some point $\alpha(s_0)$. By definition:

$$|\alpha''(s_0)| = \lim_{h \rightarrow 0} \left| \frac{\alpha'(s_0 + h) - \alpha'(s_0)}{h} \right|.$$

We have

$$\begin{aligned} |\alpha'(s_0 + h) - \alpha'(s_0)| &= \left(|\alpha'(s_0 + h)|^2 + |\alpha'(s_0)|^2 - 2 \langle \alpha'(s_0 + h), \alpha'(s_0) \rangle \right)^{\frac{1}{2}} \\ &= (2 - 2 \cos \theta_h)^{\frac{1}{2}} \\ &= (2 - 2(1 - \frac{1}{2}\theta_h^2) + \tilde{o}(\theta_h)^4)^{\frac{1}{2}} \\ &= (\theta_h^2 + \tilde{o}(\theta_h)^4)^{\frac{1}{2}}. \end{aligned}$$

Hence,

$$|\alpha''(s_0)| = \lim_{h \rightarrow 0} \left| \frac{\alpha'(s_0 + h) - \alpha'(s_0)}{h} \right| = \lim_{h \rightarrow 0} \left| \frac{\theta_h}{h} \right| = |\theta'(s_0)|.$$

i.e. $|\alpha''(s)|$ measures the changing rate of angle of tangents.

In fact, for a plane curve, let θ be the angle between $\alpha'(s_0)$ and $\alpha'(s)$, then

$$\langle \alpha'(s), \alpha'(s_0) \rangle = \cos \theta_s \implies \langle \alpha''(s), \alpha'(s_0) \rangle = -\sin \theta_s \cdot \theta'_s.$$

Notice that $\cos \theta_s$ is the projection of $\alpha'(s_0)$ on the tangent $\alpha'(s)$, hence

$$\sin \theta_s = \langle \alpha'(s_0), N(s) \rangle.$$

On the other hand, $\alpha''(s) = T'(s) = \kappa(s)N(s) = \pm|\alpha''(s)|N(s)$, this gives $\theta'_s = \pm|\alpha''(s)|$.

Let $\alpha: I \rightarrow \mathbb{R}^3$ be a space curve, parametrized by arclength, i.e. $|\alpha'(s)| = 1$, we also have $\langle \alpha'(s), \alpha''(s) \rangle = 0$, i.e. $\alpha''(s) \perp \alpha'(s)$.

Unlike case of dim 2, it does not make sense to prescribe a normal vector of a curve. However, from above discussion, we see the geometric meaning of $|\alpha''(s)|$ is the measure of how fast the point on the curve leaving the straight line. We came into following definition:



Definition 1.3.3. The *curvature* of a regular space curve $\alpha(s)$ parametrized by arclength is defined as

$$\kappa(s) = |\alpha''(s)|.$$

And the unit normal vector at $\alpha(s)$ is

$$N = \frac{\alpha''(s)}{|\alpha''(s)|}, \quad \text{for } |\alpha''(s)| > 0.$$

Remark.

- If $|\alpha''(s)| \equiv 0$ then α must be a straight line, and all unit normal vectors lie on a unit circle $\perp \alpha$.
- If $|\alpha''(s_0)| = 0$, we call s_0 a singular point of order 1. (Note. s_0 s.t. $|\alpha(s_0)| = 0$ is called a singular point of order 0) At such points, there is no well-defined normal vector.

Definition 1.3.4. The plane determined by T, N is called the *osculating plane* of $\alpha(s)$. The unit normal vector of the osculating plane

$$B = T \times N$$

is called *binormal vector*.

Remark.

- $\{T, N, B\}$ satisfies the right-hand rule.
- $|B'|$ measures how fast the point leaves the osculating plane.

If we denote θ_h be the angle between $B(s_0 + h)$ and $B(s_0)$, similar to former calculation, we have

$$\begin{aligned} |B'(s_0)| &= \lim_{h \rightarrow 0} \left| \frac{B(s_0 + h) - B(s_0)}{h} \right| \\ &= \lim_{h \rightarrow 0} \left| \frac{\sqrt{2 - 2 \cos \theta_h}}{h} \right| \\ &= |\theta'_{s_0}|. \end{aligned}$$

As we saw, at each (non-singular) point on a space curve $\alpha(s)$, we can associate an oriented orthonormal frame $\{T, N, B\}$.

Question. How these three vector fields are related to the geometry of the curve?

By definition, we write 0-order info of $\{T, N, B\}$, i.e.

$$\begin{cases} T = \alpha' \\ N = \frac{\alpha''}{|\alpha''|} \\ B = T \times N \end{cases} \implies \begin{aligned} T' &= \alpha'' = \kappa N \\ B' &= T' \times N + T \times N' = T \times N' \end{aligned} .$$

Since $|B| = 1$, we have $B' \perp B$. Also, from above we see $B' \perp T$, hence $B' \parallel N$.



Definition 1.3.5. We define

$$B' = \tau N.$$

Here $\tau(s)$ is called the torsion of $\alpha(s)$.

Next, we also want to find N' . $N = B \times T$ gives

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

Theorem 1.3.6. *The fundamental equations of a space curve (also called the Frenet equations) is given by*

$$\begin{bmatrix} T' \\ N' \\ B' \end{bmatrix} = \begin{bmatrix} 0 & \kappa & 0 \\ -\kappa & 0 & -\tau \\ 0 & \tau & 0 \end{bmatrix} \begin{bmatrix} T \\ N \\ B \end{bmatrix}. \quad (1.3.1)$$

Remark.

- (1) $\tau \equiv 0$ but $\kappa \neq 0$ at all points $\implies \alpha(s)$ is a plane curve. (Note this may be not true if we don't assume $\kappa \neq 0$, see ex.10 in Do Carmo's book)
 $\kappa \equiv 0 \implies \alpha(s)$ is a straight line.

Note $\tau \equiv 0 \implies B' = 0 \implies B$ is constant vector. Further,

$$(\alpha \cdot B)' = \alpha' \cdot B = T \cdot B = 0,$$

gives $\alpha \cdot B = \text{constant} \implies (\alpha(s) - \alpha(s_0)) \cdot B = 0$. Since $\kappa \neq 0$ at all points, the osculating plane is always well-defined, hence B is always defined, we proved α lie in some plane perpendicular to vector B .

- (2) In different textbooks, you may see the definition of τ having a different sign from here.

Friendly warning: When studying the Geometry, (even later in Riemannian Geometry), it happens a lot that different authors use different sign convention for the same definition. It's very important that you should fix your own notation, and keep it consistently!

Definition 1.3.7. $\{T, N, B\}$ is called Frenet trihedron of $\alpha(s)$, it gives a moving orthonormal basis of \mathbb{R}^3 along the curve $\alpha(s)$.

The Frenet equation describes how such moving orthonormal basis moves along $\alpha(s)$.

Remark. Note that in above discussion, we have chosen a special parameter, the arclength parameter, of $\alpha(s)$. In the study of Geometry, finding a good parametrization can simplify a lot of work and itself an important problem. In more general framework, it's called a “Gauge related” problem.

We have seen that given a regular curve $\alpha(s)$, parametrized by arclength, the Frenet equation is eq. (1.3.1), for some functions $\kappa(s) > 0$ be its curvature and $\tau(s)$ be its torsion. Conversely, we ask

Question. If we're given smooth functions $\kappa(s), \tau(s)$ with $\kappa(s) > 0$,

(1) (Existence) Does there exist a regular curve $\alpha(s)$ s.t. $\kappa(s)$ is its curvature and $\tau(s)$ is its torsion?

(2) (Uniqueness) If such curve exists, is it unique in some sense?

The answer is **YES!**

Theorem 1.3.8 (Fundamental theorem of the local theory of curves). *Let $\kappa(s), \tau(s): I \rightarrow \mathbb{R}$ be smooth functions, assume $\kappa(s) > 0$, then*

- (Existence) *There is a regular curve realize κ and τ as its curvature and torsion.*
- (Uniqueness) *If α, β are two such curves parametrized by arclength parameter, then they only differ by a rigid motion of \mathbb{R}^3 . i.e. $\exists T \in O(3), c \in \mathbb{R}^3$ s.t. $\beta = T\alpha + c$.*

Remark.

- (1) Existence follows from a Cauchy problem (initial value problem) of ODE system.
- (2) The curve is unique up to a rotation of \mathbb{R}^3 and a translation.

Proof. If we denote

$$X(s) = \begin{bmatrix} T \\ N \\ B \end{bmatrix}, \quad P(s) = \begin{bmatrix} \kappa & -\tau \\ -\kappa & \tau \end{bmatrix}.$$

Where T, N, B are viewed as **row vectors**. Then the Frenet equation writes as

$$X' = PX.$$

This is a first order linear ODE (of nine unknown functions), then by the existence and uniqueness theorem of ODEs, given any initial value

$$X(0) = \begin{bmatrix} T_0 \\ N_0 \\ B_0 \end{bmatrix}$$

witch form an orthonormal basis, the system has a unique solution that extend to whole domain I .

We need to check the solution actually is orthonormal frame for each s , notice the orthonormal relation can be written as

$$XX^t = I_3.$$

Where I_3 is the identity matrix of dimension three. Take differential on left-hand side of the equation we get

$$\begin{aligned} \frac{d}{ds}(XX^t) &= X'X^t + X(X^t)' = X'X^t + X(X')^t \\ &= PXX^t + X(PX)^t \\ &= PXX^t + XX^tP^t \\ &= PXX^t - XX^tP. \end{aligned}$$



If we denote $Y = XX^t$, we see

$$Y' = PY - YP$$

In coordinates, if we set $T = v_1, N = v_2, B = v_3$, and

$$y_{ij}(s) = \langle v_i(s), v_j(s) \rangle, \quad P = (a_{ij})_{i,j=1}^3.$$

We have $y_{ij} = y_{ji}, a_{ij} = -a_{ji}$, and then

$$\begin{aligned} \frac{d}{ds} y_{ij} &= \langle v'_i, v_j \rangle + \langle v_i, v'_j \rangle \\ &= \langle a_{ik}v_k, v_j \rangle + \langle v_i, a_{jk}v_k \rangle \\ &= a_{ik}y_{kj} + a_{jk}y_{ki} \\ &= a_{ik}y_{kj} - y_{ik}a_{kj}. \end{aligned}$$

This gives again a first order ODE system, with initial value $Y(0) = I_3$, or say $y_{ij}(0) = \delta_{ij}$, but there is an obvious solution $Y \equiv I_3$, so by uniqueness theorem, this is it. This proves $XX^t = I_3$ for any s .

Until now, we have proved the existence of orthonormal moving frame $\{T, N, B\}$. Notice T is just $\alpha'(s)$, so given initial point $\alpha(0) = \alpha_0$, integrate w.r.t s gives a valid solution

$$\alpha(s) = \alpha_0 + \int_0^s T(\xi) d\xi.$$

For the uniqueness, we need to look carefully into the initial condition we chose for the solution α , that is, choice of initial frame $\{T_0, N_0, B_0\}$ and initial point α_0 . Given two valid solution curve α, β , with initial condition (X_a, α_0) and (X_b, β_0) , we choose an orthogonal matrix $T = X_b X_a^{-1}$, a constant $c = \beta_0 - T\alpha_0$, then we see the curve

$$\tilde{\beta} = T(\alpha - \alpha_0) + \beta_0 = T\alpha + c$$

satisfy exactly the same initial condition as β , so they must agree. This proves the uniqueness up to rigid motion we stated before. \square

Remark.

- (1) **Exercise:** Check that for solution given above, κ and τ are its curvature and torsion.
- (2) The condition $\kappa > 0$ is needed for uniqueness. Can you construct a counterexample when there is one point $s.t. \kappa = 0$?
- (3) Uniqueness can be proved without knowledge of ODEs, see theorem after this remark.
- (4) We can view the ODE problem at a somehow higher point. Consider the space of all orthonormal frames, it is actually a smooth manifold. It's a little non-trivial, but we can identify the space with the three dimensional rotation group $SO(3)$, smoothly embedded into \mathbb{R}^9 , the space of three dimensional matrices. The equation, can be interpreted to a (time dependent) vector field on $SO(3)$. One can verify the vector field is tangent to the manifold, so it is actually a vector field not only in \mathbb{R}^9 but in $SO(3)$ itself. Similar to the existence and uniqueness theorem of ODEs on Euclid spaces, we have a version of such theorem for smooth manifolds. It states that for a smooth manifold M , a (maybe time dependent) smooth vector field X on M , then



with any given initial point p , there exists an integral curve on M starting at p , tangent to X everywhere, and it is unique. Using the theorem, we can say that with given initial $\{T_0, N_0, B_0\}$, there exists a unique solution $\{T(s), N(s), B(s)\}$. Note that the solution is automatically lie in $SO(n)$, no need to verify it is orthonormal.

Proof. (Uniqueness, without ODE knowledge).

Let $\alpha(s), \beta(s)$ share the same $\kappa(s), \tau(s)$ as their curvature and torsion, by similarly a rotation and a translation, we assume they have same initial condition, *i.e.* $\alpha(0) = \beta(0)$, and the Frenet frame agree at $s = 0$. We claim now we must have $\alpha(s) = \beta(s), \forall s$.

Notice $\alpha(s) = \alpha(0) + \int_{s_0}^s \alpha'(s) ds$, so it suffices to show $T_\alpha = T_\beta$, equivalently

$$|T_\alpha - T_\beta|^2 = 0.$$

Take differential we get:

$$\begin{aligned} \frac{1}{2} \frac{d}{ds} |T_\alpha - T_\beta|^2 &= \langle T_\alpha - T_\beta, T'_\alpha - T'_\beta \rangle \\ &= -\langle T_\alpha, \kappa N_\beta \rangle - \langle T_\beta, \kappa N_\alpha \rangle. \end{aligned}$$

Similar calculation gives

$$\begin{aligned} \frac{1}{2} \frac{d}{ds} |N_\alpha - N_\beta|^2 &= \langle N_\alpha, \kappa T_\beta + \tau B_\beta \rangle + \langle N_\beta, \kappa T_\alpha + \tau B_\alpha \rangle \\ \frac{1}{2} \frac{d}{ds} |B_\alpha - B_\beta|^2 &= -\langle B_\alpha, \tau N_\beta \rangle - \langle B_\beta, \tau N_\alpha \rangle. \end{aligned}$$

Sum the three equation we have

$$\frac{1}{2} \frac{d}{ds} (|T_\alpha - T_\beta|^2 + |N_\alpha - N_\beta|^2 + |B_\alpha - B_\beta|^2) = 0.$$

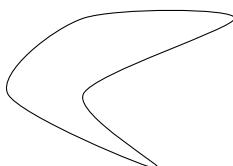
But the sum of square equals 0 at $s = s_0$, so it is identically 0, in particular, $T_\alpha = T_\beta$ for all s . \square

1.4 Global theory of plane curves

The global theory is related to “topology” of the geometric objects. For 1-dimensional geometry, *i.e.* curves, it’s always oriented. And the simplest distinction in topology is “open” and “closed”.

Definition 1.4.1 (Closed curves).

- We say $\alpha: I = [a, b] \rightarrow \mathbb{R}^3$ (or \mathbb{R}^2) is a closed regular curve, if $\alpha(a) = \alpha(b)$ and $\alpha^{(k)}(a) = \alpha^{(k)}(b)$ (in another word, $\alpha: \mathbb{S}^1 \rightarrow \mathbb{R}^3$ is a differentiable curve).
- Furthermore, if α has no self-intersection point other than $\alpha(a) = \alpha(b)$, then we call $\alpha(s)$ to be a simple closed curve.





1.4.1 Isoperimetric inequality

This is one of the oldest and most famous problem in geometry. It's still attracting mathematicians to investigate such problem in various geometric formulations nowadays.

Question. Given a closed plane curve C with. Let D be the region bounded by C . When does the region have the maximal area, if C is among all the curves with fixed length?

Answer. C must be a circle when the maximal area is achieved.

Remark. Even though we'll only handle smooth, simple closed curves in the following discussion, in general we don't have to assume the curve to be simple: \textcircled{O} has less area than O . (caution: their boundaries are intended to have the same length). Thick about how \textcircled{O} comes from O .

Proofs of the Isoperimetric inequality

Proof. 1 (Hurwitz's proof) This relies on the “Wirtinger’s inequality”.

Let $\alpha(t)$ be a closed, simple smooth curve, where t can be any parameter. The length of it is

$$L = \int_a^b \sqrt{x'(t)^2 + y'(t)^2} dt.$$

Observe that we need to find the lower bound of L^2 . Generally, for an integral $L = \int \sqrt{f} dt$, Hölder inequality (or Cauchy-Schwarz) naturally gives estimate of L . Hence, it's natural to find a “good parameter” to clear. Although the arclength s is a good candidate, it turns out in this case that another good parameter is

$$\theta = \frac{2\pi}{L}s.$$

$s \in [0, L] \Rightarrow \theta \in [0, 2\pi]$. (This parameter θ comes from the “Wirtinger’s inequality”, but of course a rescaling of wirtinger’s inequality allows us to use s as usual).

Let's take $\theta = \frac{2\pi}{L}s$, then

$$\left(\frac{dx}{d\theta} \right)^2 + \left(\frac{dy}{d\theta} \right)^2 = \left(\left(\frac{dx}{ds} \right)^2 + \left(\frac{dy}{ds} \right)^2 \right) \left(\frac{ds}{d\theta} \right)^2 = \left(\frac{L}{2\pi} \right)^2.$$

$$\Rightarrow \frac{L^2}{2\pi} = \frac{L^2}{4\pi^2} \cdot 2\pi = \int_0^{2\pi} (x'(\theta)^2 + y'(\theta)^2) d\theta.$$

Therefore,

$$\begin{aligned} 2 \left(\frac{L^2}{4\pi} - A \right) &= \int_0^{2\pi} (x'(\theta)^2 + y'(\theta)^2) d\theta - 2 \int_0^{2\pi} x(\theta)y'(\theta) d\theta \\ &= \int_0^{2\pi} x'(\theta)^2 - x(\theta)^2 + \underbrace{(y'(\theta) - x(\theta))^2}_{\geq 0} d\theta \\ &\geq \int_0^{2\pi} x'(\theta)^2 - x(\theta)^2 d\theta. \end{aligned} \tag{\star}$$

Now, the proof reduces to the following lemma.

Lemma 1.4.2 (Wirtinger's inequality). Let $f: \mathbb{R} \rightarrow \mathbb{R}$ be a 2π -periodic smooth function and $\int_0^{2\pi} f(\theta) d\theta = 0$, Then

$$\int_0^{2\pi} f(\theta)^2 d\theta \leq \int_0^{2\pi} f'(\theta)^2 d\theta,$$

and equality holds iff $f(\theta) = a \cos(\theta) + b \sin(\theta)$.

(Proof of the lemma is left as a homework problem.)

To apply this to (\star) , we need to assume $\int_0^{2\pi} x(\theta) d\theta = 0$. However, we know the center of mass of the curve is $\left(\frac{\int x(\theta) d\theta}{L}, \frac{\int y(\theta) d\theta}{L}\right)$, and by choosing the origin of \mathbb{R}^2 as the center of mass, we can guarantee $\int_0^{2\pi} x(\theta) d\theta = 0$, this yields $\star \geq 0$, i.e. $L^2 \geq 4\pi A$. Moreover, equality implies

$$x(\theta) = a \cos(\theta) + b \sin(\theta) \text{ and } y'(\theta) = x(\theta) \Rightarrow$$

$$y(\theta) = a \sin(\theta) - b \cos(\theta) + c.$$

So $(x(\theta), y(\theta))$ is a circle. \square

Proof. 2 (By Schmidt) See Do Carmo's book (page 33-35). It will be lectured by TA in a recitation. \square

Remark.

(1) There are many other proofs of Isoperimetric inequality. In the homework 3, we will use a modern tool-curve shortening flow to give a proof.

(2)

$$\begin{aligned} L^2 \geq 4\pi A &\Rightarrow \frac{L^2}{4\pi} \geq A \Rightarrow \frac{L^2}{4\pi^2 r^2} \geq \frac{A}{\pi r^2} \text{ (take } r = 1) \\ &\Rightarrow \frac{L}{2\pi} \geq \left(\frac{A}{\pi}\right)^{\frac{1}{2}} \text{ i.e. } \frac{\text{length of curve}}{\text{length of the unit circle}} \geq \left(\frac{\text{Area bounded by the curve}}{\text{Area of the unit disk}}\right)^{\frac{1}{2}}. \end{aligned}$$

• **Generalization:** Let E be a compact domain in \mathbb{R}^n with smooth boundary ∂E , then

$$\frac{\text{Area}(\partial E)}{\text{Area of the unit sphere in } \mathbb{R}^n} \geq \left(\frac{\text{Volume of } E}{\text{Volume of the unit ball}}\right)^{\frac{n-1}{n}}$$

For simplicity, we write

$$\frac{|\partial E|}{\partial B^n} \geq \left(\frac{|E|}{|B^n|}\right)^{\frac{n-1}{n}}.$$

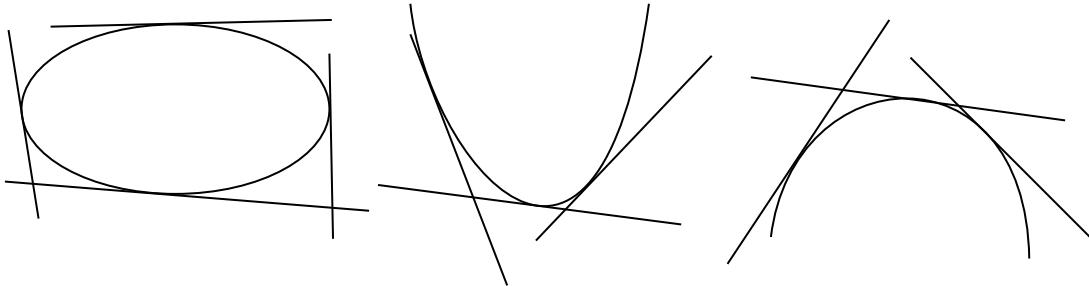
Question. Can you propose some generalizations of isoperimetric inequality? Isoperimetric inequality is one of the motivation to develop geometric measure theory!

1.4.2 Four-vertex theorem

Theorem 1.4.3. *A simple closed convex plane curve has at least four vertices.*

Remark. The four-vertex theorem holds also for simple closed non-convex curves. The proof is harder, however.

Definition 1.4.4 (Convex curves). $\alpha(s)$ is a convex curve, if at each point $\alpha(s_0)$, the whole curve lies on the same side of the tangent line.



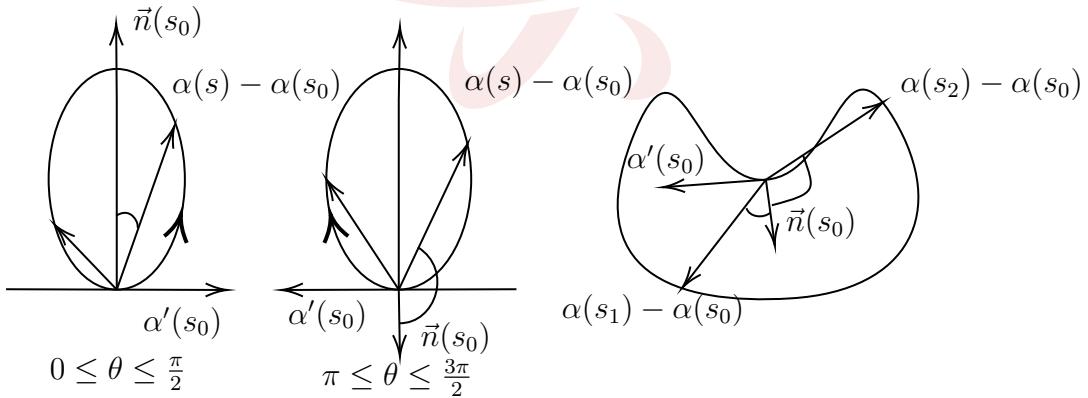
The convex curve has the following useful characterization.

Proposition 1.4.5. $\alpha(s)$ is a convex curve \Leftrightarrow at each point $\alpha(s_0)$, only one of the following holds:

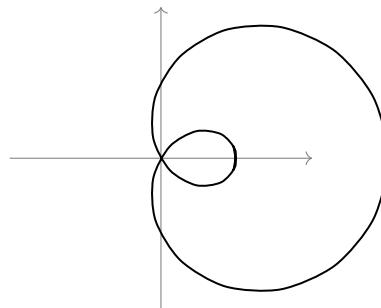
For all $s \in I$, either $(\alpha(s) - \alpha(s_0)) \cdot \vec{n}(s_0) \geq 0$ or $(\alpha(s) - \alpha(s_0)) \cdot \vec{n}(s_0) \leq 0$.

Geometrically, this means at a convex point, the angle between vector $\alpha(s) - \alpha(s_0)$ and $\vec{n}(s_0)$ should be either $[0, \frac{\pi}{2}]$ or $[\pi, \frac{3\pi}{2}]$.

Example.



Example. $\alpha(t) = ((1 + 2 \cos t) \cos t, (1 + 2 \cos t) \sin t)$, $t \in \mathbb{R}$.

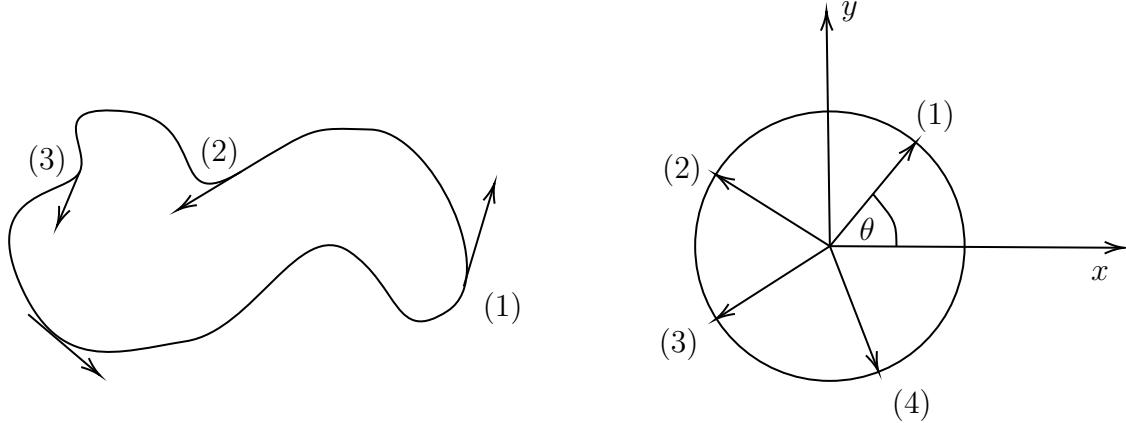




Proposition 1.4.6. $\alpha(s)$ is a simple closed curve, then

$$\alpha(s) \text{ is convex} \Leftrightarrow k(s) \geq 0 \quad \forall s \text{ or } k(s) \leq 0 \quad \forall s.$$

Previously, we have seen that $k(s)$ measures the rate of change of the angle between tangent vectors. Let's see another similar application. Let $\alpha(s)$ be parametrized by arclength, then $t(s) \equiv \alpha'(s)$ is a unit tangent vector, i.e. $|t(s)| = 1$.



Let θ be the angle between $t(s)$ and the x -axis, i.e. $t(s) = (\cos \theta, \sin \theta)$

$$t'(s) = (-\sin \theta, \cos \theta) \frac{d\theta}{ds} = \frac{d\theta}{ds} \cdot \vec{n} \quad \left. \begin{array}{l} \\ \text{on the other hand, } t'(s) = k \cdot \vec{n} \end{array} \right\} \Rightarrow \boxed{k(s) = \frac{d\theta}{ds}}.$$

As an application, if $k(s) \not\equiv 0$, then $s = s(\theta)$ is defined so that $\frac{ds}{d\theta} = \frac{1}{k}$, i.e. θ can be used as a parameter of $\alpha(s)$. Such θ is called the angle parameter.

! In the study of geometry, the sign of the curvature is a very important thing to keep in mind.

Definition 1.4.7. Let $\alpha: I \rightarrow \mathbb{R}^3$ be a regular curve. The point at which $k'(t_0) = 0$ is called a vertex of α . (critical point of the curvature $k(t)$)

Proof of proposition 1.4.6.

Claim 1: $\alpha(s)$ is Globally convex \Rightarrow either $k \geq 0$ or $k \leq 0$ locally for all s .

W.L.O.G., we assume c is oriented counterclockwise, \vec{n} is the inner unit normal vector. We'll show

$$\text{convex} \Rightarrow k \geq 0 \text{ for all } s.$$

Assuming not, then $\exists s_0$ such that $k(s_0) < 0$. By the continuity of $k(s)$, we can assume $k(s_0) = \min k(s)$. Establish a coordinate system at $\alpha(s_0)$ such that $\alpha(s_0)$ is the origin, $\alpha'(s_0)$ corresponds to the x -axis and $\vec{n}(s_0)$ to the y -axis. We'll show that $\exists s_1, s_2$ such that

$$\langle \alpha(s_1), \vec{n}(s_0) \rangle < 0, \quad \langle \alpha(s_2), \vec{n}(s_0) \rangle > 0.$$

Consider the function

$$f(s) = \langle \alpha''(s), \vec{n}(s_0) \rangle,$$

then $f(s_0) = k(s_0) \leq 0$, which implies that there exists a neighborhood $I_\epsilon = (s_0 - \epsilon, s_0 + \epsilon)$, so that $f(s) < 0$ for $s \in I_\epsilon$.

$$\Rightarrow \langle \alpha''(s), \vec{n}(s_0) \rangle < 0 \Rightarrow \langle \alpha'(s), \vec{n}(s_0) \rangle < \langle \alpha(s_0), \vec{n}(s_0) \rangle = 0$$

$$\Rightarrow \langle \alpha(s), \vec{n}(s_0) \rangle < \langle \alpha(s_0), \vec{n}(s_0) \rangle = 0.$$

So there exists an s_1 such that $\langle \alpha(s_1), \vec{n}(s_0) \rangle < 0$.

If for all $s \in I$, $\langle \alpha(s), \vec{n}(s_0) \rangle \leq 0$, then this means that all points lie on the opposite side of \vec{n} . Hence, \vec{n} is “outer” normal, a contradiction to our assumption on the direction of \vec{n} . So $\exists s_2$ such that $\alpha'(s_2) > 0$. But this contradicts the assumption on convexity.

Claim 2: $k \geq 0 \Rightarrow$ global convexity.

If not, there exists an s_0 such that the curve has points on both sides of the tangent line of $\alpha(s_0)$. Consider the height function

$$h(s) = \langle \alpha(s) - \alpha(s_0), \vec{n}(s_0) \rangle,$$

then $\exists s_1, s_2$ such that $h(s_1) < 0 = h(s_0) < h(s_2)$. We can assume that $s_0 < s_1 < s_2 < s_0 + l$, where l is the length of $\alpha(s)$. By the continuity of h , we can further assume

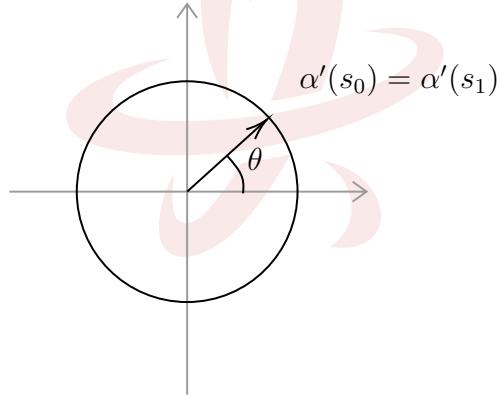
$$\begin{aligned} h(s_1) &= \min h(s), \quad h(s_2) = \max h(s). \\ \Rightarrow h'(s_1) &= \langle \alpha'(s_1), \vec{n}(s_0) \rangle = 0 \Rightarrow \alpha'(s_1) \perp \vec{n}(s_0) \\ h'(s_2) &= \langle \alpha'(s_2), \vec{n}(s_0) \rangle = 0 \Rightarrow \alpha'(s_2) \perp \vec{n}(s_0), \end{aligned}$$

and we also know $\alpha'(s_0) \perp \vec{n}(s_0)$.

\therefore at least two of $\alpha'(s_0), \alpha'(s_1), \alpha'(s_2)$ have the same direction. Let's assume.

$$\alpha'(s_0) = \alpha'(s_1) \quad (\because \text{they have the same length})$$

Note that they are unit vectors, i.e. images are on \mathbb{S}^1 .



As we have discussed in the lecture, if θ is the angle between $t(s)$ and a fixed direction

$$k = \frac{d\theta}{ds}.$$

Hence, we can consider a function:

$$\theta(s) = \int_{s_0}^s k(s) ds.$$

By assumption, $\theta(s)$ is non-decreasing ($k \geq 0$) and $\theta(s_0) = 0$

$$\theta(s_0 + L) = \int_{s_0}^{s_0+L} k(s) ds = 2\pi.$$

(Fact: for a simple closed curve in \mathbb{R}^2 , $\int_c k ds = 2\pi$)

Since for each unit vector $\alpha'(s)$, we have a unique $\theta(s) \in [0, 2\pi]$

$$\alpha'(s_0) = \alpha'(s_1) \Rightarrow \theta(s_0) = \theta(s_1) \in [0, 2\pi] \quad \left(\because \theta : [s_0, s_0 + L] \xrightarrow{\sim} [0, 2\pi] \right).$$

But

$$\begin{aligned} s_0 < s_1 &\Rightarrow \theta(s_0) = \text{constant on } [s_0, s_1] \\ &\Rightarrow \alpha'(s) = \text{constant on } [s_0, s_1], \alpha'(s) = \alpha'(s_0) \\ &\Rightarrow \int_{s_0}^{s_1} \langle \alpha'(s), \vec{n}_0 \rangle ds = \langle \alpha(s_1) - \alpha(s_0), \vec{n}_0 \rangle = h(s_1). \end{aligned}$$

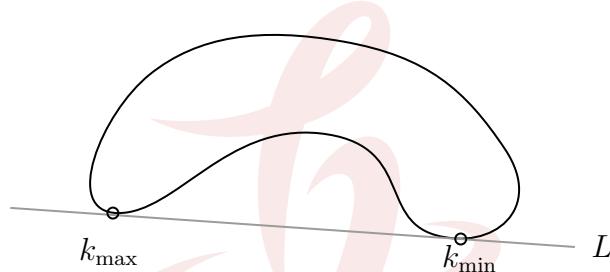
This contradicts $h(s_1) < 0$

□

Further explanation of the four-vertex theorem(sketch)

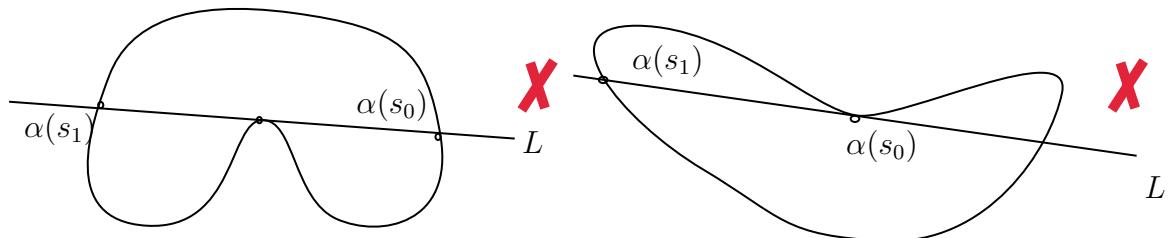
Let L be the line passing through $\alpha(s_0)$ and $\alpha(s_1)$, and $\alpha(s_0)$ is a k_{\min} point and $\alpha(s_1)$ is a k_{\max} point.

Claim 1: It can't happen that all points lie on the same side of L , i.e. the configuration in this illustration is impossible.

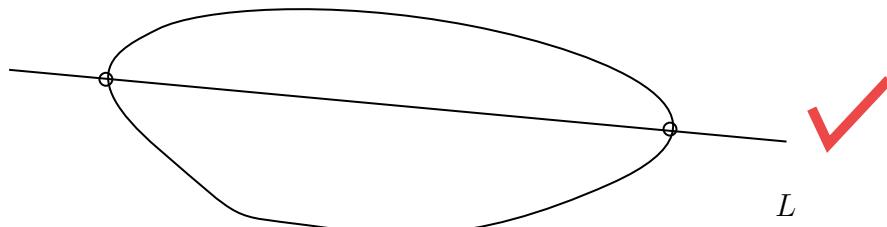


(Reason: simple closed + convexity $\Rightarrow \theta(s)$ is increasing on $[0, 2\pi]$, the same argument as the previous page.) This implies that there must be points on both sides of L .

Claim : No other points of C meet L .



(Reason: same as Claim 1.) Hence, Claim 1 + Claim 2 \Rightarrow

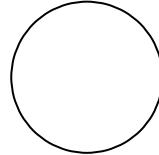


Claim 3: \exists a third and a fourth vertex. (See the proof)

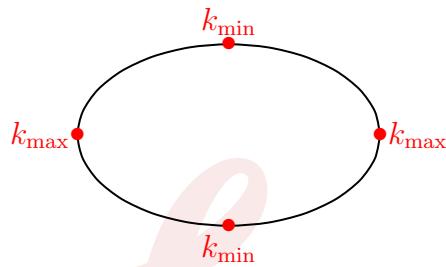
Exercise. Let $\alpha(s) = (x(s), y(s))$ be a simple closed curve in \mathbb{R}^2 . Let $\tilde{\alpha}(s)$ be the image of $\alpha(s)$ under stereographic projection. Show that if $\alpha(s_0)$ is a vertex of $\alpha(s)$, then $\tilde{\alpha}(s_0)$ has vanishing torsion.

Example.

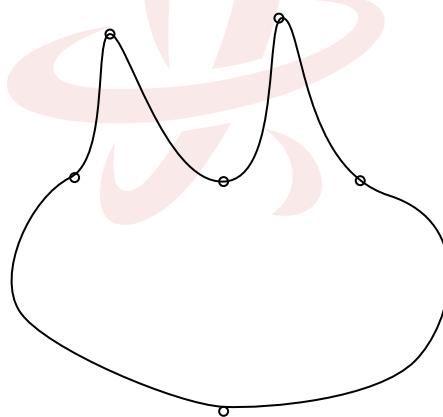
- The circle with radius r and curvature $k = \frac{1}{r}$ has infinitely many vertices.



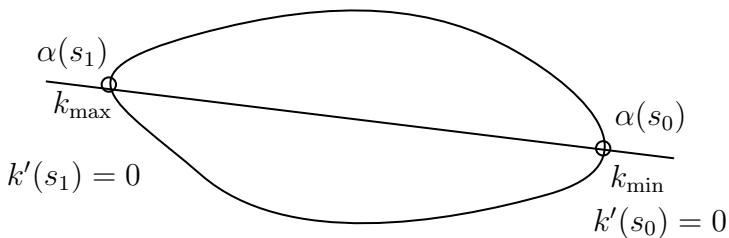
- An ellipse has four vertices.



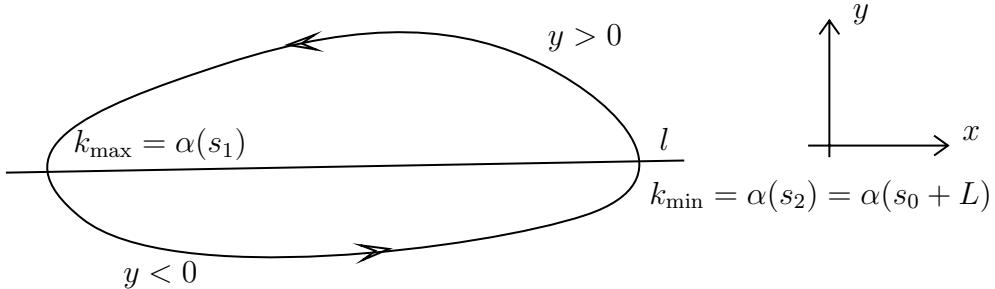
- Although this is nonconvex, it has more than four vertices.



Proof of theorem 1.4.3. Let $\alpha(s)$ be parametrized by arclength. First, since the curvature $k(s)$ is a continuous function on I , it must have maximum and minimum, at which $k'(s) = 0$, i.e. $\alpha(s)$ has at least 2 vertices. Let $\alpha(s_0)$ be a k_{\min} point, $\alpha(s_1)$ be a k_{\max} point. Consider a line l connecting $\alpha(s_0)$ and $\alpha(s_1)$. For convenience, we assume line l coincides with x -axis.



The First observation is: on l , there is no other point of $\alpha(s)$. Hence, $\alpha(s)$ is divided into two pieces. If not, assume $\alpha(s_2)$ is a third point, and W.L.O.G. assume $k'(s_2) = 0$. The tangent line at $\alpha(s_2)$ must be the same as l . Since the curve α is convex, the whole curve $\alpha(s)$ must lie on the same side of l . This forces the tangent lines of $\alpha(s_0)$ and $\alpha(s_1)$ can only be l . But $\alpha(s_0)$ is a k_{\min} point and $\alpha(s_1)$ is a k_{\max} point, which implies $k(s_0) = k(s_1) = 0$. Therefore, $k \equiv 0$ on α , a contradiction.



Next, we look for the third vertex. If $\alpha(s)$ has only two vertices at $\alpha(s_0)$ and $\alpha(s_1)$, then from s_0 to s_1 , $k'(s) > 0$ and from s_1 to $s_0 + L$, $k'(s) < 0$

$$\begin{aligned} &\Rightarrow y \cdot k'(s) \geq 0, \forall s \\ &\Rightarrow 0 < \int_{\alpha} y \cdot k'(s) ds = - \int_{\alpha} y'(s) k ds. \end{aligned}$$

Note that if

$$\begin{aligned} \alpha(s) &= (x(s), y(s)), t(s) = \alpha'(s) (x'(s), y'(s)). \\ t'(s) &= (x''(s), y''(s)) = k \vec{n} = k(-y', x') \Rightarrow -k'(s)k = x'' \\ \therefore \int_{\alpha} y' k ds &= \int_{\alpha} x'' ds = 0. \end{aligned}$$

A contradiction!. Hence, there must be a third vertex, say $\alpha(s_2)$, at which $k'(s_2) = 0$.

Note that $k'(s)$ changes its sign at vertices, so the number of vertices must be even. Then there are at least 4 vertices. \square

Remark. The proof of the four-vertex theorem for non-convex case can be found in Montiel-Ros's book Chapter 9.6. (4-vertex theorem for space curves: simple closed curve on a convex surface has at least four points with vanishing torsion.)

1.4.3 Minkowski problem(1-d)

Theorem 1.4.8 (1-d Minkowski problem). *Given a periodic, strictly positive function k , satisfying the following condition:*

$$\int_0^{2\pi} \frac{\cos \theta}{k} d\theta = \int_0^{2\pi} \frac{\sin \theta}{k} d\theta = 0.$$

There is an oval in \mathbb{R}^2 (i.e. simple closed strictly convex curve) such that the curvature function is k .

Definition 1.4.9. A plane curve $\alpha(t)$ is strictly convex iff $\alpha(t)$ is convex and at each point, the tangent line meets with $\alpha(t)$ at only one point.

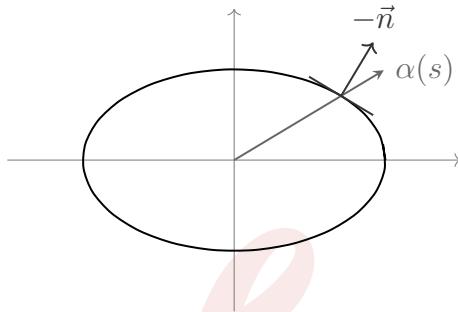
Proposition 1.4.10. A simple closed curve is strictly convex iff with inward unit normal vector field, the curvature function $k > 0$.

Minkowski problem: Given a strictly positive, periodic function k , does there exist a simple closed convex curve α with k as the curvature function?

Remark. This is a prescribed curvature problem. There are a lot of similar questions in geometry. Such problems are usually related to solving certain P.D.E.

Let's derive a differential equation for the above problem. Let α be a strictly convex curve, then $k > 0$, and we can use the angle parameter θ , i.e.

$$\frac{d\theta}{ds} = k, \quad \frac{ds}{d\theta} = \frac{1}{k}$$



Consider a function

$$h(s) = -\langle \alpha(s), \vec{n}(s) \rangle \text{ support function.}$$

(Recall $\int_C h(s) ds = 2 \cdot \text{Area}$).

Clearly $h(0) = h(2\pi)$ if we use $h(\theta) = -\langle \alpha(s(\theta)), \vec{n}(s(\theta)) \rangle$.

$$\begin{aligned} h'(\theta) &= -\langle \alpha'(s) \frac{ds}{d\theta}, \vec{n}(s) \rangle - \langle \alpha(\theta), \frac{d\vec{n}}{ds} \frac{ds}{d\theta} \rangle \\ &= -\langle \alpha(\theta), -k \cdot \vec{t} \cdot \frac{1}{k} \rangle = \langle \alpha(\theta), \vec{t}(s(\theta)) \rangle. \end{aligned}$$

Hence, $h'(0) = h'(2\pi)$.

We also conclude that

$$\begin{aligned} \alpha(\theta) &= \langle \alpha(\theta), \vec{t} \rangle \cdot \vec{t} + \langle \alpha(\theta), \vec{n} \rangle \cdot \vec{n} \\ &= h'(\theta) \vec{t} - h(\theta) \vec{n}, \end{aligned}$$

i.e. the curve is determined by the support function h .

$$\left(\alpha(s) = h'(s) \frac{ds}{d\theta} \vec{t} - h(s) \vec{n} = h'(s) \frac{1}{k} \vec{t} - h(s) \vec{n} \right)$$

$$\begin{aligned} h''(\theta) &= \langle \alpha'(s) \frac{ds}{d\theta}, \vec{t} \rangle + \langle \alpha(\theta), \frac{d\vec{t}}{ds} \frac{ds}{d\theta} \rangle \\ &= \frac{1}{k} + \langle \alpha(\theta), k \vec{n} \cdot \frac{1}{k} \rangle = \frac{1}{k} - h. \end{aligned}$$

i.e.
$$h''(\theta) + h(\theta) = \frac{1}{k}.$$

Hence, if $\alpha(s) = \alpha(\theta)$ is a strictly convex closed curve, the support function $h(\theta) = -\langle \alpha, \vec{n} \rangle$ satisfies a second linear o.d.e.

$$h''(\theta) + h = \frac{1}{k}.$$

Observation: If $\exists h$ that satisfies the equation above. Note $\theta \in [0, 2\pi]$, then

$$\begin{aligned} \int_0^{2\pi} \cos \theta \frac{1}{k} d\theta &= \int_0^{2\pi} \cos \theta \cdot (h''\theta + h) d\theta \\ &= \int_0^{2\pi} \sin \theta \cdot h'(\theta) + \int_0^{2\pi} \cos \theta \cdot h \\ &= - \int_0^{2\pi} \cos \theta \cdot h(\theta) + \int_0^{2\pi} \cos \theta \cdot h = 0. \end{aligned}$$

Similarly,

$$\int_0^{2\pi} \sin \theta \cdot \frac{1}{k} d\theta = 0,$$

i.e. if k is the curvature of a strictly convex curve, it must satisfy

$$\int_0^{2\pi} \cos \theta \cdot \frac{1}{k} d\theta = \int_0^{2\pi} \sin \theta \cdot \frac{1}{k} d\theta = 0.$$

In fact, from o.d.e, we can directly construct the solution like this:

$$h(\theta) = -\cos \theta \int_0^\theta \frac{\sin \psi}{k} d\psi + \sin \theta \int_0^\theta \frac{\cos \psi}{k} d\psi.$$

Recall that $\vec{t}(s) = (\cos \theta, \sin \theta)$, $\vec{n}(s) = (-\sin \theta, \cos \theta)$. Since

$$\begin{aligned} \alpha(\theta) &= h'(\theta)\vec{t} - h(\theta)\vec{n} \\ &= \left(\cos \theta \sin \theta \int_0^\theta \frac{\sin \psi}{k} d\psi + \cos^2 \theta \int_0^\theta \frac{\cos \psi}{k} d\psi, \sin^2 \theta \int_0^\theta \frac{\sin \psi}{k} d\psi + \sin \theta \cos \theta \int_0^\theta \frac{\cos \psi}{k} d\psi \right) \\ &\quad - \left(\sin \theta \cos \theta \int_0^\theta \frac{\sin \psi}{k} d\psi - \sin^2 \theta \int_0^\theta \frac{\cos \psi}{k} d\psi, -\cos^2 \theta \int_0^\theta \frac{\sin \psi}{k} d\psi + \sin \theta \cos \theta \int_0^\theta \frac{\cos \psi}{k} d\psi \right) \\ &= \left(\int_0^\theta \frac{\cos \psi}{k} d\psi, \int_0^\theta \frac{\sin \psi}{k} d\psi \right) \end{aligned}$$

$\alpha(s)$ is closed $\Leftrightarrow h(0) = h(2\pi)$, $h'(0) = h'(2\pi) \Leftrightarrow \int_0^{2\pi} \cos \theta \cdot \frac{1}{k} d\theta = \int_0^{2\pi} \sin \theta \cdot \frac{1}{k} d\theta = 0$.

Remark. In general (higher dimensional case) solving a similar P.D.E. equation is highly nontrivial!

Cheng-Yau 1976 CPAM: given a $C^{k,\alpha}$ positive function K on the sphere \mathbb{S}^n ($k \geq 3$), which satisfies

$$\int_{\mathbb{S}^n} \frac{x_i}{K} dV_{\mathbb{S}^n} = 0,$$

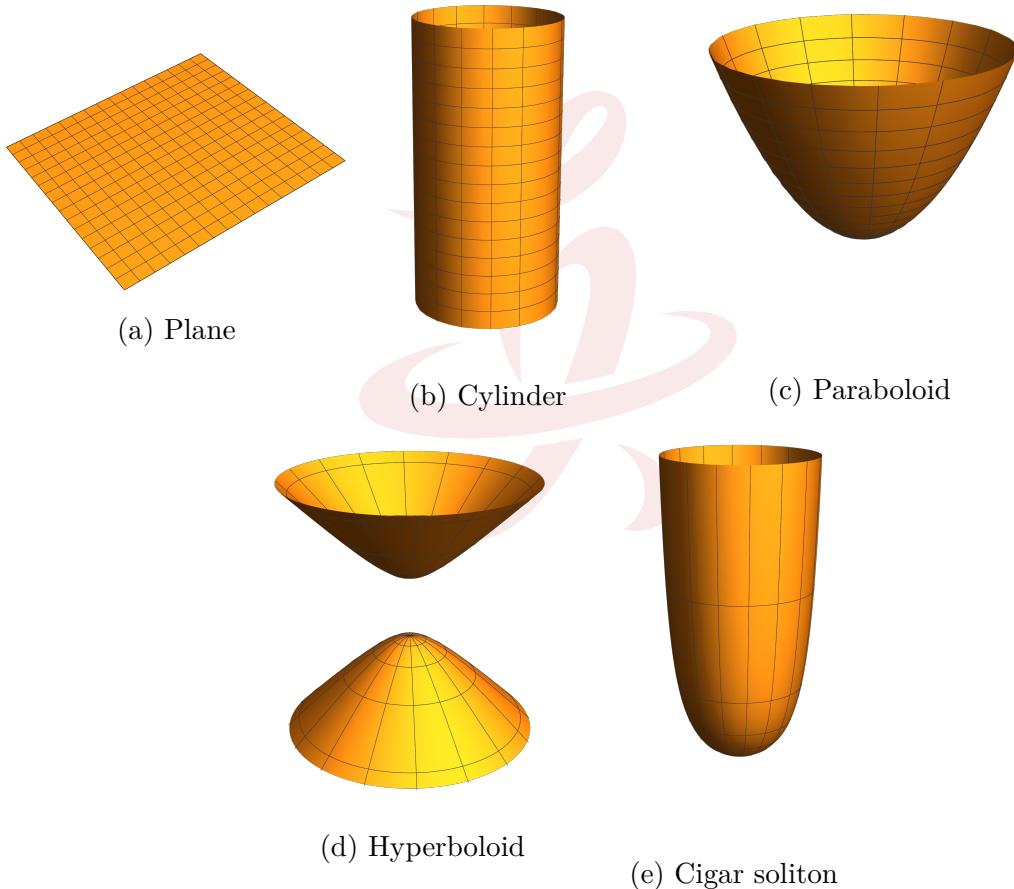
where x_1, x_2, \dots, x_{n+1} are coordinate functions on \mathbb{S}^n . Then there is a strictly convex closed hypersurface $M^n \hookrightarrow \mathbb{R}^{n+1}$ such that the Gaussian curvature is K .



Chapter 2

Differential Geometry of Surfaces

A First Look



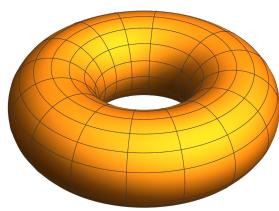
Surface collection 1

Example.

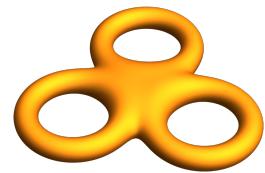
- Collection 1 are complete non-compact surfaces.
- Collection 2 are compact surfaces without boundary (closed).



(a) \mathbb{S}^2



(b) \mathbb{T}^2

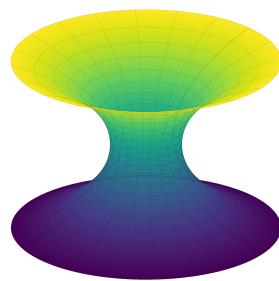


(c) Σ_g for $g = 3$

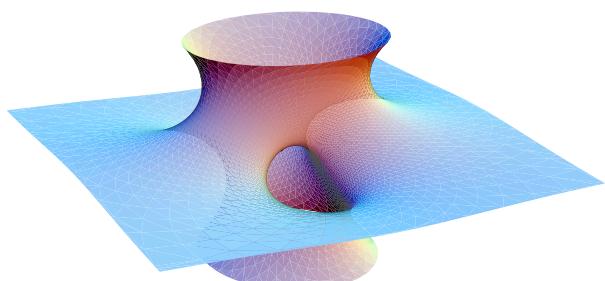
Surface collection 2



(a) Helicoid



(b) Catenoid

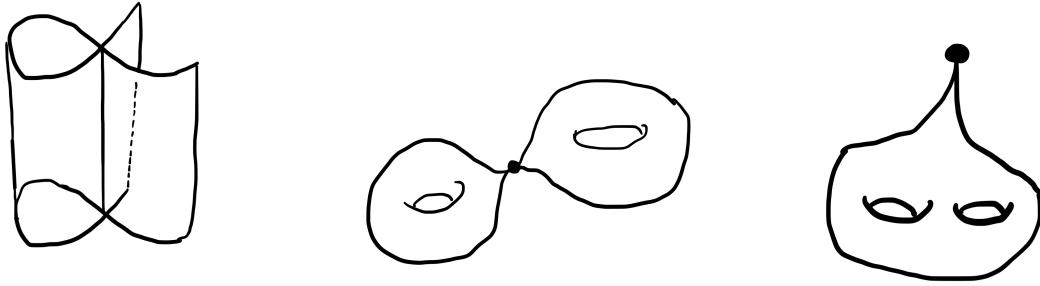


(c) Costa minimal surface



(d) Soap bubble

Surface collection 3



(b) Nodal surfaces

(c) Cusp

(a) Self-intersected

“Surface” collection 4

- Collection 3 are so called minimal surfaces, a very important class of surfaces. The term “minimal” intuits smallest area in certain sense.
- There are surfaces will NOT be investigated in this course, the ones with self-intersection, node points or cusps, and non-orientable surfaces.

2.1 Definition of Regular Surface

Definition 2.1.1 (Regular surfaces in \mathbb{R}^3).

A subset $S \subset \mathbb{R}^3$ is called a regular surface, if $\forall p \in S$, $\exists V \subset \mathbb{R}^3$ neighborhood of p , an open set $U \subset \mathbb{R}^2$ and a trivialization map

$$F: U \rightarrow V \cap S.$$

s.t. F is smooth, homeomorphism onto its image, and regular.

Remark.

(1) F is homeomorphism means both F and F^{-1} are continuous map.

(2) F is “regular” means $\forall p \in U$, dF_p is an injection as linear map $\mathbb{R}^2 \rightarrow \mathbb{R}^3$.

Let’s see what the term “regular” means:

Assume F is written as $F(u, v) = (x(u, v), y(u, v), z(u, v))$, at $p \in U$,

$$dF_p : T_p U \rightarrow T_{F(p)} S$$

is a linear map. On \mathbb{R}^2 , coordinate vector fields $\{\frac{\partial}{\partial u}, \frac{\partial}{\partial v}\}$ form a basis. On \mathbb{R}^3 we also have standard basis $\{\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z}\}$. Then

$$dF_p \begin{bmatrix} \frac{\partial}{\partial u} \\ \frac{\partial}{\partial v} \end{bmatrix} = \begin{bmatrix} \frac{\partial x}{\partial u} & \frac{\partial y}{\partial u} & \frac{\partial z}{\partial u} \\ \frac{\partial x}{\partial v} & \frac{\partial y}{\partial v} & \frac{\partial z}{\partial v} \end{bmatrix} \begin{bmatrix} \frac{\partial}{\partial x} \\ \frac{\partial}{\partial y} \\ \frac{\partial}{\partial z} \end{bmatrix}.$$

Hence

$$\begin{aligned}
 \mathrm{d}F_p \text{ is injective} &\iff \ker \mathrm{d}F_p = 0 \\
 &\iff \frac{\partial(x, y, z)}{\partial(u, v)} \text{ has rank 2} \\
 &\iff \frac{\partial F}{\partial u} \text{ & } \frac{\partial F}{\partial v} \text{ are linearly independent} \\
 &\iff \frac{\partial F}{\partial u} \times \frac{\partial F}{\partial v} \neq 0. \\
 &\quad (\text{Geometrically this defines the normal vector field of the tangent plane}) \\
 &\iff \text{One of the following minors is non-zero:} \\
 &\quad \left| \frac{\partial(x, y)}{\partial(u, v)} \right|, \quad \left| \frac{\partial(x, z)}{\partial(u, v)} \right|, \quad \left| \frac{\partial(y, z)}{\partial(u, v)} \right|
 \end{aligned}$$

(Geometrically, this means (u, v) can be viewed as coordinate at $p \in S$ via F . In fact, since “ $\mathrm{d}F_p$ is injective” is an open condition, (u, v) serves as a local coordinate chart in a neighborhood of p)

We also call F to be a local parametrization of S . Note that such F is usually not globally defined.

From the definition, we see a regular surface in \mathbb{R}^3 is characterized by at each point, we can find a “smooth” slice chart in a neighbourhood of the point. The term “slice chart” means coordinate chart with local part of the surface containing in the chart as a slice.

Question. Consider two points p, q on the surface, live close to each other. It might happen that their corresponding coordinate chart overlap. Then in the intersection of two charts, there are two different parametrizations. What relation between these two parametrizations should be?

Set-up: $F_1: U_1 \rightarrow V_1 \cap S$, $(u, v) \mapsto F_1(u, v)$, $F_2: U_2 \rightarrow V_2 \cap S$, $(\alpha, \beta) \mapsto F_2(\alpha, \beta)$

Let $W = V_1 \cap V_2 \cap S$, since F_i is homeomorphism, $F_1^{-1}(W) \subset U_1$, $F_2^{-1}(W) \subset U_2$.

Claim: (Very important).

$G = F_2^{-1} \circ F_1: F_1^{-1}(W) \rightarrow F_2^{-1}(W)$ is a diffeomorphism, i.e. both G and G^{-1} are smooth functions.

The importance of this claim leads us to give an intrinsic definition of a regular surface S . i.e. a regular surface is obtained by padding up open sets in \mathbb{R}^2 , in a smooth way. Later in differential geometry course, we'll define a smooth manifold by such intrinsic definition. The diffeomorphism G above is called the transition map. Different property of G determines different structure. If G is only a homeomorphism, then S is a topological surface. If G is a bi-holomorphism, then S is a complex surface.

The proof of the claim needs the inverse function theorem.

Theorem 2.1.2 (Inverse function thm). $U \subset \mathbb{R}^n$ open. $F: U \rightarrow \mathbb{R}^n$ is a C^1 map, $p \in U$. If $\mathrm{d}F_p: \mathbb{R}^n \rightarrow \mathbb{R}^n$ is an isomorphism, then there is a neighbourhood of p and a neighbourhood of $F(p)$. s.t. $F: V \rightarrow W$ is invertible. Moreover F^{-1} is also C^1 . If condition is substituted to F smooth, then F^{-1} has same smoothness.

Remark. From linear algebra, a linear operator on finite dimensional vector space is injective iff it's surjective. Hence it's sufficient to check $\det(\mathrm{d}F_p) \neq 0$, i.e. $\mathrm{d}F_p$ is non-singular.

!! Apriori, we don't know if F_2^{-1} is smooth, since we have not defined what "smooth map" on a surface mean.

Proof of claim. Since F_1 and F_2 are homeomorphism, G, G^{-1} are continuous. S is a regular surface, so at $p \in U_1$, $(dF_1)_p: \mathbb{R}^2 \rightarrow \mathbb{R}^3$ is injective. W.L.O.G. we can assume

$$\left| \frac{\partial(x, y)}{\partial(u, v)} \right| \neq 0 \text{ at } p.$$

Consider a map $h: F_1^{-1}(W) \times (-\varepsilon, \varepsilon) \rightarrow \mathbb{R}^3$, $(u, v, t) \mapsto (x(u, v), y(u, v), z(u, v) + t)$. Then h has Jacobian

$$\det \begin{bmatrix} x_u & y_u & z_u \\ x_v & y_v & z_v \\ 0 & 0 & 1 \end{bmatrix} = \det \begin{bmatrix} x_u & y_u \\ x_v & y_v \end{bmatrix} \neq 0 \text{ at } p.$$

By inverse function theorem, \exists a neighbourhood $D \subset \mathbb{R}^3$ of (p, t) s.t. h is invertible on D , and h^{-1} smooth. Now since $F_1^{-1} \circ F_2 = h^{-1} \circ F_2|_{t=0}$, and RHS is smooth, we conclude that $F_1^{-1} \circ F_2$ is smooth. Similarly G^{-1} is smooth. \square

Now we give an intrinsic definition (No need to assume $S \subset \mathbb{R}^3$).

Definition 2.1.3. Topological space S (second countable, Hausdorff) is called a regular surface if S has a covering $\{V_\alpha, f_\alpha\}$ s.t.

(1) $f_\alpha: V_\alpha \rightarrow f_\alpha(V_\alpha) \stackrel{\text{open}}{\subset} \mathbb{R}^2$ is a homeomorphism.

(2) If $V_\alpha \cap V_\beta \neq \emptyset$, then

$$f_\beta \circ f_\alpha^{-1}: f_\alpha(V_\alpha \cap V_\beta) \rightarrow f_\beta(V_\alpha \cap V_\beta)$$

is a diffeomorphism, called the transition map.

Remark. In higher dimension, this definition yields "smooth manifold".

2.2 Examples of Regular Surfaces

Example (1). $\mathbb{R}^2 \hookrightarrow \mathbb{R}^3$ is a regular surface with (trivial) global parametrization

$$F(x, y) = (x, y, 0).$$

Example (2). Standard 2-sphere $\mathbb{S}^2 = \{(x, y, z) : x^2 + y^2 + z^2 = 1\}$. This is a very important example, we'll give (local) parametrization for \mathbb{S}^2 in 3 ways.

(a) Parametrization induced from \mathbb{R}^3 .

If the point is on upper hemisphere, let $U = \{x^2 + y^2 < 1\}$,

$$F_1: U \rightarrow \mathbb{S}^2, (x, y) \mapsto (x, y, \sqrt{1 - x^2 - y^2}).$$

Check definition:

F_1 is smooth ✓.

$F_1: U \rightarrow F_1(U)$ is homeomorphism, since F_1^{-1} is projection onto xy -plane, is also continuous.

F_1 is regular:

$$\frac{\partial F_1}{\partial x} = (1, 0, -\frac{x}{\sqrt{1-x^2-y^2}}), \quad \frac{\partial F_1}{\partial y} = (0, 1, -\frac{y}{\sqrt{1-x^2-y^2}}).$$

Clearly they are linearly independent.

Similarly, if the point is on lower hemisphere, we have

$$F_2: U \rightarrow \mathbb{S}^2, (x, y) \mapsto (y, x, -\sqrt{1-x^2-y^2}).$$

However, $F_1(U) \cup F_2(U)$ can not fully cover \mathbb{S}^2 , points on the equator are left. To cover them, we add 4 more charts:

$F_3(y, z) = (\sqrt{1-y^2-z^2}, y, z)$	(front hemisphere)
$F_4(y, z) = (-\sqrt{1-y^2-z^2}, z, y)$	(back)
$F_5(z, x) = (x, \sqrt{1-x^2-z^2}, z)$	(right)
$F_6(z, x) = (z, -\sqrt{1-x^2-z^2}, x)$	(left)

We can check F_2-F_6 also satisfy the definition. Hence we have given each point a smooth chart, and \mathbb{S}^2 is regular.

Exercise. Check transition maps between F_1-F_6 are smooth.

(b) Geographical parametrization.

Let $U = \{(\theta, \varphi) \in \mathbb{R}^2 : 0 < \theta < 2\pi, 0 < \varphi < \pi\}$,

$$\begin{aligned} F_1: U \rightarrow \mathbb{S}^2, (\theta, \varphi) \mapsto (\cos \theta \sin \varphi, \sin \theta \sin \varphi, \cos \varphi) &\quad (\text{missing half of } \{y=0\} \cap \mathbb{S}^2) \\ F_2: U \rightarrow \mathbb{S}^2, (\theta, \varphi) \mapsto (\sin \theta \sin \varphi, \cos \varphi, \cos \theta \sin \varphi) &\quad (\text{missing half of } \{x=0\} \cap \mathbb{S}^2) \\ F_3: U \rightarrow \mathbb{S}^2, (\theta, \varphi) \mapsto (\cos \varphi, \cos \theta \sin \varphi, \sin \theta \sin \varphi) &\quad (\text{missing half of } \{z=0\} \cap \mathbb{S}^2). \end{aligned}$$

Clearly $\mathbb{S}^2 \subset F_1(U) \cup F_2(U) \cup F_3(U)$, each F_i is smooth and regular. To see they are homeomorphism, we can compute e.g.

$$F_1^{-1}(x, y, z) = \left(\arccos \frac{x}{\sqrt{x^2+y^2}}, \arccos z \right).$$

(c) Stereographic parametrization.

Consider the ray connecting north pole $(0, 0, 1)$ and point (x, y, z) on \mathbb{S}^2 . Then there is a unique point (u, v) on xy -plane on the ray, the projection is given by

$$p_N: \mathbb{S}^2 \setminus \{N\} \rightarrow \mathbb{R}^2, (x, y, z) \mapsto \left(\frac{x}{1-z}, \frac{y}{1-z} \right) =: (u, v)$$

which is rational map, with inverse

$$p_N^{-1}(u, v) = \left(\frac{2u}{1+u^2+v^2}, \frac{2v}{1+u^2+v^2}, 1 - \frac{2}{1+u^2+v^2} \right)$$

also rational and normal.

Similarly consider the projection from $S = (0, 0, -1)$, $p_S(x, y, z) = (\frac{y}{1+z}, \frac{x}{1+z})$, these two charts can cover \mathbb{S}^2 .

Exercise. Check the transition function

$$p_S \circ p_N^{-1} = \left(\frac{u}{u^2 + v^2}, \frac{v}{u^2 + v^2} \right).$$

Remark. In the stereographic projection parametrization, if we identify \mathbb{R}^2 with \mathbb{C}^1 , and introduce complex coordinate

$$w_1 = \frac{x}{1-z} + \frac{y}{1-z}i, \quad w_2 = \frac{x}{1+z} - \frac{y}{1+z}i.$$

Then we can check

$$w_1 \cdot w_2 = 1 \quad \text{and} \quad p_S \circ p_N^{-1}(w_1) = w_2.$$

In this way, we have given a “complex structure” on \mathbb{S}^2 , the resulting surface is an 1 dim complex manifold, called \mathbb{CP}^1 . You’ll learn more about \mathbb{CP}^n in complex / algebraic geometry.

!! \mathbb{S}^2 is a very important example in geometry. One should keep this example in mind and try to understand and explore it in studding geometry. \mathbb{S}^2 is a (strictly) convex surface, has maximal number of \mathbb{S}^1 action (This tells the moment polytope is a line segment). It has 3-rotation axis (3 Killing vector fields). It looks the same everywhere (homogeneous). However, since every circle on \mathbb{S}^2 can shrink to a point, without obstruction, i.e. $\pi_1(\mathbb{S}^2) = 0$, the fundamental group does not play a role here.

Example (3). Graph of a function, i.e. $(x, y, z = f(x, y))$ is a regular surface. More generally, if a surface S can be expressed (locally or globally) as graph of smooth functions, then S is a regular surface.

Parametrization is given by

$$F: U \rightarrow S, \quad (x, y) \mapsto (x, y, f(x, y)).$$

We have

- (a) F is smooth ✓
- (b) F is homeomorphism, $F^{-1}(x, y, z) = (x, y)$.
- (c) F is regular $\det \text{Jac}(dF) = 1$.

Example (4). More generally, the level set of a smooth function $f(x, y, z)$ at a regular value is a regular surface.

Definition 2.2.1 (Critical point (value) & regular point (value)). Let $F: U \subset \mathbb{R}^m \rightarrow \mathbb{R}^n$ be smooth map.

- If $dF_p: \mathbb{R}^m \rightarrow \mathbb{R}^n$ is surjective, i.e. $\text{rank } dF_p = n$, then p is called a regular point. $c \in \mathbb{R}^n$ is called a regular value if $\forall p \in F^{-1}(c)$ is regular point. If $F^{-1}(c)$ is empty we also call c a regular point.
- If dF_p is not surjective, then p is called a critical point, and $F(p)$ is called a critical value.

Remark. If c is a regular value, then $F^{-1}(c)$ is a smooth embedded submanifold of \mathbb{R}^n , with codimension n .

From linear algebra, dF_p is surjective $\iff \dim \ker dF_p = m - n$. Hence, when we talk about “regular” point / value, it only makes sense when $m \geq n$.

Now, let’s consider the case we’re interested in. Let

$$\begin{aligned} f: \mathbb{R}^3 &\longrightarrow \mathbb{R} \quad \text{is smooth function} \\ (x, y, z) &\longmapsto f(x, y, z). \end{aligned}$$

We compute df_p , $p \in U \subset \mathbb{R}^3 = \text{span}\{\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z}\}$, $\mathbb{R}^1 = \{\frac{\partial}{\partial w}\}$:

$$\left[df_p \left(\frac{\partial}{\partial x} \right) \right] h = \frac{\partial}{\partial x} (h \circ f)(p) = \frac{\partial h}{\partial w} \frac{\partial f}{\partial x}, \quad \forall h \text{ smooth function in } w.$$

Hence

$$df_p \left(\frac{\partial}{\partial x} \right) = \frac{\partial f}{\partial w} \frac{\partial}{\partial w}.$$

i.e.

$$df_p \begin{bmatrix} \frac{\partial}{\partial x} \\ \frac{\partial}{\partial y} \\ \frac{\partial}{\partial z} \end{bmatrix} = \begin{bmatrix} \frac{\partial f}{\partial x} \\ \frac{\partial f}{\partial y} \\ \frac{\partial f}{\partial z} \end{bmatrix} \frac{\partial}{\partial w}.$$

Hence p is critical value $\iff \text{rank} \begin{bmatrix} \frac{\partial f}{\partial x} \\ \frac{\partial f}{\partial y} \\ \frac{\partial f}{\partial z} \end{bmatrix}_p < 1 \iff \frac{\partial f}{\partial x} = \frac{\partial f}{\partial y} = \frac{\partial f}{\partial z} = 0 \text{ at } p$.

This is exactly how we define the “critical point” of $f(x, y, z)$ formerly. p is a regular point \iff at least one of partial derivatives is nonzero at p .

Proposition 2.2.2 (Level surface is regular). *Let $f: U \subset \mathbb{R}^3 \rightarrow \mathbb{R}$ be a smooth function. c is regular value of f , then*

$$f^{-1}(c) = \{(x, y, z) \in U : f(x, y, z) = c\}$$

is a regular surface (in U).

For example, $f(x, y, z) = x^2 + y^2 + z^2$, then $\forall c > 0$, level surface $f^{-1}(c)$ is regular. This is exactly the sphere of radius \sqrt{c} .

Proof. $\forall p \in U$ s.t. $f(p) = c$, write $p = (x, y, z)$. Since c is regular value, at least one of $f_x(p), f_y(p), f_z(p)$ is non-vanishing. Wlog assume $f_z(p) \neq 0$. Then by implicit function theorem, \exists a neighbourhood of (x, y) s.t. $z = h(x, y)$ and $f(x, y, h(x, y)) = c$ locally. Hence near p we have a local parametrization given by graph $(x, y, h(x, y))$, then $f^{-1}(c)$ is regular by example (3). \square

Theorem 2.2.3 (Implicit function). *Let $U \subset \mathbb{R}^m$, $V \subset \mathbb{R}^n$ be open sets, $F: U \times V \rightarrow \mathbb{R}^n$ be smooth (Only need C^1) map*

$$(x^1, \dots, x^m, y^1, \dots, y^n) \mapsto (f^1, \dots, f^n).$$

If $f(x_0, y_0) = 0$ and $\frac{\partial(f^1, \dots, f^n)}{\partial(y^1, \dots, y^n)}$ has full rank (i.e. rank n) at (x_0, y_0) , then \exists a neighbourhood $x_0 \in U_0 \subset U$, $y_0 \in V_0 \subset V$ and $h: U_0 \rightarrow V_0$ a smooth map, s.t. locally $(y^1, \dots, y^n) = h(x^1, \dots, x^m)$ and $F(x^1, \dots, x^m, h(x^1, \dots, x^m)) = 0$.

Remark. The implicit function theorem is one of the most frequently used theorems in geometry and PDE theory. As an exercise, please review the version you learned in previous class. In geometry, roughly speaking, the implicit function theorem can be understood as: the tangent plane determines the “small” neighbourhood of a point on a regular surface.

In example (3), we see the graph of a smooth function $f(x, y)$ is a regular surface. The converse is also true locally.

Proposition 2.2.4. *S is a regular surface in \mathbb{R}^3 , $p \in S$, then there is a neighbourhood U of p s.t. U is a graph of a smooth function (Either $z = f_1(x, y)$ or $y = f_2(z, x)$ or $x = f_3(y, z)$).*

Proof. S is regular \implies near p we have local parametrization

$$F: U \subset \mathbb{R}^2 \longrightarrow S \subset \mathbb{R}^3 \\ (u, v) \longmapsto (x(u, v), y(u, v), z(u, v)).$$

Since dF_p is injective \implies at least one of

$$\left| \frac{\partial(x, y)}{\partial(u, v)} \right|, \quad \left| \frac{\partial(y, z)}{\partial(u, v)} \right|, \quad \text{or} \quad \left| \frac{\partial(z, x)}{\partial(u, v)} \right|$$

is non-vanishing. If we assume $\left| \frac{\partial(x, y)}{\partial(u, v)} \right| \neq 0$, then by the inverse (implicit) function thm, u, v are functions of x, y i.e.

$$\begin{cases} x = x(u, v) \\ y = y(u, v) \end{cases} \longleftrightarrow \begin{cases} u = u(x, y) \\ v = v(x, y) \end{cases}.$$

Hence above local parametrization F can be rewritten as

$$\tilde{F}(x, y) = (x, y, z(u(x, y), v(x, y))) = (x, y, z(x, y)).$$

□

On a regular surface S , one prefers to find a “nice” coordinate (local parametrization) to carry out computation to analyze geometric properties. If there is a possible local parametrization, the following proposition says it suffices to check (1) and (3) in the definition, and only part of (2), then this parametrization is indeed a parametrization on S .

Proposition 2.2.5. *S is a regular surface, $F: U \rightarrow \mathbb{R}^3$ is a (local) parametrization, near some point p , if F is smooth and regular, also F is bijective, then F^{-1} is also continuous.*

Proof. Essentially by the implicit function thm, refer to Do Carmo’s book. □

Example. We have checked \mathbb{S}^2 is a regular surface by using the local parameter induced from \mathbb{R}^3 . Hence once we write the spherical coordinate, then clearly it gives a local parametrization by above proposition.

Example (Torus). Rotating $(y - \sqrt{2})^2 + z^2 = 1$ around z -axis, then the resulting surface is a torus

$$(\sqrt{x^2 + y^2} - \sqrt{2})^2 + z^2 = 1.$$

This is a level surface of $f(x, y, z) = (\sqrt{x^2 + y^2} - \sqrt{2})^2 + z^2$ and 1 is a regular value. Hence it's a regular surface. It's convenient to use the following parametrization

$$\begin{cases} x = (\sqrt{2} + \cos \theta) \sin \varphi \\ y = (\sqrt{2} + \cos \theta) \cos \varphi \\ z = \sin \theta \end{cases}.$$

Exercise (Homework). Show that the two-sheeted cone, with its vertex at origin

$$\{(x, y, z) \in \mathbb{R}^3 : x^2 + y^2 - z^2 = 0\}$$

is not a regular surface.

Exercise. $P = \{(x, y, z) : x = y\}$, let $X: U \rightarrow \mathbb{R}^3$ given by

$$X(u, v) = (u + v, u - v, uv)$$

where $U = \{(u, v) \in \mathbb{R}^2 : u > v\}$. Clearly $X(U) \subset P$. Is X a parametrization of P ?

2.3 Differential Functions on a regular surface

Question (1). How to define a function on \mathbb{S}^2 ?

In calculus, we have seen this is just $f(x, y, z)|_{\mathbb{S}^2}$, but what does this mean? If $p \in$ upper half semi-sphere $\Rightarrow f(x, y, \sqrt{1 - x^2 - y^2}) \Rightarrow f$ is just a function on

$$U = (x, y) \in \mathbb{R}^2 : x^2 + y^2 < 1.$$

More precisely, if we let $F: U \rightarrow \mathbb{S}^2$ be the local parametrization,

$$(x, y) \mapsto (x, y, \sqrt{1 - x^2 - y^2}),$$

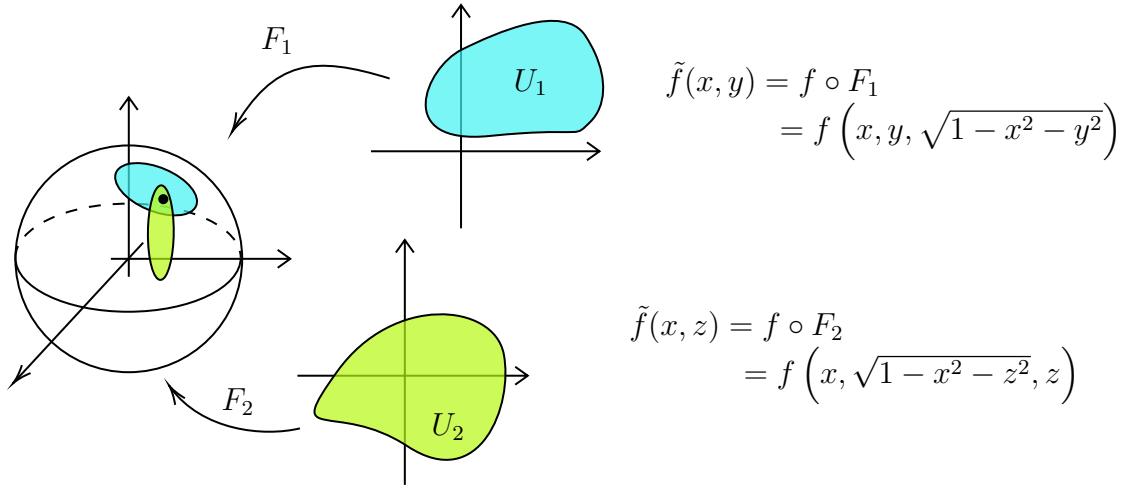
then $\tilde{f}(x, y): U \rightarrow \mathbb{R}, \tilde{f}(x, y) = f \circ F$.

Similarly, if the point lies on other five charts(see section 2.2). There is also a function \tilde{f} essentially defined on an open set of \mathbb{R}^2 to associate f .

Question (2). What does it mean by a “smooth” (or differentiable) function on \mathbb{S}^2 ?

f is smooth near $p \Leftrightarrow \tilde{f}: U \subset \mathbb{R}^2 \rightarrow \mathbb{R}$ is smooth,
 $(\because F: U \subset \mathbb{R}^2 \rightarrow \mathbb{S}^2$ is smooth)

Question (3). p could lie on two charts, (*i.e.* we can associate two coordinate charts near p , will the “smoothness” of f be affected?)



Smoothness is not affected by the coordinate change. Moreover, it's easy to apply the chain rule to find relation of differentials of f between different coordinate charts.

Definition 2.3.1 (Differential function). S is a regular surface in \mathbb{R}^3 . A function f is said to be differentiable at $p \in S$, if for a local parametrization near p

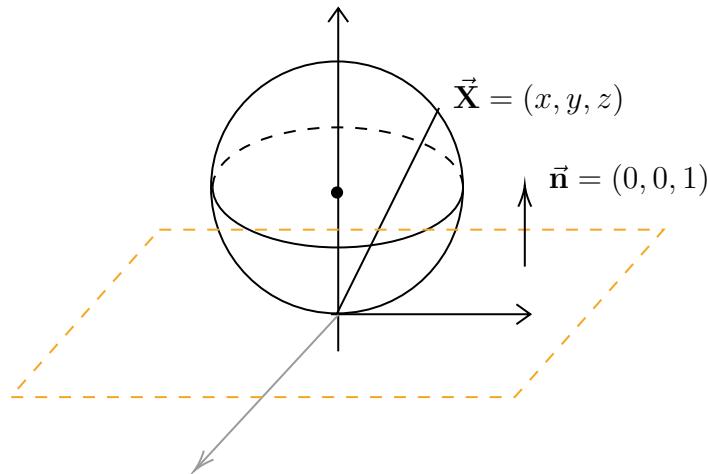
$$x: U \subset \mathbb{R}^2 \rightarrow \mathbb{R}^3,$$

the function $f \circ x: \mathbb{R}^2 \rightarrow \mathbb{R}$ is differentiable at $x^{-1}(p)$

Remark. $f \circ x$ is well-defined, since the differentiability is not affected by a change of parameter, e.g. if $y: V \subset \mathbb{R}^2 \rightarrow \mathbb{R}^3$ is another parametrization near p , $f \circ y = f \circ x \circ (\underbrace{x^{-1} \circ y}_{\text{change of parameter}})$ is differentiable.

Example. Consider $x^2 + y^2 + (z - 1)^2 = 1$.

(1) Consider $\vec{\mathbf{X}} = (x, y, z)$ be the position vector field in \mathbb{R}^3 . Let $f(x, y, z) = \vec{\mathbf{X}} \cdot \vec{\mathbf{n}}$ where $\vec{\mathbf{n}} = (0, 0, 1)$ is the unit normal of xy plane.



$\Rightarrow f(x, y, z) = z$. At point $(x, y, z) \in \mathbb{S}^2$, $z > 1$, $f(x, y, z) = 1 + \sqrt{1 - x^2 - y^2}$, where $x^2 + y^2 < 1$, it's a smooth function.

(2) Consider $d^2(x, y, z) = x^2 + y^2 + z^2 = |\vec{\mathbf{X}}|^2$, d is the distance function on \mathbb{R}^2 . $d^2|_{\mathbb{S}^2} = 2z = 2f$ in (1), hence it's a smooth function.

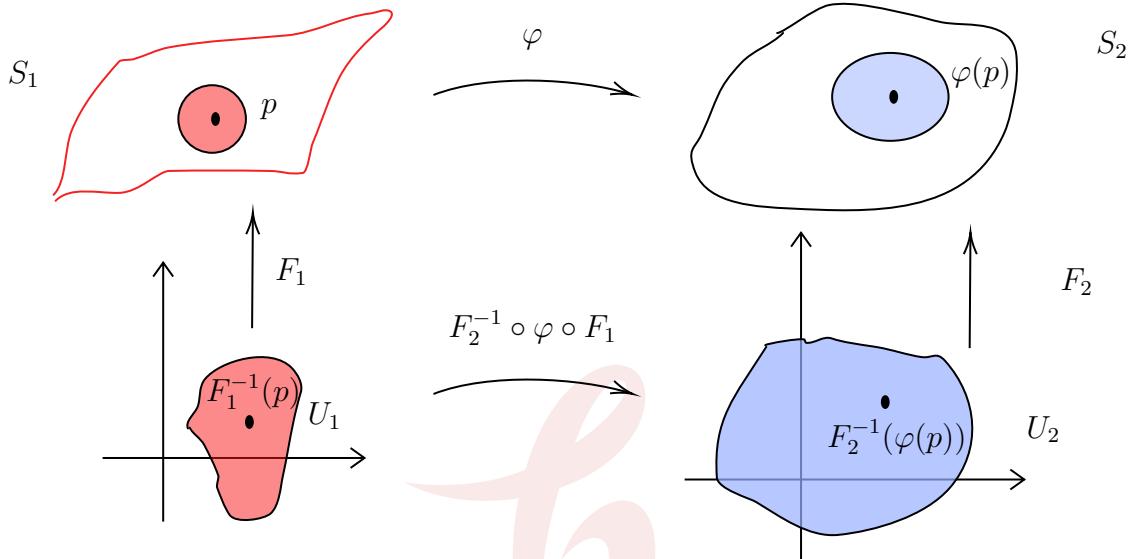


Exercise. How does the function f look like in other coordinate charts?

Definition 2.3.2 (Differentiable mapping between two surfaces). S_1, S_2 are regular surfaces, $\varphi: S_1 \rightarrow S_2$ is a mapping that maps $p \in S_1$ to $\varphi(p) \in S_2$. We say φ is differentiable at $p \in S_1$, if for some parametrization

$$F: U_1 \rightarrow S_1 (\ni p), \quad F_2: U_2 \rightarrow S_2 (\ni \varphi(p))$$

$F_2^{-1} \circ \varphi \circ F_1: U_1 \rightarrow U_2$ is differentiable at $F_1^{-1}(p)$.



Locally, if (u, v) serves as coordinate of p , $F_2^{-1} \circ \varphi \circ F_1 = (\varphi_1, \varphi_2)$, then φ is differentiable iff φ^1 and φ^2 are differentiable Functions.

Remark. In the future, we won't explicitly write F_1 and F_2 , but simply write $\varphi: S_1 \rightarrow S_2$ locally as $\varphi(u, v) = (\varphi^1(u, v), \varphi^2(u, v))$.

Definition 2.3.3 (Diffeomorphism). S_1 and S_2 are regular surfaces. S_1 is diffeomorphic to S_2 if $\exists f: S_1 \rightarrow S_2$ such that both f and f^{-1} are differentiable.

Remark. Diffeomorphism is the equivalent relation we often use in differential geometry. Later, we'll introduce a “stronger” equivalent relation after defining the 1st fundamental form.

Question. Can you give an intuitive example of “Diffeomorphism” between two surfaces?

Example. Identity map/ \mathbb{R}^2 with translation action, rotation action/ $\mathbb{S}^2(1)$ by changing radius.

! All diffeomorphism of a surface is a group. (Lie group) (because the composition (multiplication of the group) of two diffeomorphism is also a diffeomorphism).

Example. $x^2 + y^2 + z^2 = 1$ is diffeomorphic to $(\frac{x}{a})^2 + (\frac{y}{b})^2 + (\frac{z}{c})^2 = 1 (a, b, c \neq 0)$.

Proof. Consider $\varphi: \mathbb{R}^3 \rightarrow \mathbb{R}^3$

$$(x, y, z) \mapsto (ax, by, cz).$$



This is a diffeomorphism of \mathbb{R}^3 . (what is $\varphi|_{\mathbb{S}^2}$?)

If $p \in \mathbb{S}^2$ lies on the upper semi-sphere, we use parametrization

$$F(x, y) = (x, y, \sqrt{1 - x^2 - y^2}) : U \subset \mathbb{R}^2 \rightarrow \mathbb{R}^3.$$

So near p

$$\varphi|_{\mathbb{S}^2} = (ax, by, cz) = (u, v, w) \Rightarrow \left(\frac{u}{a}\right)^2 + \left(\frac{v}{b}\right)^2 + \left(\frac{w}{c}\right)^2 = 1.$$

By checking points in other five charts on \mathbb{S}^2 , we obtain $\varphi: \mathbb{S}^2 \rightarrow$ ellipsoid is a diffeomorphism. (φ^{-1} is self-clear in the above expression.) \square

2.4 Tangent plane and differential of a map

- Let S be a regular surface, $p_0 \in S$. In Calculus, we defined the tangent plane at $p_0: T_{p_0}S$ as follows: if $F: U \subset \mathbb{R}^2 \rightarrow \mathbb{R}^3$ is a local parametrization near p_0

$$(u, v) \mapsto (x(u, v), y(u, v), z(u, v)).$$

Since F is regular, $\Rightarrow \frac{\partial F}{\partial u} \wedge \frac{\partial F}{\partial v}$ is a normal vector of the tangent plane. Hence, $T_{p_0}S$ has the equation

$$\left(\frac{\partial F}{\partial u} \wedge \frac{\partial F}{\partial v} \right) \cdot (p - p_0) = 0, \quad p \in \mathbb{R}^3.$$

However, this definition has some deficiency:

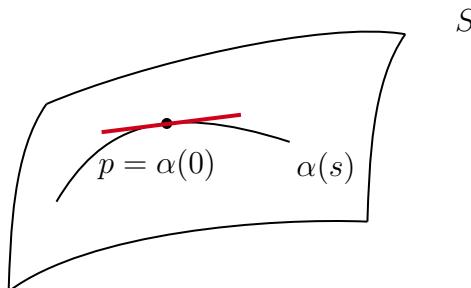
- (1) We “have” not checked what happened if we change the parameter.

(In geometry, whenever you define a concept by using some parametrization, you should always check that the concept doesn’t depend on the choice of your parametrization, so it’s a well-defined definition.)

- (2) When we write the equation of the tangent plane, we have used Euclidean inner product in \mathbb{R}^3 .

(The tangent space should be an intrinsic object, i.e. it depends on the surface itself only.)

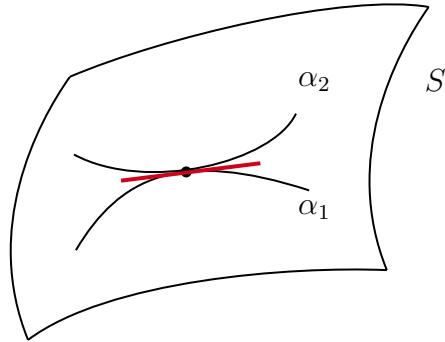
Definition 2.4.1 (Tangent vector). V is called a tangent vector at $p \in S$ if \exists a smooth curve $\alpha: (-\epsilon, \epsilon) \rightarrow S$ with $\alpha(0) = p$ such that $\alpha'(0) = V$.



Definition 2.4.2 (Tangent space). $T_p S$ = all tangent vectors at p . (i.e. Tangent space is the collection of all tangent vectors of equivalent classes of curves passing through p .)



Here, we say two curves $\alpha_1: (-\epsilon, \epsilon) \rightarrow S, \alpha_2: (-\epsilon, \epsilon) \rightarrow S$ are equivalent at p if $\alpha_1(0) = \alpha_2(0)$ and $\alpha'_1(0) = \alpha'_2(0)$.



Remark.

- (1) This definition is sufficient in the following study of the course. Later, we will give another definition of tangent space by viewing a tangent vector as an operator acting on some equivalent class of C^∞ functions at a point. (*i.e.* a tangent vector is a “directional derivative”, which satisfies “Linearity” and “Leibniz rule”) This will tell us how to take derivative of a function on a surface.
- (2) In algebraic geometry course, you’ll also see another definition of tangent vector (space) of an algebraic variety. You should make a comparison with these definitions, This is more abstract.

Claim: Local expression of tangent vector is independent of the choice of local parametrization.

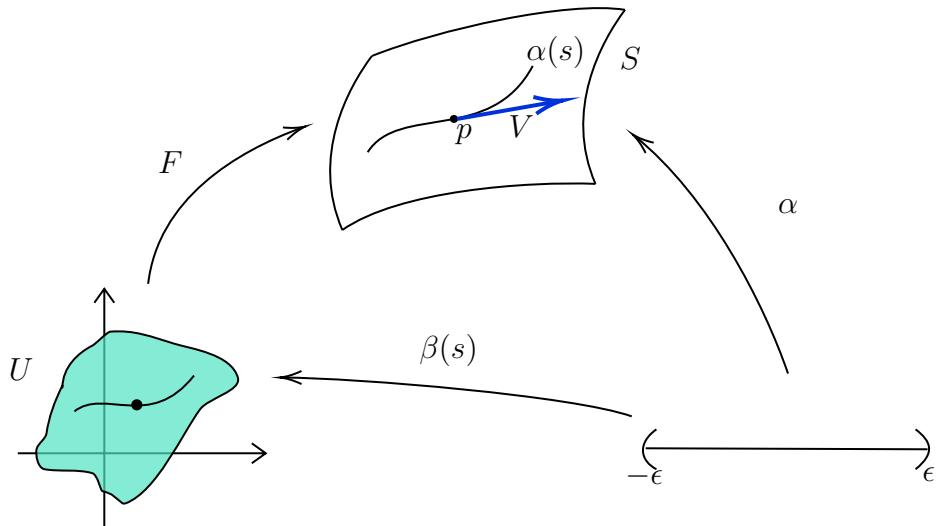
Proof. Let $\alpha(s): (-\epsilon, \epsilon) \rightarrow S$ be the regular curve such that $\alpha'(0) = V$ for the given tangent vector V at p . Choose a local parametrization near p ,

$$\begin{aligned} F: U \subset \mathbb{R}^2 &\rightarrow S \\ (u, v) &\mapsto (x(u, v), y(u, v), z(u, v)), \end{aligned}$$

then $\alpha(s) = (x(u(s), v(s)), y(u(s), v(s)), z(u(s), v(s)))$. In fact, if we define

$$\beta(s) = F^{-1} \circ \alpha(s): (-\epsilon, \epsilon) \rightarrow U \subset \mathbb{R}^2,$$

then $\alpha(s) = F \circ \beta(s)$.





$$V = \alpha'(0) = \frac{\partial(x, y, z)}{\partial(u, v)} \cdot \frac{\partial(u, v)}{\partial s} \Big|_{s=0}. \quad (1)$$

Now, let G be another parametrization

$$\begin{aligned} G: V &\rightarrow S \\ (\alpha, \beta) &\mapsto (x(\alpha, \beta), y(\alpha, \beta), z(\alpha, \beta)). \end{aligned}$$

Let $\gamma: (-\epsilon, \epsilon) \rightarrow V$ be $\gamma(s) = G^{-1} \circ \alpha(s): (-\epsilon, \epsilon) \rightarrow V$, then $\alpha(s) = G \circ \gamma(s)$, and

$$\alpha'(0) = \frac{\partial(x, y, z)}{\partial(\alpha, \beta)} \cdot \frac{\partial(\alpha, \beta)}{\partial s} \Big|_{s=0}. \quad (2)$$

(1) and (2) are essentially the same by the chain rule, *i.e.*

$$\frac{\partial(x, y, z)}{\partial(u, v)} \cdot \frac{\partial(u, v)}{\partial s} \Big|_{s=0} = \frac{\partial(x, y, z)}{\partial(\alpha, \beta)} \cdot \underbrace{\frac{\partial(\alpha, \beta)}{\partial(u, v)} \cdot \frac{\partial(u, v)}{\partial(\alpha, \beta)}}_{\text{identity matrix}} \cdot \frac{\partial(\alpha, \beta)}{\partial s} \Big|_{s=0}$$

□

Proposition 2.4.3. Let $F: U \subset \mathbb{R}^2 \rightarrow S$ be a local parametrization near p with $F(q) = p$, then $dF_q(\mathbb{R}^2) = T_p S$.

Proof.

$$(1) dF_q(\mathbb{R}^2) \subset T_p S$$

$\forall V \in \mathbb{R}^2$, let $\beta(t) = q + tV \in \mathbb{R}^2$, then $\beta'(0) = v$. Let $\alpha(t) = F(\beta(t))$ is a C^∞ - curve passing through p , and

$$T_p S \ni \alpha'(0) = dF_q(\beta'(0)) = dF_q(V)$$

$$(2) T_p S \subset dF_q(\mathbb{R}^2)$$

$V \in T_p S \Rightarrow \exists \alpha(t): (-\epsilon, \epsilon) \rightarrow S$ such that $\alpha(0) = p$ and $\alpha'(0) = V$. Let $\beta(t) = F^{-1}(\alpha(t))$, then $\alpha(t) = F(\beta(t))$. We remark $\beta(t)$ is a C^∞ -curve in \mathbb{R}^2 . (Because we have checked the transition function is C^∞ and F^{-1} comes from the composition of transition function) Thus,

$$V = \alpha'(0) = dF_q(\beta'(0)) \in \text{im } dF_q$$

□

Remark.

- (1) $T_p S$ is the full image of linear space under a linear map, thus $T_p S$ is a linear space of dimension 2.
- (2) dF_q is injective $\Rightarrow F_u(q), F_v(q)$ are linearly independent, and they are tangent vectors of coordinate curve $F(u, v_0)$ and $F(u_0, v)$ at $(u_0, v_0) = q$, which implies that $T_p S = \text{span}\{F_u(q), F_v(q)\}$.
- (3) $TS = \bigsqcup_{p \in S} T_p S = \{(p, V) | p \in S, V \in T_p S\}$. This set can be given a smooth coordinate covering, and is called the tangent bundle of S , which is a 4-d smooth manifold. The projection

$$\begin{aligned} \pi: TS &\rightarrow S \\ (p, V) &\mapsto p \end{aligned}$$

is C^∞



Tangent vector, tangent space, tangent bundle and tangent vector field

(1) On \mathbb{R}^n .

- A vector is $V = (v^1, v^2, \dots, v^n)$.
- A standard basis is $\{e_1, e_2, \dots, e_n\}$, where $e_i = (0, \dots, \overset{i^{th}}{1}, \dots, 0)$.
 $\Rightarrow V = \sum_{i=1}^n v^i e_i$.
- f is smooth in \mathbb{R}^n , the directional derivative along a vector v at p is

$$(D_V f)(p) = \langle \nabla f, V \rangle_p = \sum_{i=1}^n v^i \frac{\partial f}{\partial x^i} \Big|_p = \left(\sum_{i=1}^n v^i \frac{\partial}{\partial x^i} \right) f \Big|_p.$$

Hence, we can identify $e_i = \frac{\partial}{\partial x^i}$ for $i = 1, 2, \dots, n$ and shall call $\frac{\partial}{\partial x^i}$ the coordinate vector (field).

$$\Rightarrow V = \sum_{i=1}^n v^i e_i = \sum_{i=1}^n v^i \frac{\partial}{\partial x^i}.$$

- Note in this way, we actually view a vector V as a first order linear operator acting on smooth functions, i.e. for $p \in \mathbb{R}^n$

$$V_p: C^\infty(\mathbb{R}^n) \rightarrow \mathbb{R},$$

$$f \mapsto V(f)(p) = (D_V f)(p) = \left(v^i \frac{\partial f}{\partial x^i} \right)(p).$$

Furthermore, this defines

$$V: C^\infty(\mathbb{R}^n) \rightarrow C^\infty(\mathbb{R}^n)$$

$$f \mapsto V(f).$$

The operator V satisfies

$$\begin{cases} (V + kW)f = V(f) + kW(f) & (\text{Linearity}) \\ V(fg) = V(f)g + fV(g) & (\text{Leibniz rule}) \end{cases}$$

(2) S is a regular surface in \mathbb{R}^3 , $p \in S$

- $C^\infty(S) =$ all smooth functions on S .
- We have defined $V \in T_p S$, if \exists a smooth curve $\alpha: (-\epsilon, \epsilon) \rightarrow S$ such that $\alpha(t) = p$, $\alpha'(0) = V$.
- To compute V , we choose a local parametrization

$$F: U(\subset \mathbb{R}^2) \longrightarrow S \subset \mathbb{R}^3$$

$$(y^1, y^2) \longmapsto (x^1, x^2, x^3).$$

$\Rightarrow \alpha(s) = F(y^1(s), y^2(s))$ (This is to say we consider $\alpha: (-\epsilon, \epsilon) \rightarrow U \xrightarrow{F} S$).

$$\Rightarrow V = \alpha'(0) = \left(\sum_{i=1}^2 \frac{\partial x^1}{\partial y^i} \frac{dy^i}{ds}, \sum_{i=1}^2 \frac{\partial x^2}{\partial y^i} \frac{dy^i}{ds}, \sum_{i=1}^2 \frac{\partial x^3}{\partial y^i} \frac{dy^i}{ds} \right) \Big|_{p(s=0)}.$$

Notice V is a vector in \mathbb{R}^3 , by using notation in item 1

$$V_p = \sum_{\alpha=1}^3 \left(\sum_{i=1}^2 \frac{\partial x^\alpha}{\partial y^i} \frac{dy^i}{ds} \right) \frac{\partial}{\partial x^\alpha} \Big|_p.$$

Clearly, the linearity and Leibniz rule hold for the

$$V_p: C^\infty(S) \rightarrow \mathbb{R}$$

$$f \mapsto V_p(f) = \left(\left(\sum_{\alpha=1}^3 \sum_{i=1}^2 \frac{\partial x^\alpha}{\partial y^i} \frac{dy^i}{ds} \frac{\partial}{\partial x^\alpha} \right) f \right) (p). \quad (\text{a})$$

Note that during the lecture, we have shown

$$T_p S = dF_{F^{-1}(p)}(\mathbb{R}^2) = \text{span} \{ F_{y^1}, F_{y^2} \}.$$

Moreover,

$$F_{y^i} = \sum_{\alpha=1}^3 \frac{\partial x^\alpha}{\partial y^i} \frac{\partial}{\partial x^\alpha},$$

by using the notation in item 1, and we can write

$$F_{y^i} = \frac{\partial F}{\partial y^i} = dF_{F^{-1}(p)} \left(\frac{\partial}{\partial y^i} \right), \quad i = 1, 2.$$

$$\Rightarrow T_p S = \text{span} \left\{ dF_{F^{-1}(p)} \left(\frac{\partial}{\partial y^1} \right), dF_{F^{-1}(p)} \left(\frac{\partial}{\partial y^2} \right) \right\},$$

since $dF_{F^{-1}(p)}: \mathbb{R}^2 \rightarrow T_p S$ is a linear isomorphism. By abusing notation here (actually not)

$$T_p S = \text{span} \left\{ \frac{\partial}{\partial y^1}, \frac{\partial}{\partial y^2} \right\},$$

and

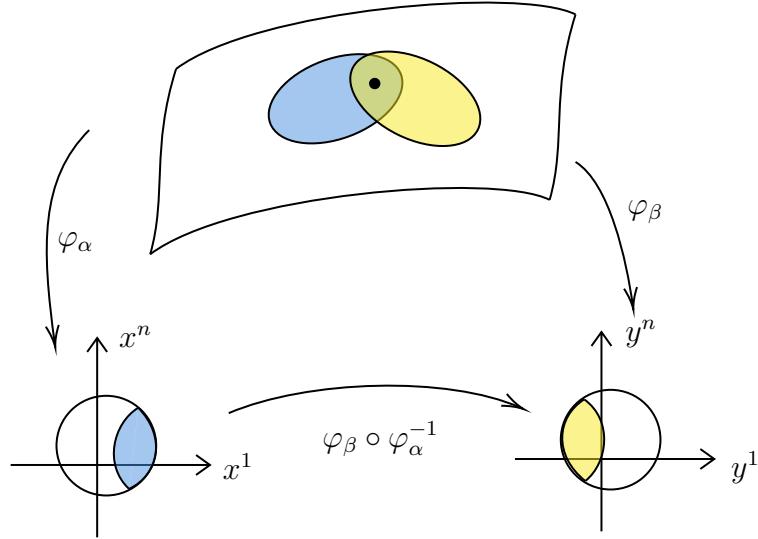
$$V_p(f) = \left(\sum_{i=1}^2 \frac{dy^i}{ds} \frac{\partial}{\partial y^i} \right) (f)(p).$$

Hence,

$$T_p S = \{ \text{all tangent vectors } v \text{ at } p \}.$$

Remark. If M is a smooth manifold of dimension n . By definition, M is a topological manifold (*i.e.* Hausdorff + second countable + locally Euclidean) that admits a smooth structure, which means that \exists a covering $\{(U_\alpha, \varphi_\alpha)\}_{\alpha \in \Lambda}$ of M such that

- $\varphi_\alpha: U_\alpha \rightarrow \varphi_\alpha(U_\alpha) \subset \mathbb{R}^n$ is a homeomorphism.
- $\varphi_\beta \circ \varphi_\alpha^{-1}: \varphi_\alpha(U_\alpha \cap U_\beta) \rightarrow \varphi_\beta(U_\alpha \cap U_\beta)$ is C^∞ , $\forall \alpha, \beta$ such that $U_\alpha \cap U_\beta \neq \emptyset$.



Note that $\varphi_\alpha: U_\alpha \rightarrow \varphi_\alpha(U_\alpha)$ actually endow a coordinate on the chart U_α , i.e. $p \in U_\alpha$, $\varphi_\alpha(p) = (x^1(p), x^2(p), \dots, x^n(p))$. Hence, $p \in M$, choose U_α as its coordinate chart

$$\Rightarrow T_p M = \text{span} \left\{ \frac{\partial}{\partial x^1}, \dots, \frac{\partial}{\partial x^n} \right\}.$$

Note that if at p , there are two coordinate charts

$$\left\{ U, (x^1, \dots, x^n) \right\} \text{ and } \left\{ V, (y^1, \dots, y^n) \right\},$$

and a vector $V \in T_p S$ is expressed as

$$V = \sum_{i=1}^n V^i \frac{\partial}{\partial x^i} = \sum_{\alpha=1}^n \tilde{V}^\alpha \frac{\partial}{\partial y^\alpha},$$

then

$$\tilde{V}^\alpha = V^i \frac{\partial y^\alpha}{\partial x^i}$$

(3) Tangent (vector) bundle

In (2), we have seen that the tangent space $T_p S$ of a regular surface does not depend on how we “put” S inside \mathbb{R}^3 , and that $T_p S = \text{span} \left\{ \frac{\partial}{\partial y^1}, \frac{\partial}{\partial y^2} \right\}$ for (y^1, y^2) a local coordinate in a neighborhood of p . This discussion holds for any smooth manifold.

In the following, let's just give the general discussion.

- Let M be a smooth manifold, $\forall p \in M$, $T_p M$ is the tangent space at p . Define

$$TM = \bigsqcup_{p \in M} T_p M = \left\{ (p, V) \mid p \in M, V \in T_p M \right\},$$

then there is a projection map

$$\pi: TM \rightarrow M$$

$$(p, V) \mapsto p.$$

We shall show that the total space of $TM \rightarrow M$ is a $2n$ -dim smooth manifold such that $\pi: TM \rightarrow M$ is a smooth map. To achieve this goal, we need to define a smooth structure on the total space TM .

- M is a smooth manifold, by definition, \exists a countable covering $\{(U_\alpha, \varphi_\alpha)\}_{\alpha \in \Lambda}$ such that

– $\varphi_\alpha: U_\alpha \rightarrow \varphi(U_\alpha) \subset \mathbb{R}^n$ is a homeomorphism,

$$\varphi_\alpha(p) = (x_\alpha^1(p), x_\alpha^2(p), \dots, x_\alpha^n(p)).$$

– $\varphi_\beta \circ \varphi_\alpha^{-1}: \varphi_\alpha(U_\alpha \cap U_\beta) \rightarrow \varphi_\beta(U_\alpha \cap U_\beta)$ is smooth, $\forall \alpha, \beta$ such that $U_\alpha \cap U_\beta \neq \emptyset$.

- For each U_α , $\pi^{-1}(U_\alpha)$ contains all pairs $(p, V), p \in U_\alpha, V \in T_p M$. We define local trivialization (local coordinate chart near (p, V)) by letting

$$\tilde{\varphi}_\alpha: \pi^{-1}(U_\alpha) \rightarrow U_\alpha \times \mathbb{R}^n$$

$$(p, V) \mapsto (\varphi_\alpha(p), V^1, V^2, \dots, V^n).$$

Note $\tilde{\varphi}_\alpha(p) = (x_\alpha^1(p), x_\alpha^2(p), \dots, x_\alpha^n(p))$, $V = \sum_{i=1}^n V^i(p) \frac{\partial}{\partial x^i}$, then

$$\tilde{\varphi}_\alpha^{-1}(x_\alpha^1, \dots, x_\alpha^n; V^1, \dots, V^n) = \left(p, \sum V^i \frac{\partial}{\partial x^i} \right),$$

i.e. $\tilde{\varphi}_\alpha$ is bijective and $\tilde{\varphi}_\alpha(\pi^{-1}(U_\alpha))$ is an open set. Then $\{\tilde{\varphi}_\alpha^{-1}(U_\alpha \times \mathbb{R}^n)\}_{\alpha \in \Lambda}$ is a countable covering of TM . Moreover, this defines a topology on TM , such that

$$\tilde{\varphi}_\alpha: \pi^{-1}(U_\alpha) \rightarrow U_\alpha \times \mathbb{R}^n$$

is a homeomorphism. Next, if $\pi^{-1}(U_\alpha) \cap \pi^{-1}(U_\beta) \neq \emptyset$ ($\Leftrightarrow U_\alpha \cap U_\beta \neq \emptyset$), let $p \in U_\alpha \cap U_\beta$ and

$$\tilde{\varphi}_\alpha(p, V) = (x_\alpha^1(p), \dots, x_\alpha^n(p); V_\alpha^1, \dots, V_\alpha^n)$$

$$\tilde{\varphi}_\beta(p, V) = (x_\beta^1(p), \dots, x_\beta^n(p); V_\beta^1, \dots, V_\beta^n)$$

$$\begin{aligned} &\Rightarrow \tilde{\varphi}_\beta \circ \tilde{\varphi}_\alpha^{-1}(x_\alpha^1(p), \dots, x_\alpha^n(p); V_\alpha^1, \dots, V_\alpha^n) \\ &= (x_\beta^1(p), \dots, x_\beta^n(p); V_\beta^1, \dots, V_\beta^n), \end{aligned}$$

where

$$V_p = \sum_{i=1}^n V_\alpha^i \frac{\partial}{\partial x_\alpha^i} = \sum_{j=1}^n V_\beta^j \frac{\partial}{\partial x_\beta^j}$$

$$V_\beta^j = \sum_{i=1}^n V_\alpha^i \frac{\partial y_\beta^j}{\partial x_\alpha^i},$$

i.e.

$$\begin{aligned} & \tilde{\varphi}_\beta \circ \tilde{\varphi}_\alpha^{-1} (x_\alpha^1(p), \dots, x_\alpha^n(p); V_\alpha^1, \dots, V_\alpha^n) \\ &= \left(\varphi_\beta \circ \varphi_\alpha^{-1} (x_\alpha^1, \dots, x_\alpha^n); \sum_{i=1}^n V_\alpha^i \frac{\partial y_\beta^1}{\partial x_\alpha^i}, \dots, \sum_{i=1}^n V_\alpha^i \frac{\partial y_\beta^n}{\partial x_\alpha^i} \right). \end{aligned}$$

Hence, $\tilde{\varphi}_\beta \circ \tilde{\varphi}_\alpha^{-1}$ is smooth since $\varphi_\beta \circ \varphi_\alpha^{-1}$ is smooth, and the transition function on the vector part is just linear.

- The Hausdorff property of TM is also clear from the Hausdorff property of M .
- With the smooth structure defined above, Clearly $\pi: TM \rightarrow M$ is a smooth map since π is just a projection (when expressed in coordinate).

Tangent vector field

Definition 2.4.4. A smooth vector field V is a C^∞ -map

$$V: M \rightarrow TM$$

such that $\pi \circ V = \text{id}_M$. In a coordinate chart $(U_\alpha, (x_\alpha^1, \dots, x_\alpha^n))$,

$$V = \sum_{i=1}^n V_\alpha^i(x) \frac{\partial}{\partial x_\alpha^i}$$

Remark.

- (1) A smooth vector field is also called a smooth section of the tangent (vector) bundle.
- (2) Since the tangent vector is linear and satisfies the Leibniz rule, so is the vector field. Hence,

$$\begin{aligned} V: C^\infty(M) &\rightarrow C^\infty(M) \\ f &\mapsto V(f) \end{aligned}$$

is characterized by $V(fg) = V(f)g + fV(g)$.

Exercise.

- (1) \mathbb{S}^1 : unit circle. $T\mathbb{S}^1 \simeq \mathbb{S}^1 \times \mathbb{R}$ is a diffeomorphism.

Intuitive observation of this diffeomorphism: we can choose local charts on \mathbb{S}^1 by

$$\theta \in (0, 2\pi) = U, \quad \varphi \in (\frac{\pi}{2}, \frac{3\pi}{2}) = V$$

i.e. $\varphi = \theta + \frac{\pi}{2}$, which is simply a rotation.

$$T\mathbb{S}^1|_U = \left\{ \left(\theta, a(\theta) \frac{\partial}{\partial \theta} \right) \right\}$$

$$T\mathbb{S}^1|_V = \left\{ \left(\varphi, a(\varphi) \frac{\partial}{\partial \varphi} \right) \right\}.$$

In this case, the transition function is just linear by rotation. Hence, $T\mathbb{S}^1|_U$ and $T\mathbb{S}^1|_V$ can be glued by shifting $\frac{\pi}{2}$.



(2) \mathbb{S}^2 unit sphere. However, $T\mathbb{S}^2 \not\cong \mathbb{S}^2 \times \mathbb{R}^2$. To see this, we take stereographical parametrization. (Since there are only two coordinate charts)

$$p_N: \mathbb{S}^2 - \{N\} \rightarrow \mathbb{R}^2$$

$$(x, y, z) \mapsto \left(\frac{x}{1-z}, \frac{y}{1-z} \right)$$

$$p_S: \mathbb{S}^2 - \{S\} \rightarrow \mathbb{R}^2$$

$$(x, y, z) \mapsto \left(\frac{y}{1+z}, \frac{x}{1+z} \right).$$

The transition function is given by

$$p_S \circ p_N^{-1}(x, y) = \left(\frac{y}{x^2 + y^2}, \frac{x}{x^2 + y^2} \right) = (u, v)$$

$$\Rightarrow \begin{cases} \frac{\partial}{\partial x} = -2uv \frac{\partial}{\partial u} + (v^2 - u^2) \frac{\partial}{\partial v} \\ \frac{\partial}{\partial y} = (u^2 - v^2) \frac{\partial}{\partial u} - 2uv \frac{\partial}{\partial v} \end{cases}.$$

Note $(x, y) = (0, 0)$ is just the North Pole and $(u, v) = (0, 0)$ is just the South Pole. At these two points, the coordinate vector fields are zero vectors, e.g. $\frac{\partial}{\partial x}, \frac{\partial}{\partial y}$ are zero vectors at the South Pole. This means that we can not extend the tangent plane in the trivialization $p_N^{-1}(\mathbb{R}^2)$ passing through the South Pole, hence we can not have a global trivialization of $T\mathbb{S}^2$. $T\mathbb{S}^2 \not\cong \mathbb{S}^2 \times \mathbb{R}^2$

Next, we would like to mention a more abstract way to think about the tangent space.

- M is a smooth manifold, $p \in M$
- $C_p^\infty(M) = \{\text{all } C^\infty \text{ functions on } M \text{ vanishing at } p\}$
 $C_p^\infty(M)^2 = \{\text{all finite sums } \sum f_i g_i \text{ with } f_i, g_i \in C_p^\infty(M)\}$
 $\Rightarrow C^\infty(M) = \{\text{constant functions}\} \oplus C_p^\infty(M) = \mathbb{R} \oplus C_p^\infty(M).$
- Let V be a tangent vector at p , $V: C^\infty(M) \rightarrow \mathbb{R}$ and $V|_{\mathbb{R}} = 0$. Moreover, it's easy to see by the Leibniz rule that $V|_{C_p^\infty(M)^2} = 0$
 $\Rightarrow V: C_p^\infty(M)/C_p^\infty(M)^2 \rightarrow \mathbb{R}$

is a linear map, i.e. $V \in \left(C_p^\infty(M)/C_p^\infty(M)^2 \right)^*$

$\Rightarrow T_p M \simeq \left(C_p^\infty(M)/C_p^\infty(M)^2 \right)^*$ is an isomorphism. Hence, we can define tangent space $T_p M$ as $\left(C_p^\infty(M)/C_p^\infty(M)^2 \right)^*$

This definition tells that a tangent vector is a linear map on $C^\infty(M)$ vanishing on constants and only depends on the first order Taylor's expansion of a function f at p .

In algebraic geometry language, the vanishing ideals $C_p^\infty(M)$ are the maximal ideals in the algebra of smooth functions, with $C_p^\infty(M)^2$ the second power. More generally, for any maximal ideal I in a commutative algebra A , one may define the tangent space as $(I/I^2)^*$.

Remark. This last part is not required in this course.

Definition 2.4.5 (Differential of a map). Let S_1, S_2 be regular surfaces, $f: S_1 \rightarrow S_2$ is a C^∞ map. Its differential at p

$$df_p: T_p S_1 \rightarrow T_{f(p)} S_2$$

is defined as follows:

$\forall v \in T_p S_1$, take an $\alpha(s): (-\epsilon, \epsilon) \rightarrow S_1$ such that $\alpha'(0) = v, \alpha(0) = p$. Then $df_p(v)$ is defined as

$$df_p(v) = \left. \frac{d}{ds} \right|_{s=0} f(\alpha(s)) \in T_{f(p)} S_2. \quad (1)$$

Remark. Although in the definition above, we do not involve coordinate, in practice we usually need to do computation with coordinate.

- $df_p: T_p S_1 \rightarrow T_{f(p)} S_2$ is a linear map.

Proof. On S_1 near p , we choose local parametrization $F: U \rightarrow S_1$. On S_2 near $f(p)$, we choose local parametrization $G: V \rightarrow S_2$. We have seen

$$\begin{aligned} dF_p(\mathbb{R}^2) &= T_p S_1 \\ dG_{f(p)}(\mathbb{R}^2) &= T_{f(p)} S_2, \end{aligned}$$

and $dF_p, dG_{f(p)}$ are both invertible linear maps. Hence, we have the following diagram.

$$\begin{array}{ccccc} S_1 & \xrightarrow{f} & S_2 & & T_p S_1 \xrightarrow{df_p} T_{f(p)} S_2 \\ \uparrow F & & \uparrow G & \xrightarrow{\text{linearize at } p} & \uparrow dF_p \\ \mathbb{R}^2 \supset U & \xrightarrow{d(G^{-1} \circ f \circ F)} & V \subset \mathbb{R}^2 & & \mathbb{R}^2 \xrightarrow{d(G^{-1} \circ f \circ F)_p} \mathbb{R}^2 \end{array}$$

By the chain rule,

$$d(G^{-1} \circ f \circ F)_p = dG_{f(p)}^{-1} \circ df_p \circ dF_{F^{-1}(p)}.$$

From calculus, we know $d(G^{-1} \circ f \circ F)_p: \mathbb{R}^2 \rightarrow \mathbb{R}^2$ is a linear map and $dF_p, dG_{f(p)}^{-1}$ are linear maps. Hence, we conclude $df_p: T_p S_1 \rightarrow T_{f(p)} S_2$ is also linear. \square

Remark.

(a) In eq. (1), if taking $S_2 = \mathbb{R}$, then we have defined the “differential of a smooth function f ”

$$df_p(v) = \left. \frac{d}{ds} \right|_{s=0} (f(\alpha(s))),$$

where $df_p(v)$ should be understood as the “directional derivation” of f at p . Now df_p is a covector, belonging to $T_p^* S$, the dual space of $T_p S = \{\text{all linear maps } \omega: T_p S \rightarrow \mathbb{R}\}$. $T_p^* S$ is also a linear space. If $T_p S = \text{span}\{e_1, e_2\}$, then $T_p^* S = \text{span}\{e_1^*, e_2^*\}$ where

$$e_i^*(e_j) = \begin{cases} 1 & i = j \\ 0 & i \neq j. \end{cases}$$

Note: globally not all covectors can be written as df Due to the obstruction from topology, *i.e.* $H^1(M, \mathbb{R})$.

(b) Later, you may also see (with other definition of tangent vector) $df_p(V) = V(f)(p)$, where $V(f)$ means taking derivative of f along V .

(c) $d(f+g)_p(V) = df_p(V) + dg_p(V)$
 $d(f \cdot g)_p(V) = df_p(V)g(p) + f(p)dg_p(V)$ (Leibniz rule)

Exercise.

- (1) $\text{Id}: M \rightarrow M$ is the identity map. $\Rightarrow d(\text{Id})_p(V) = V$.
 (2) Compute the differential of a rotational map on \mathbb{S}^2 . We use local parametrization on \mathbb{S}^2 :

$$(\sin \varphi \cos \theta, \sin \varphi \sin \theta, \cos \varphi)^t = p.$$

Consider the rotation of \mathbb{S}^2 around the z -axis in counterclockwise direction about degree α

$$\begin{aligned} \Rightarrow R(\alpha)(p) &= (\sin \varphi \cos(\theta + \alpha), \sin \varphi \sin(\theta + \alpha), \cos \varphi)^t \\ &= (\sin \varphi (\cos \theta \cos \alpha - \sin \theta \sin \alpha), \sin \varphi (\sin \theta \cos \alpha + \cos \theta \sin \alpha), \cos \varphi)^t \\ &= \underbrace{\begin{pmatrix} \cos \alpha & -\sin \alpha & 0 \\ \sin \alpha & \cos \alpha & 0 \\ 0 & 0 & 1 \end{pmatrix}}_A \begin{pmatrix} \sin \varphi \cos \theta \\ \sin \varphi \sin \theta \\ \cos \varphi \end{pmatrix}. \end{aligned}$$

Note $R(\alpha): \mathbb{S}^2 \rightarrow \mathbb{S}^2$ is a linear action (map). To compute dR_p , we need to know for $v \in T_p \mathbb{S}^2$, what is $dR_p(v)$?

Let $\gamma(s)$ be the curve on S such that $\gamma'(0) = v$, then

$$\begin{aligned} dR_p(v) &= \frac{d}{ds} \Big|_{s=0} R_p(\gamma(s)) \\ &= \frac{d}{ds} \Big|_{s=0} (A \cdot \gamma(s)) = A \cdot \gamma'(0) = A \cdot v, \end{aligned}$$

this means $dR_p(v)$ is the rotation of the vector v about degree alpha. (see)

- (3) Let $f: S_1 \rightarrow S_2$ be a diffeomorphism of two regular surfaces. Then at $p \in S_1$, $df_p: T_p S_1 \rightarrow T_{f(p)} S_2$ is a linear isomorphism. The converse is only true locally.

Definition 2.4.6 (Local diffeomorphism). S_1, S_2 are regular surfaces, $p \in S_1$, the map $\varphi: S_1 \rightarrow S_2$ is called a local diffeomorphism at p , if \exists a neighborhood U of p such that $\varphi: U \rightarrow \varphi(U)$ is a diffeomorphism.

Proposition 2.4.7 (Inverse function (mapping) theorem). $\varphi: S_1 \rightarrow S_2$ is a differentiable map, $p \in S_1$. If $\varphi: T_p S_1 \rightarrow T_{\varphi(p)} S_2$ is an isomorphism, then \exists a neighborhood U of p such that $\varphi: U \rightarrow \varphi(U)$ is a local diffeomorphism at p .

Exercise. (Following item 2)

- (1) Find the rotational map of \mathbb{S}^2 around other 2 axes.

$$B = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \beta & -\sin \beta \\ 0 & \sin \beta & \cos \beta \end{pmatrix} \quad C = \begin{pmatrix} \cos \gamma & 0 & -\sin \gamma \\ 0 & 1 & 0 \\ \sin \gamma & 0 & \cos \gamma \end{pmatrix}$$



(2) What can you observe from matrices A , B and C ?

(Their determinant is 1 and form a basis of $SO(3) = \{all\ rotational\ maps\ of\ \mathbb{S}^2\}$. Observe that the rotations of \mathbb{S}^2 should preserve the lengths and angles over \mathbb{S}^2 . This is just based on “observation” later, and after we define the lengths and angles in \mathbb{S}^2 we’ll check this.)

