

# Differential Geometry Lecture Notes



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# Preface

## Textbook Reference

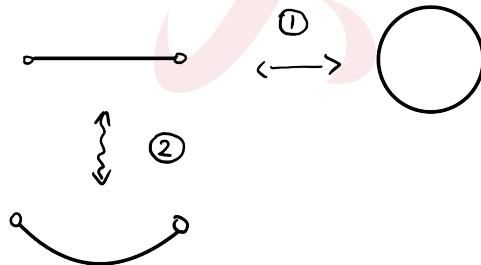
- (1) Do Carmo: Differential Geometry of Curves and Surfaces.
- (2) Sebastián Montiel, Antonio Ros: Curves and Surfaces.
- (3) Chinese Title, add later

## Course Introduction

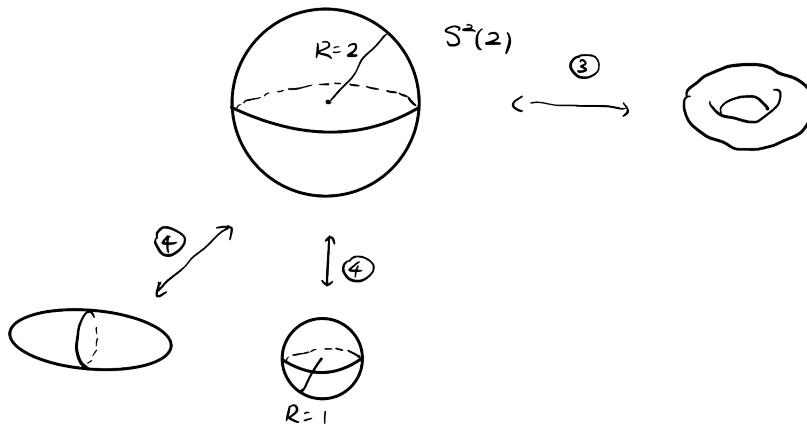
The Goal of this course is to study the “differential geometry of curves and surfaces”.

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

**Example 0.0.1.** 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 0.0.2.** In the following picture, (3) differs by “topology”, but in (4)  $\mathbb{S}^2(1)$  is more curved than  $\mathbb{S}^2(2)$ , even topologically they are the same.(either homeomorphically or diffeomorphically).



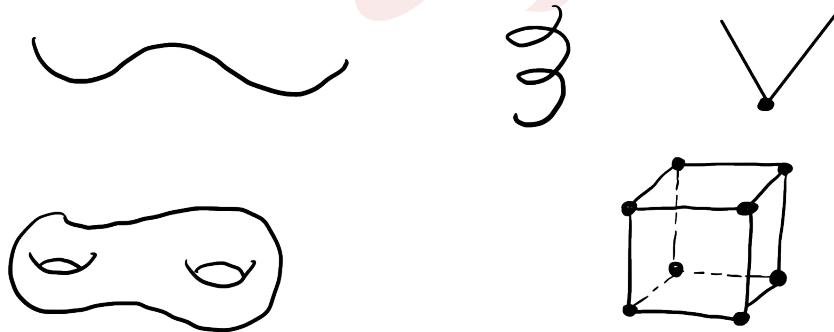
The “Curved property” also affects geometric quantities, like length, area, volume, angle between the curves, etc.

**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 0.0.3.** 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:  $(\theta, \varphi)$  or  $(\varphi, \theta)$  are “essential” coordinates on  $\mathbb{S}^2$ .

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

(Caution:  $(\theta, \varphi)$  is outer normal, while  $(\varphi, \theta)$  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 0.0.4.** 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 0.0.5** (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  $\varphi$  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,

$$\begin{aligned} \varphi(\tilde{e}_k) &= \varphi \left( \sum_{j=1}^n B_k^j e_j \right) = \sum_{j=1}^n B_k^j \varphi(e_j) \quad (\text{linearity}) \\ &= \sum_{i,j=1}^n B_k^j A_j^i e_i = \sum_{i,j,p=1}^n B_k^j A_j^i (B^{-1})_i^p \tilde{e}_p \end{aligned}$$

*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  $C^\infty$  map,

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

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

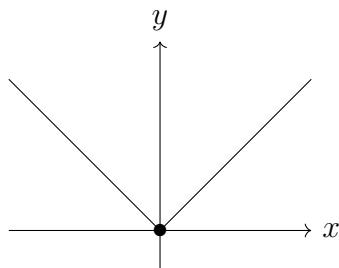
*Remark.*



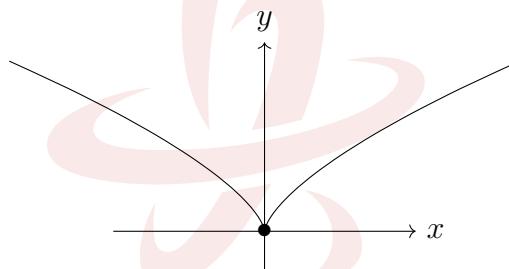
- 1)  $a, b$  could be finite number or infinity.
- 2) Same curve may have different parametrizations.
- 3) The parametrization automatically gives the direction of the motion on the curve.
- 4) “Differentiable” just means  $\alpha(t)$  is a  $C^\infty$  map, it does not say the (trace of) curve can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

**Example 1.2.2.**

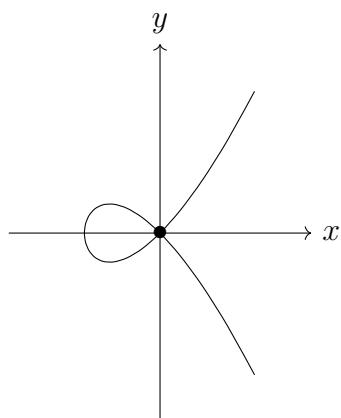
(1)  $\alpha(t) = (t, |t|)$  is not a differentiable curve.



(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)  $\alpha$  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  $\beta(t) = (t, t^{\frac{2}{3}})$ , this also parametrizes (2), but it's not a differentiable curve!

**Definition 1.2.3.** Let  $\alpha(t): I \rightarrow \mathbb{R}^3$  be a parametrized differentiable curve, then at  $t_0 \in I$ .

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

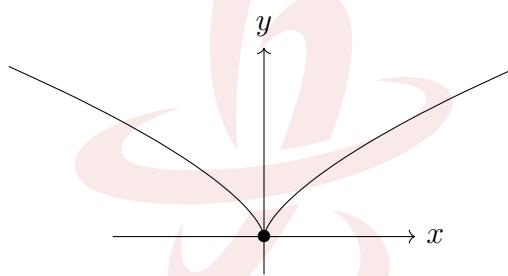
is the velocity of  $\alpha(t)$  at  $t_0$ .

- (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.

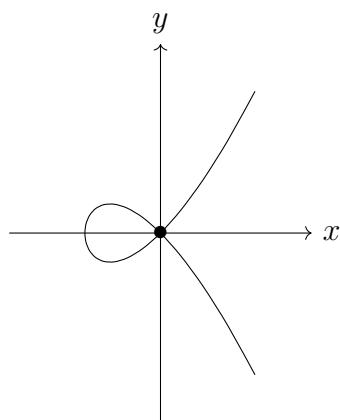
**Question:** What can you say about  $C^\infty$  parametrization for a regular curve?

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

**Example 1.2.4.**  $\alpha(t) = (t^3, t^2)$  is not a regular curve. (Since  $\alpha'(0) = 0$ )



**Example 1.2.5.**  $\alpha(t) = (t^2 - 1, t^3, t)$  is a regular curve.



**Definition 1.2.6.** 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 1.2.7.** 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 meanie 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 1.2.8.** 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  $\alpha$  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  $90^\circ$  rotation of the tangent vector.

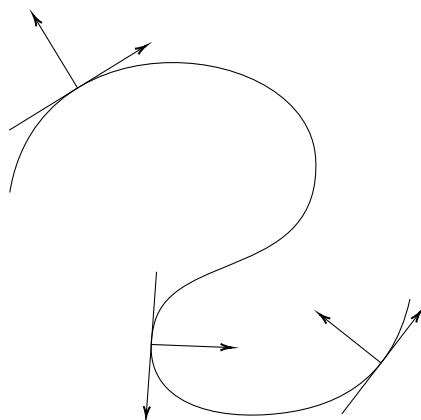


Figure 1.3.1: Example of a plane curve and its tangent and normal

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  $|\alpha''(s_0)|$  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  $\theta$  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  $\alpha$  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  $\theta_h$  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  $\alpha$  lie in some plane perpendicular to vector  $B$ .

- (2) In different textbooks, you may see the definition of  $\tau$  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  $\kappa$  and  $\tau$  as its curvature and torsion.*
- (Uniqueness) *If  $\alpha, \beta$  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  $\alpha$ , that is, choice of initial frame  $\{T_0, N_0, B_0\}$  and initial point  $\alpha_0$ . Given two valid solution curve  $\alpha, \beta$ , with initial condition  $(X_a, \alpha_0)$  and  $(X_b, \beta_0)$ , 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  $\beta$ , 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,  $\kappa$  and  $\tau$  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

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

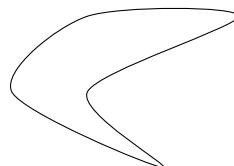
But the sum of square equals 0 at  $s = s_0$ , so it is identically 0, in particular,  $T_\alpha = T_\beta$  for all  $s$ .  $\square$

## 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  $\alpha$  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  $\theta$  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  $2\pi$ -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  $\partial E$ , 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

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

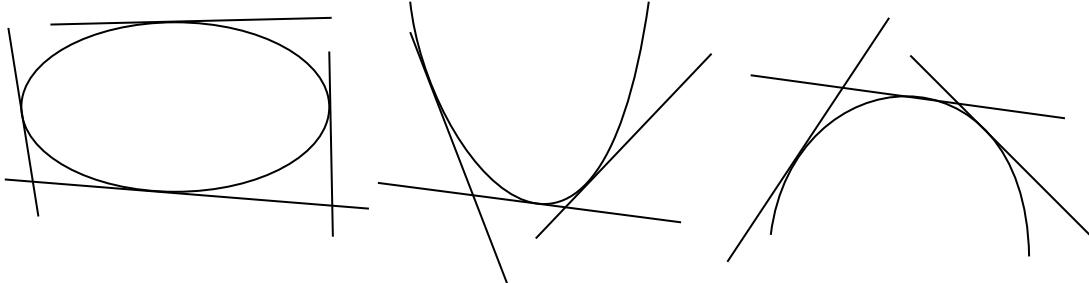
**Question.** Can you propose some generalizations of isoperimetric inequality? Isoperimetric inequality is one of the motivation to develop geometric measure theory!

### 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.



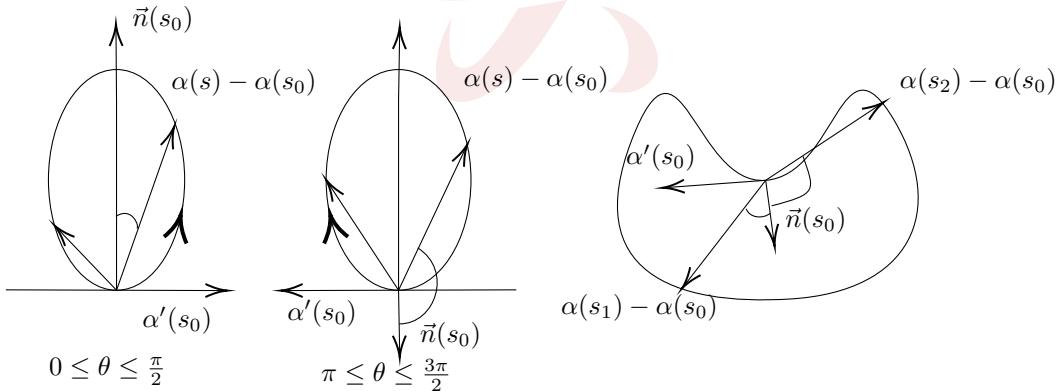
The convex curve has the following useful characterization.

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

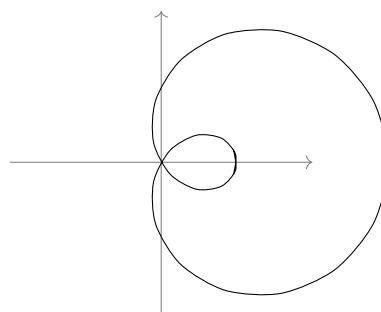
For all  $s \in I$ , either  $(\alpha(s) - \alpha(s_0)) \cdot \vec{n}(s_0) \geq 0$  or  $(\alpha(s) - \alpha(s_0)) \cdot \vec{n}(s_0) \leq 0$ .

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 1.4.6.**



**Example 1.4.7.**  $\alpha(t) = ((1 + 2 \cos t) \cos t, (1 + 2 \cos t) \sin t)$ ,  $t \in \mathbb{R}$ .

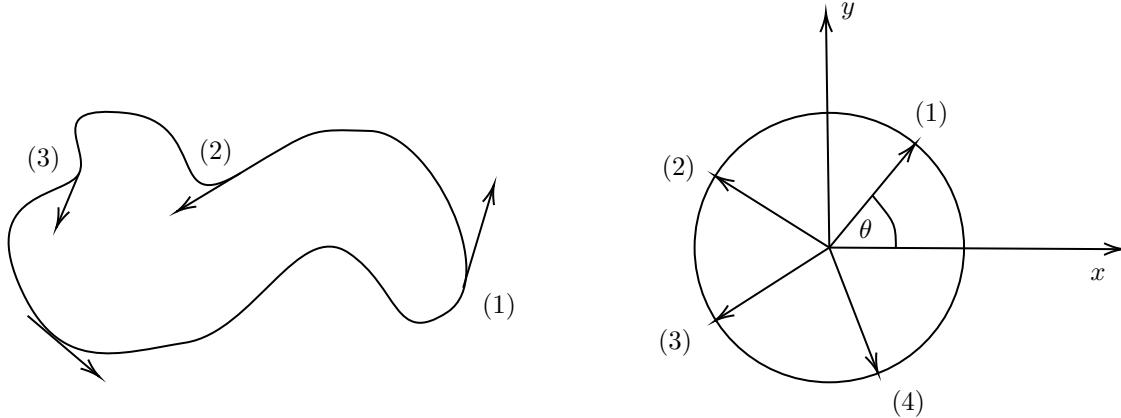




**Proposition 1.4.8.**  $\alpha(s)$  is a simple closed curve, then

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

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  $\theta$  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.  $\theta$  can be used as a parameter of  $\alpha(s)$ . Such  $\theta$  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 1.4.9.** Let  $\alpha: I \rightarrow \mathbb{R}^3$  be a regular curve. The point at which  $k'(t_0) = 0$  is called a vertex of  $\alpha$ . (critical point of the curvature  $k(t)$ )

*Proof of proposition 1.4.8.*

**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

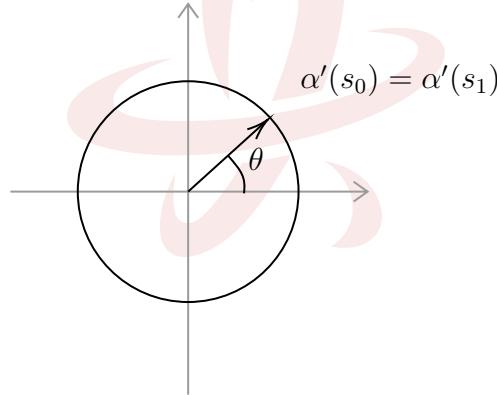
$$\begin{aligned} h(s_1) &= \min h(s), \quad h(s_2) = \max h(s). \\ \Rightarrow h'(s_1) &= \langle \alpha'(s_1), \vec{n}(s_0) \rangle = 0 \Rightarrow \alpha'(s_1) \perp \vec{n}(s_0) \\ h'(s_2) &= \langle \alpha'(s_2), \vec{n}(s_0) \rangle = 0 \Rightarrow \alpha'(s_2) \perp \vec{n}(s_0), \end{aligned}$$

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  $\theta$  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)

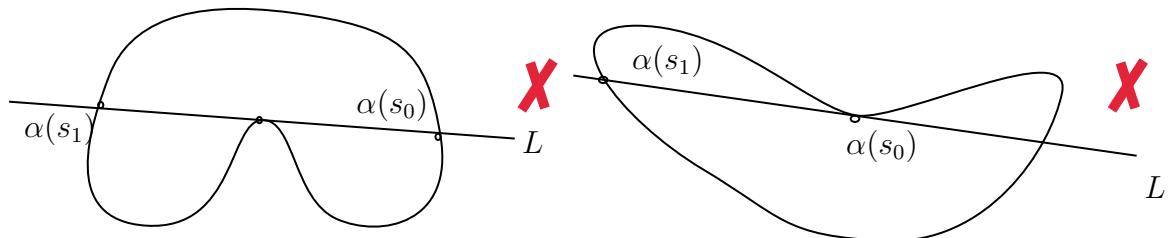
Let  $L$  be the line passing through  $\alpha(s_0)$  and  $\alpha(s_1)$ , and  $\alpha(s_0)$  is a  $k_{\min}$  point and  $\alpha(s_1)$  is a  $k_{\max}$  point.

**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.

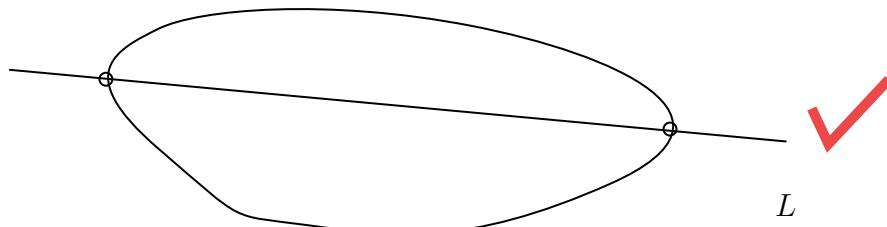


(Reason: simple closed + convexity  $\Rightarrow \theta(s)$  is increasing on  $[0, 2\pi]$ , the same argument as the previous page.) This implies that there must be points on both sides of  $L$ .

**Claim :** No other points of  $C$  meet  $L$ .



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



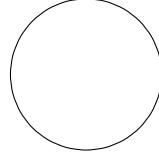
**Claim 3:**  $\exists$  a third and a fourth vertex. (See the proof)



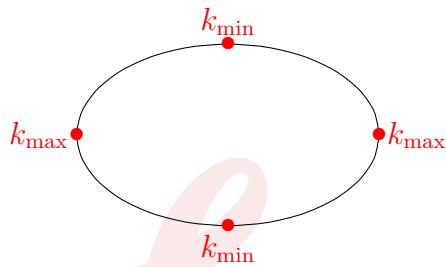
**Exercise.** Let  $\alpha(s) = (x(s), y(s))$  be a simple closed curve in  $\mathbb{R}^2$ . Let  $\tilde{\alpha}(s)$  be the image of  $\alpha(s)$  under stereographic projection. Show that if  $\alpha(s_0)$  is a vertex of  $\alpha(s)$ , then  $\tilde{\alpha}(s_0)$  has vanishing torsion.

**Example 1.4.10.**

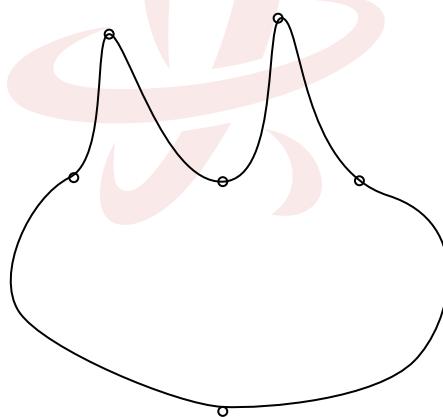
- The circle with radius  $r$  and curvature  $k = \frac{1}{r}$  has infinitely many vertices.



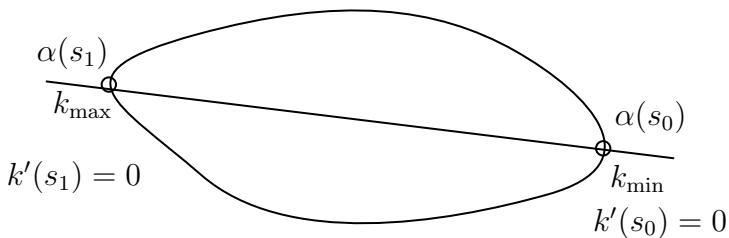
- An ellipse has four vertices.



- 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  $\alpha$  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  $\alpha$ , 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-dim)

**Theorem 1.4.11** (1-dim 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 1.4.12.** 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.

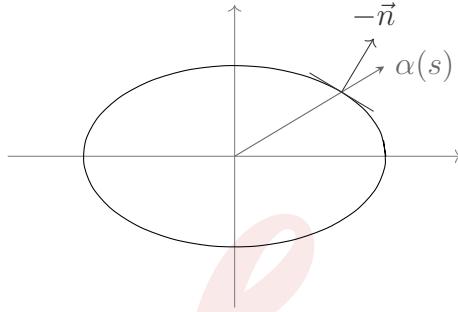
**Proposition 1.4.13.** A simple closed curve is strictly convex iff with inward unit normal vector field, the curvature function  $k > 0$ .

**Minkowski problem:** Given a strictly positive, periodic function  $k$ , does there exist a simple closed convex curve  $\alpha$  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  $\alpha$  be a strictly convex curve, then  $k > 0$ , and we can use the angle parameter  $\theta$ , 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  $h(\theta) = -\langle \alpha(s(\theta)), \vec{n}(s(\theta)) \rangle$ .

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

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  $h$ .

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

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

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

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



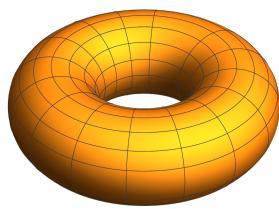
## Surface collection 1

### Example 2.0.1.

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



(a)  $\mathbb{S}^2$



(b)  $\mathbb{T}^2$

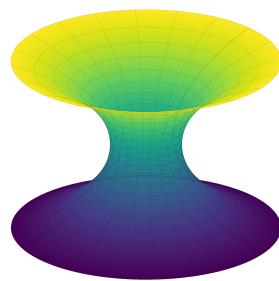


(c)  $\Sigma_g$  for  $g = 3$

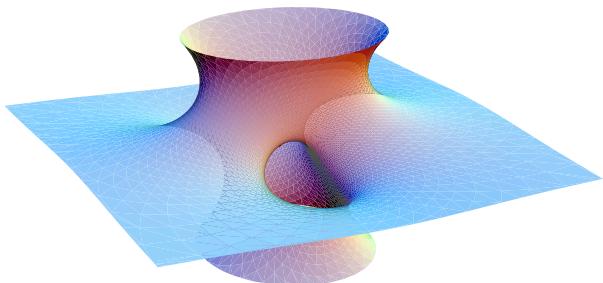
Surface collection 2



(a) Helicoid



(b) Catenoid

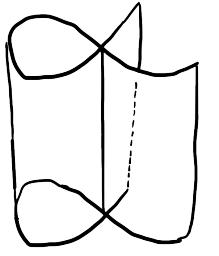


(c) Costa minimal surface

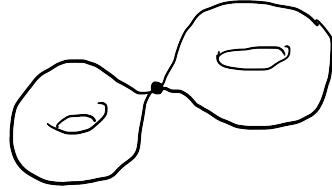


(d) Soap bubble

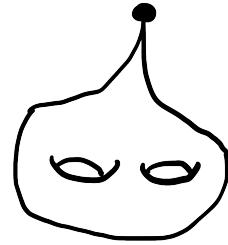
Surface collection 3



(a) Self-intersected



(b) Nodal surfaces



(c) Cusp

“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.

!! A priori, 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 2.2.1.**  $\mathbb{R}^2 \hookrightarrow \mathbb{R}^3$  is a regular surface with (trivial) global parametrization

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

**Example 2.2.2.** 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 2.2.3.** 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 2.2.4.** More generally, the level set of a smooth function  $f(x, y, z)$  at a regular value is a regular surface.

**Definition 2.2.5** (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

$$f: \mathbb{R}^3 \rightarrow \mathbb{R} \text{ is smooth function}$$

$$(x, y, z) \mapsto f(x, y, z).$$

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 2.2.6** (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. W.L.O.G. 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 2.2.3.  $\square$

**Theorem 2.2.7** (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 2.2.3, we see the graph of a smooth function  $f(x, y)$  is a regular surface. The converse is also true locally.

**Proposition 2.2.8.**  *$S$  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 theorem,  $u, v$  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 2.2.9.**  *$S$  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 theorem, refer to Do Carmo’s book. □

**Example 2.2.10.** *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 2.2.11** (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,

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

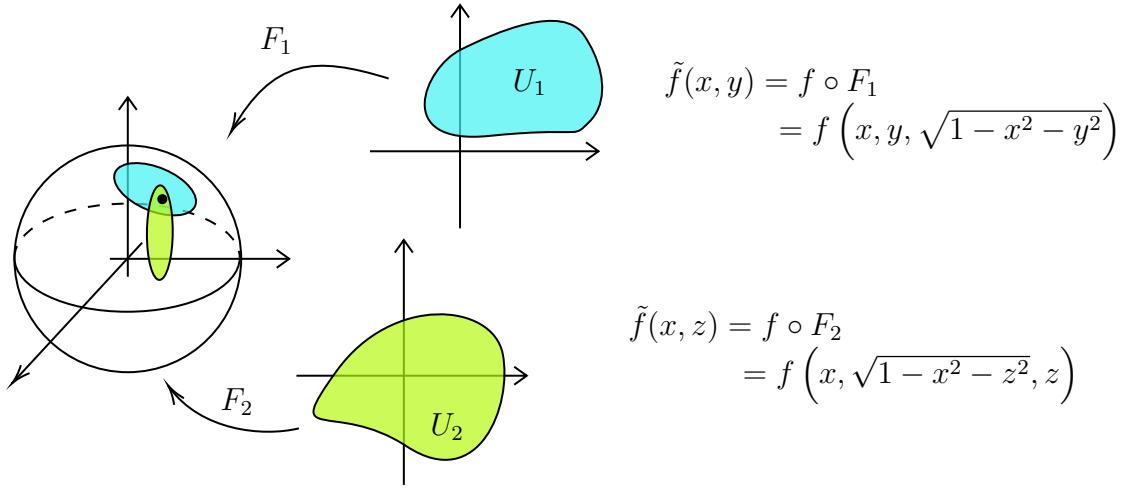
then  $\tilde{f}(x, y): U \rightarrow \mathbb{R}$ ,  $\tilde{f}(x, y) = f \circ F$ .

Similarly, if the point lies on other five charts(see example 2.2.2). 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  $p$

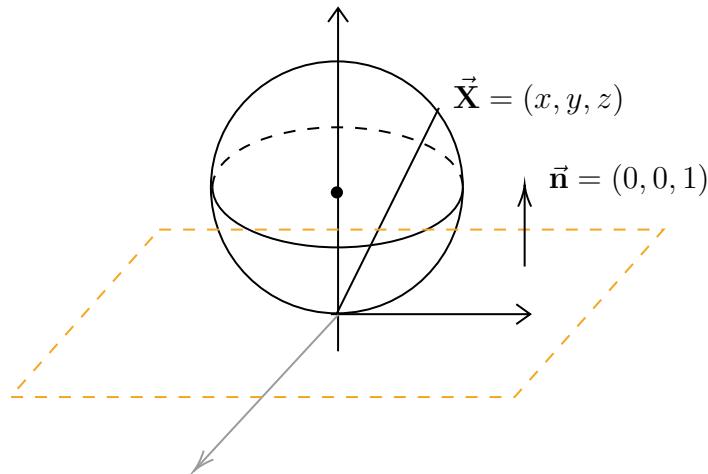
$$x: U \subset \mathbb{R}^2 \rightarrow \mathbb{R}^3,$$

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 2.3.2.** 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.

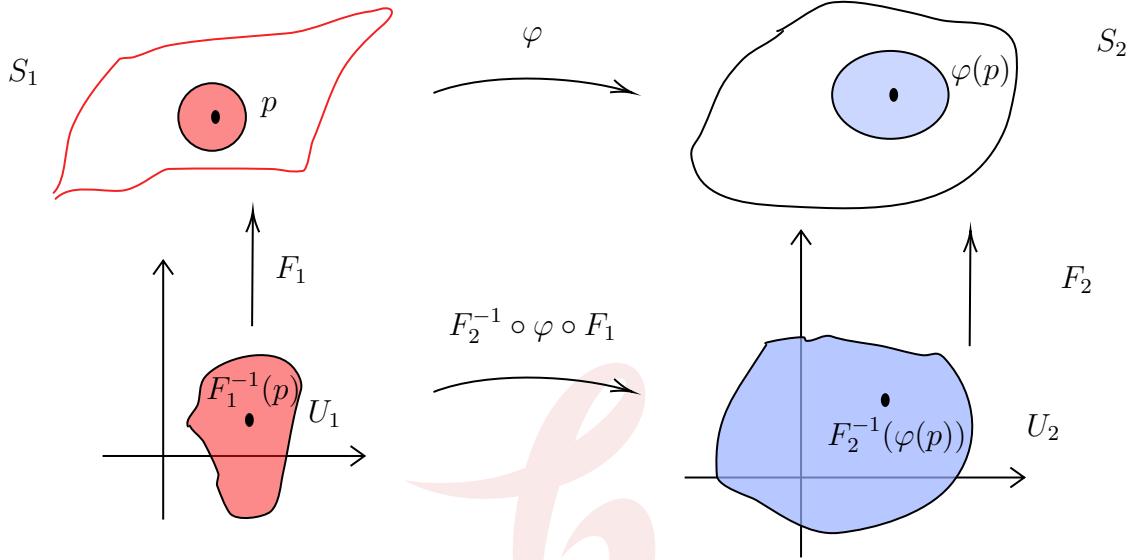


**Exercise.** How does the function  $f$  look like in other coordinate charts?

**Definition 2.3.3** (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  $\varphi$  is differentiable at  $p \in S_1$ , if for some parametrization

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

$F_2^{-1} \circ \varphi \circ F_1: U_1 \rightarrow U_2$  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  $\varphi$  is differentiable iff  $\varphi^1$  and  $\varphi^2$  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 2.3.4** (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 2.3.5.** 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 2.3.6.**  $x^2 + y^2 + z^2 = 1$  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. ( $\varphi^{-1}$  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:

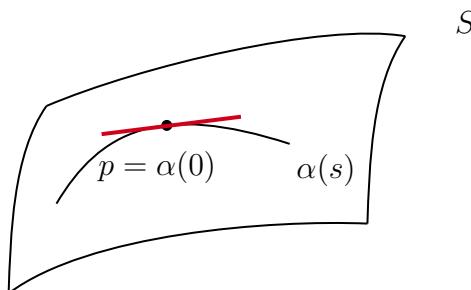
- (1) We “have” not checked what happened if we change the parameter.

(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.)

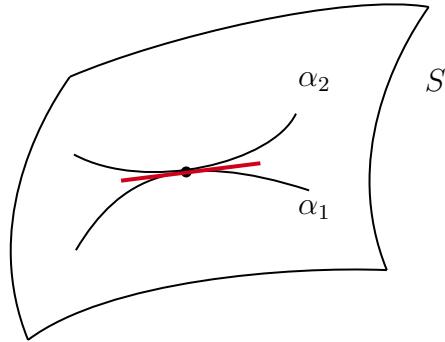
**Definition 2.4.1** (Tangent vector).  $V$  is called a tangent vector at  $p \in S$  if  $\exists$  a smooth curve  $\alpha: (-\epsilon, \epsilon) \rightarrow S$  with  $\alpha(0) = p$  such that  $\alpha'(0) = V$ .



**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  $C^\infty$  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.

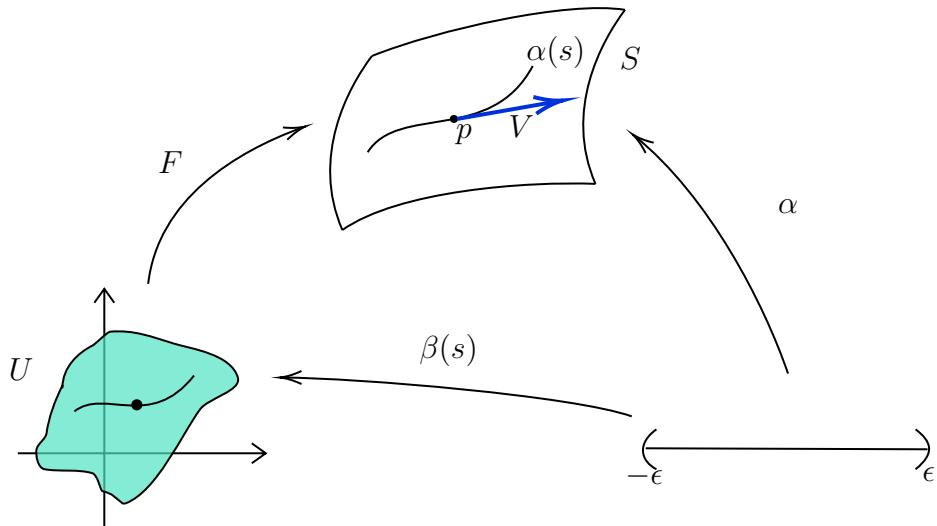
*Proof.* Let  $\alpha(s): (-\epsilon, \epsilon) \rightarrow S$  be the regular curve such that  $\alpha'(0) = V$  for the given tangent vector  $V$  at  $p$ . Choose a local parametrization near  $p$ ,

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

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  $C^\infty$ - 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  $C^\infty$ -curve in  $\mathbb{R}^2$ . (Because we have checked the transition function is  $C^\infty$  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  $C^\infty$



## 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

$$\begin{aligned} V: C^\infty(\mathbb{R}^n) &\rightarrow C^\infty(\mathbb{R}^n) \\ f &\mapsto V(f). \end{aligned}$$

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

$$\begin{aligned} F: U(\subset \mathbb{R}^2) &\longrightarrow S \subset \mathbb{R}^3 \\ (y^1, y^2) &\longmapsto (x^1, x^2, x^3). \end{aligned}$$

$\Rightarrow \alpha(s) = F(y^1(s), y^2(s))$  (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

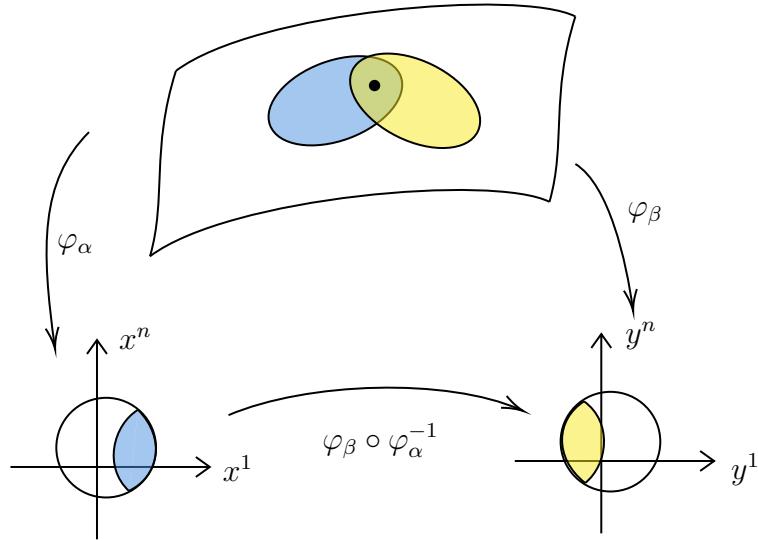
$$V_p(f) = \left( \sum_{i=1}^2 \frac{dy^i}{ds} \frac{\partial}{\partial y^i} \right) (f)(p).$$

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  $C^\infty$ ,  $\forall \alpha, \beta$  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  $U_\alpha$ , i.e.  $p \in U_\alpha$ ,  $\varphi_\alpha(p) = (x^1(p), x^2(p), \dots, x^n(p))$ . Hence,  $p \in M$ , choose  $U_\alpha$  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  $U_\alpha$ ,  $\pi^{-1}(U_\alpha)$  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  $\pi$  is just a projection (when expressed in coordinate).

### Tangent vector field

**Definition 2.4.4.** A smooth vector field  $V$  is a  $C^\infty$ -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  $C^\infty$  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  $\alpha$

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

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  $SO(3) = \{\text{all rotational maps of } \mathbb{S}^2\}$ . 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.)

(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.

## 2.5 Orientation of a regular surface

**Question.** Consider  $\mathbb{S}^2$  with spherical parametrization, are following two parametrizations the same?

- $(\varphi, \theta) \mapsto (\sin \varphi \cos \theta, \sin \varphi \sin \theta, \cos \varphi)$
- $(\theta, \varphi) \mapsto (\sin \varphi \cos \theta, \sin \varphi \sin \theta, \cos \varphi)$

The answer is NO! They give different normal directions which decide “inside” and “outside” of  $\mathbb{S}^2$ .

**Recall:**  $\mathbb{R}^2$  is orientable. It has two orientations. Given a basis  $\{e_1, e_2\}$ , let

$$J_+ = \left\{ E_+ = \{e_1^+, e_2^+\} : E_+ \text{ has same orientation as } E. \right.$$

$$\text{i.e. } \begin{bmatrix} e_1^+ \\ e_2^+ \end{bmatrix} = \underbrace{\begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}}_{A_+} \begin{bmatrix} e_1 \\ e_2 \end{bmatrix} \text{ and } \det A_+ > 0 \Big\};$$

$$J_- = \left\{ E_- = \{e_1^-, e_2^-\} : E_- \text{ has same orientation as } E. \right.$$

$$\text{i.e. } \begin{bmatrix} e_1^- \\ e_2^- \end{bmatrix} = A_- \begin{bmatrix} e_1 \\ e_2 \end{bmatrix} \text{ and } \det A_- > 0 \Big\}.$$

Then either  $J_+$  or  $J_-$  gives an orientation of  $\mathbb{R}^2$ .

**Question.**

- (1) Let  $S$  be a regular surface, how can we define orientation?
- (2) Are all surfaces orientable?

Assume we have two parametrizations around  $p$ :

$$\begin{aligned} F: U \rightarrow S &\quad T_p S \cong \mathbb{R}^2 = \text{span}\{F_u, F_v\} \\ G: V \rightarrow S &\quad T_p S \cong \mathbb{R}^2 = \text{span}\{G_\alpha, G_\beta\}. \end{aligned}$$

Note near  $p$ ,  $F(u, v) = G(\alpha, \beta) \implies$

$$\begin{bmatrix} G_\alpha \\ G_\beta \end{bmatrix} = \begin{bmatrix} u_\alpha & v_\alpha \\ u_\beta & v_\beta \end{bmatrix} \begin{bmatrix} F_u \\ F_v \end{bmatrix}.$$

i.e. Two parametrizations  $F$  and  $G$  give the same orientation iff

$$\left| \frac{\partial(u, v)}{\partial(\alpha, \beta)} \right| > 0.$$

**Definition 2.5.1** (Orientation of a regular surface). We say a regular surface  $S$  is orientable if there exists a coordinate chart covering of  $S$ , s.t. if a point  $p$  belongs to two charts, then the induced basis on  $T_p S$  by the two parametrizations have the same orientation in above sense.

*Remark.*

- (1) “Orientation” is a global intrinsic property. “Orientability” is essentially reflected by the topology of the surface. In algebraic topology course, you’ll see that the orientability is determined by the 1st Stiefel-Whitney class in  $H^1(M, \mathbb{Z}/2\mathbb{Z})$  for a vector bundle on topological manifold  $M$ . With additional “smooth” structure on  $M$ , we have more ways to check the orientability, for example,  $\exists$  a nowhere vanishing top differential form (or say, a volume form).
- (2) One of important applications of “orientation” in this course (and later in Riemann Geometry) is allowing us to define “integration” on a regular surface.

**Exercise.** Give a definition of orientation of  $\mathbb{R}^n$  as a vector space.

**Example 2.5.2.**  $\mathbb{S}^2$  is orientable.

Consider the stereographic parametrization

$$\begin{aligned} \pi_N: \mathbb{S}^2 \setminus \{N\} &\longrightarrow \mathbb{R}^2 \\ (x, y, z) &\longmapsto (u, v) = \left( \frac{x}{1-z}, \frac{y}{1-z} \right). \\ \pi_N^{-1}(u, v) &= \left( \frac{2u}{1+u^2+v^2}, \frac{2v}{1+u^2+v^2}, 1 - \frac{2}{1+u^2+v^2} \right). \\ \pi_S: \mathbb{S}^2 \setminus \{S\} &\longrightarrow \mathbb{R}^2 \\ (x, y, z) &\longmapsto (\alpha, \beta) = \left( \frac{y}{1+z}, \frac{x}{1+z} \right). \\ \pi_S^{-1}(\alpha, \beta) &= \left( \frac{2\beta}{1+\alpha^2+\beta^2}, \frac{2\alpha}{1+\alpha^2+\beta^2}, \frac{2}{1+\alpha^2+\beta^2} - 1 \right). \end{aligned}$$

Clearly  $\mathbb{S}^2 = \pi_N^{-1}(U) \cup \pi_S^{-1}(V)$ . To see the orientation, we compute the Jacobian of change from one chart to another.  $(u, v) \rightarrow (\alpha, \beta)$ . Now

$$\begin{cases} u = \frac{x}{1-z} \\ v = \frac{y}{1-z} \end{cases} , \quad \begin{cases} \alpha = \frac{y}{1+z} \\ \beta = \frac{x}{1+z} \end{cases} .$$

Hence

$$\begin{cases} u\alpha = v\beta \\ u\beta + v\alpha = 1 \end{cases} \implies \begin{cases} u = \frac{\beta}{\alpha^2+\beta^2} \\ v = \frac{\alpha}{\alpha^2+\beta^2} \end{cases} .$$

Then

$$\frac{\partial(u, v)}{\partial(\alpha, \beta)} = \begin{pmatrix} -\frac{2\alpha\beta}{(\alpha^2+\beta^2)^2} & \frac{\alpha^2-\beta^2}{(\alpha^2+\beta^2)^2} \\ \frac{\beta^2-\alpha^2}{(\alpha^2+\beta^2)^2} & -\frac{2\alpha\beta}{(\alpha^2+\beta^2)^2} \end{pmatrix} \implies \det > 0.$$



**Example 2.5.3.** The graph  $(x, y, f(x, y))$  is always orientable.

- Normal vector field and orientation.

Since in this course, we consider the regular surface  $S$  in  $\mathbb{R}^3$ , at each  $p \in S$ , there is a unique tangent plane  $T_p S$ , which is a 2 dim linear subspace of  $\mathbb{R}^3$ . Hence we can talk about the normal vector field on  $S$ . Now we want a “well-defined” normal by taking “unit normal vector  $\vec{n}$ ” at  $p$ .

Let's check  $\vec{n}$  under change of parameter. Let  $F: U \rightarrow S$  be a parametrization around  $p$ . Then

$$T_p S = \text{span}\{F_u, F_v\} \implies \vec{n}_F = \frac{F_u \times F_v}{|F_u \times F_v|}.$$

(Note the cross product here already assigns a direction of  $\vec{n}$ ).

If  $G: V \rightarrow S$  is another parametrization around  $p$ . Then

$$T_p S = \text{span}\{G_\alpha, G_\beta\}, \quad \vec{n}_G = \frac{G_\alpha \times G_\beta}{|G_\alpha \times G_\beta|}.$$

Let  $\Phi = G^{-1} \circ F: U \cap V \rightarrow U \cap V$  be the transition map. Then

$$\begin{cases} F_u = G_\alpha \alpha_u + G_\beta \beta_u \\ F_v = G_\alpha \alpha_v + G_\beta \beta_v \end{cases} \quad i.e. \quad \begin{pmatrix} F_u \\ F_v \end{pmatrix} = \begin{pmatrix} \alpha_u & \beta_u \\ \alpha_v & \beta_v \end{pmatrix} \begin{pmatrix} G_\alpha \\ G_\beta \end{pmatrix}.$$

$$\implies F_u \times F_v = \det\left(\frac{\partial(\alpha, \beta)}{\partial(u, v)}\right) G_\alpha \times G_\beta. \text{ Hence}$$

$$\vec{n}_F = \text{sign} \det\left(\frac{\partial(\alpha, \beta)}{\partial(u, v)}\right) \cdot \vec{n}_G.$$

**Definition 2.5.4** (Unit normal vector field).  $U \subset S$  open subset, a unit normal vector field on  $U$  is a smooth map

$$\begin{aligned} \vec{n}: U &\longrightarrow \mathbb{R}^3 \\ p &\longmapsto \vec{n}_p \text{ (unit normal at } p\text{).} \end{aligned}$$

**Proposition 2.5.5.** A regular surface is orientable  $\iff$  there is a unit normal vector field  $\vec{n}: S \rightarrow \mathbb{R}^3$  defined everywhere on  $S$ .

*Remark.* On an orientable regular surface, the “unit” normal vector field has image on  $\mathbb{S}^2$ , i.e. there is a smooth map

$$\begin{aligned} \vec{n}: S &\longrightarrow \mathbb{S}^2 = \{x^2 + y^2 + z^2 = 1\} \\ p &\longmapsto \vec{n}_p. \end{aligned}$$

This  $\vec{n}$  is called the *Gauss map* of the surface. Later we'll see that the differential of  $\vec{n}$  determines how the surface is curved in  $\mathbb{R}^3$ .

*Proof.* “ $\implies$ ”: If  $S$  is orientable, then  $\exists$  a coordinate chart covering  $\{F_\alpha(U_\alpha)\}_{\alpha \in \Lambda}$  of  $S$ ,  $(F_\alpha: U_\alpha \rightarrow S, S = \bigcup_{\alpha \in \Lambda} F_\alpha(U_\alpha))$ . s.t. on  $U_\alpha \cap U_\beta \neq \emptyset$ ,

$$\det\left(\frac{\partial(u_\alpha, u_\beta)}{\partial(u_\beta, v_\beta)}\right) > 0.$$

Hence at  $p \in U_\alpha \cap U_\beta$ ,

$$\vec{n}_p = \frac{F_{u_\alpha} \times F_{v_\alpha}}{|F_{u_\alpha} \times F_{v_\alpha}|} = \frac{F_{u_\beta} \times F_{v_\beta}}{|F_{u_\beta} \times F_{v_\beta}|}.$$

(This guarantees that we can extend the normal vector in one chart to another)

Hence we can well define  $\vec{n}: S \rightarrow \mathbb{R}^3$ . The smoothness of  $\vec{n}$  can be checked in local coordinates.

“ $\Leftarrow$ ”: Let  $\vec{n}: S \rightarrow \mathbb{R}^3$  be the unit normal vector field defined on  $S$ . Let  $\{F_\alpha: U_\alpha \rightarrow S\}$  be a coordinate chart covering of  $S$ . Then on each  $F_\alpha(U_\alpha)$ ,

$$\vec{n}_\alpha = \frac{F_{u_\alpha} \times F_{v_\alpha}}{|F_{u_\alpha} \times F_{v_\alpha}|}.$$

On  $U_\alpha \cap U_\beta$  at some point  $p$ , we have

$$\frac{F_{u_\alpha} \times F_{v_\alpha}}{|F_{u_\alpha} \times F_{v_\alpha}|} = \text{sign} \det \left( \frac{\partial(u_\beta, v_\beta)}{\partial(u_\alpha, v_\alpha)} \right) \cdot \frac{F_{u_\beta} \times F_{v_\beta}}{|F_{u_\beta} \times F_{v_\beta}|}.$$

Since  $\vec{n}_\alpha$  and  $\vec{n}_\beta$  agree at  $p$ , we see

$$\det \left( \frac{\partial(u_\beta, v_\beta)}{\partial(u_\alpha, v_\alpha)} \right) > 0.$$

□

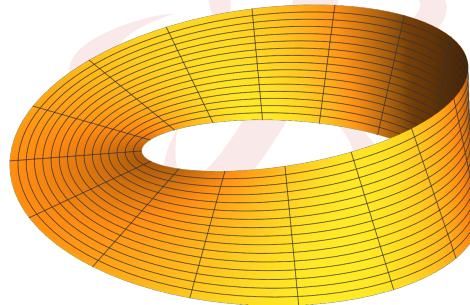


Figure 2.5.1: Möbius strip

**Example 2.5.6** (Non-orientated surface). *Möbius strip  $M$*  (fig. 2.5.1)

Consider the line segment  $AB$  with equation  $-\frac{1}{2} \leq z \leq \frac{1}{2}, y = 1, x = 0$ , rotating along a circle  $x^2 + y^2 = 1$ . When the center  $c$  moves about angle  $u$  away from  $y$ -axis, the line  $A'B'$  is in the plane determined by  $z$ -axis and  $c'$  and the angle between  $A'B'$  and  $z$ -axis is  $\frac{u}{2}$ .

Let  $U = \{(u, v) : 0 < u < 2\pi, -\frac{1}{2} < v < \frac{1}{2}\}$ , then

$$F(u, v) = ((1 - v \sin \frac{u}{2}) \sin u, (1 - v \sin \frac{u}{2}) \cos u, v \cos \frac{u}{2}).$$



This almost covers  $M$ , except at  $u = 0$ . To cover this, we consider rotation  $AB$  when the center lies on  $x$ -axis. We have parametrization

$$G(\alpha, \beta) = ((1 - \beta \sin\left(\frac{\pi}{4} + \frac{\alpha}{2}\right)) \cos \alpha, (1 - \beta \sin\left(\frac{\pi}{4} + \frac{\alpha}{2}\right)) \sin \alpha, \beta \cos\left(\frac{\pi}{4} + \frac{\alpha}{2}\right)).$$

$$V = \{(\alpha, \beta) : 0 < \alpha < 2\pi, -\frac{1}{2} < \beta < \frac{1}{2}\}.$$

Now the missing part is on  $u = \frac{\pi}{2}$ .

Consider  $F(U) \cap G(V)$ , it contains two pieces

$$W_1 = \{F(u, v) : 0 < u < \frac{\pi}{2}\}, \quad W_2 = \{F(u, v) : \frac{\pi}{2} < u < 2\pi\}.$$

On  $W_1$ ,

$$\begin{cases} \alpha = u + \frac{3}{2}\pi \\ \beta = -v \end{cases} \implies \left| \frac{\partial(\alpha, \beta)}{\partial(u, v)} \right| = -1.$$

On  $W_2$ ,

$$\begin{cases} \alpha = u - \frac{\pi}{2} \\ \beta = v \end{cases} \implies \left| \frac{\partial(\alpha, \beta)}{\partial(u, v)} \right| = 1.$$

No matter how we change parametrization in  $W_1$  or  $W_2$ , we can not guarantee that  $\left| \frac{\partial(\alpha, \beta)}{\partial(u, v)} \right|$  is positive everywhere. (*i.e.*  $\vec{n}$  has to change sign). Hence  $M$  is non-orientable.

*Remark.* In the following of this course, we only care about orientable surfaces. *i.e.* surfaces having well-defined unit normal vector field everywhere.

## 2.6 The 1<sup>st</sup> fundamental form on $S$

The 1<sup>st</sup> fundamental form on  $S$  inherits from the Euclidean inner product of  $\mathbb{R}^3$ . It allows us to measure geometric quantities like

- Distance between pairs;
- Angle between curves;
- Area of a region;
- etc.

It is an intrinsic, globally defined concept on  $S$ . In the language of Riemannian Geometry, the 1<sup>st</sup> fundamental form is also called the “pull-back” Riemannian metric on  $S$ . It’s related to the “isometric immersion (embedding)” in Riemannian Geometry course.

! The 1<sup>st</sup> fundamental form determines the “intrinsic geometry”.

We first give the definition of the 1<sup>st</sup> fundamental form, then explain where it comes from.

Let  $S \subset \mathbb{R}^3$  be a regular surface.  $\forall p \in S$ , we take local parametrization

$$\begin{aligned} \varphi: U \subset \mathbb{R}^2 &\longrightarrow S \\ (u, v) &\longmapsto \varphi(u, v) = (x, y, z). \end{aligned}$$

and  $p = \varphi(u_0, v_0)$ , then

$$\begin{aligned}\varphi_u(u_0, v_0) &= (x_u, y_u, z_u) \Big|_{(u_0, v_0)} \in \mathbb{R}^3 \\ \varphi_v(v_0, v_0) &= (x_v, y_v, z_v) \Big|_{(u_0, v_0)} \in \mathbb{R}^3.\end{aligned}$$

And  $T_p S \cong \mathbb{R}^2 = \text{span}\{\varphi_u(u_0, v_0), \varphi_v(u_0, v_0)\}$ .

Define

$$E = \langle \varphi_u, \varphi_u \rangle_p \quad F = \langle \varphi_u, \varphi_v \rangle_p \quad G = \langle \varphi_v, \varphi_v \rangle.$$

The 1st fundamental form at  $p \in S$  is defined as

$$I_p = E du^2 + 2F du dv + G dv^2.$$

To understand this, let's start with inner product in  $\mathbb{R}^3$ .

$$\mathbb{R}^3 = \text{span}\{e_1, e_2, e_3\} = \text{span}\left\{\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z}\right\} = \text{span}\left\{\frac{\partial}{\partial x^1}, \frac{\partial}{\partial x^2}, \frac{\partial}{\partial x^3}\right\}.$$

Here, since for each vector  $v$  with length 1, it uniquely determines a directional derivative  $\nabla_v$  and vice versa. Hence we can identify  $e_1 = (1, 0, 0)$  with  $\frac{\partial}{\partial x^1}$ , and  $e_2 = \frac{\partial}{\partial x^2}$ ,  $e_3 = \frac{\partial}{\partial x^3}$ .

The inner product on  $\mathbb{R}^3$  is

$$\begin{aligned}g_{\mathbb{R}^3}: \mathbb{R}^3 \times \mathbb{R}^3 &\longrightarrow \mathbb{R} \\ (v, w) &\longmapsto \langle v, w \rangle, \quad v, w \text{ vectors in } \mathbb{R}^3.\end{aligned}$$

Satisfy:

- $g(v, w) = g(w, q)$
- $g(av_1 + bv_2, w) = ag(v_1, w) + bg(v_2, w)$
- $g(v, v) \geq 0$  and  $g(v, v) = 0 \iff v = 0$ .

If  $v = \sum_{i=1}^3 v^i \frac{\partial}{\partial x^i}$ ,  $w = \sum_{j=1}^3 w^j \frac{\partial}{\partial x^j}$ , then

$$g_{\mathbb{R}^3}(v, w) = \sum_{i,j=1}^3 \delta_{ij} v^i w^j, \quad \text{where } \delta_{ij} = \begin{cases} 1 & i = j \\ 0 & i \neq j \end{cases}.$$

$(\mathbb{R}^3)^*$ , dual space of  $\mathbb{R}^3$  is defined as follows:

For a vector  $v \in \mathbb{R}^3$ , we define an element  $\alpha_v \in (\mathbb{R}^3)^*$  by

$$\alpha_v = g_{\mathbb{R}^3}(v, \cdot): \mathbb{R}^3 \rightarrow R, \quad w \mapsto \alpha_v(w) = g_{\mathbb{R}^3}(v, w).$$

The dual basis of  $\{e_1, e_2, e_3\} = \{\frac{\partial}{\partial x^1}, \frac{\partial}{\partial x^2}, \frac{\partial}{\partial x^3}\}$  is

$$\{e_1^*, e_2^*, e_3^*\} = \{\mathrm{d}x^1, \mathrm{d}x^2, \mathrm{d}x^3\}.$$

s.t.  $e_i^*(e_j) = g(e_i, e_j) = \delta_{ij}$ . Then  $(\mathbb{R}^3)^* = \text{span}\{e_1^*, e_2^*, e_3^*\} = \text{span}\{\mathrm{d}x^1, \mathrm{d}x^2, \mathrm{d}x^3\}$ . Hence

$$\alpha_v = \sum_{i=1}^3 v^i \mathrm{d}x^i, \quad v^1 = \left\langle v, \frac{\partial}{\partial x^i} \right\rangle, \quad g_{\mathbb{R}^3}(v, \cdot) = \alpha_v \in (\mathbb{R}^3)^*.$$



By relaxing  $v$  in  $g_{\mathbb{R}^3}(v, \cdot)$ , we can view  $g_{\mathbb{R}^3}$  as a symmetric element in  $(\mathbb{R}^3)^* \otimes (\mathbb{R}^3)^*$ . From linear algebra,

$$\text{Sym}((\mathbb{R}^3)^* \otimes (\mathbb{R}^3)^*) = \text{span}\{\mathrm{d}x^i \mathrm{d}x^j = \mathrm{d}x^j \mathrm{d}x^i\}_{i,j=1,2,3}.$$

Hence we can write

$$g_{\mathbb{R}^3} = \delta_{ij} \mathrm{d}x^i \mathrm{d}x^j = (\mathrm{d}x^1)^2 + (\mathrm{d}x^2)^2 + (\mathrm{d}x^3)^2.$$

Now let  $S \subset \mathbb{R}^3$  with local parametrization given at the beginning of this section, i.e.  $x^i = x^i(u, v)$ . We have

$$\mathrm{d}x^1 = x_u^1 \mathrm{d}u + x_v^1 \mathrm{d}v, \quad \mathrm{d}x^2 = x_u^2 \mathrm{d}u + x_v^2 \mathrm{d}v, \quad \mathrm{d}x^3 = x_u^3 \mathrm{d}u + x_v^3 \mathrm{d}v.$$

Then we consider restrict  $g_{\mathbb{R}^3}$  on  $TS$ ,

$$\begin{aligned} g_{\mathbb{R}^3}|_{TS} &= (x_u^1 \mathrm{d}u + x_v^1 \mathrm{d}v)^2 + (x_u^2 \mathrm{d}u + x_v^2 \mathrm{d}v)^2 + (x_u^3 \mathrm{d}u + x_v^3 \mathrm{d}v)^2 \\ &= ((x_u^1)^2 + (x_u^2)^2 + (x_u^3)^2) \mathrm{d}u^2 + 2(x_u^1 x_v^1 + x_u^2 + x_v^2 + x_u^3 x_v^3) \mathrm{d}u \mathrm{d}v \\ &\quad + ((x_v^1)^2 + (x_v^2)^2 + (x_v^3)^2) \mathrm{d}v^2 \\ &= \langle \varphi_u, \varphi_u \rangle \mathrm{d}u^2 + 2 \langle \varphi_u, \varphi_v \rangle \mathrm{d}u \mathrm{d}v + \langle \varphi_v, \varphi_v \rangle \mathrm{d}v^2 \\ &= E \mathrm{d}u^2 + 2F \mathrm{d}u \mathrm{d}v + G \mathrm{d}v^2. \end{aligned}$$

Therefore, we see the 1st fundamental form is just the restriction of Euclidean inner product of  $\mathbb{R}^3$  on  $TS$ .

Recall:  $\varphi: U \subset \mathbb{R}^2 \rightarrow S, p \in S$ , then

$$\mathrm{d}\varphi_p: T_{(u_0, v_0)}U \rightarrow T_pS, \quad T_{(u_0, v_0)}U \cong \mathbb{R}^2 = \text{span}\{\frac{\partial}{\partial u}, \frac{\partial}{\partial v}\}.$$

Then

$$\mathrm{d}\varphi_p(\frac{\partial}{\partial u}) = \varphi_u, \quad \mathrm{d}\varphi_p(\frac{\partial}{\partial v}) = \varphi_v.$$

We get

$$\begin{aligned} I_p(\frac{\partial}{\partial u}, \frac{\partial}{\partial u}) &= E = g_{\mathbb{R}^3}(\varphi_u, \varphi_u) = g_{\mathbb{R}^3}(\mathrm{d}\varphi_p(\frac{\partial}{\partial u}), \mathrm{d}\varphi_p(\frac{\partial}{\partial u})) \\ I_p(\frac{\partial}{\partial u}, \frac{\partial}{\partial v}) &= F = g_{\mathbb{R}^3}(\varphi_u, \varphi_v) = g_{\mathbb{R}^3}(\mathrm{d}\varphi_p(\frac{\partial}{\partial u}), \mathrm{d}\varphi_p(\frac{\partial}{\partial v})) \\ I_p(\frac{\partial}{\partial v}, \frac{\partial}{\partial v}) &= G = g_{\mathbb{R}^3}(\varphi_v, \varphi_v) = g_{\mathbb{R}^3}(\mathrm{d}\varphi_p(\frac{\partial}{\partial v}), \mathrm{d}\varphi_p(\frac{\partial}{\partial v})). \end{aligned}$$

Therefore, the 1st fundamental form is a positive definite bilinear form defined on  $T_pS \cong T_{(u_0, v_0)}U$ .

*Remark.* In Riemannian Geometry, the generalization of above defines a “pull-back” metric  $\varphi^*g$  by  $\varphi: M \rightarrow N$ .

**Exercise.** Consider a vector  $v \in T_pS$ , compute  $I_p(v, v)$ .

*Remark.* Since  $I_p = (\mathrm{d}u, \mathrm{d}v) \begin{pmatrix} E & F \\ F & G \end{pmatrix} \begin{pmatrix} \mathrm{d}u \\ \mathrm{d}v \end{pmatrix}$ , we might also refer  $\begin{pmatrix} E & F \\ F & G \end{pmatrix}$  as the 1st fundamental form.

**Theorem 2.6.1.** *I* is independent of local parametrization.

*Proof.* Let  $\varphi(u, v)$  and  $\psi(\alpha, \beta)$  be two local parametrizations near  $p$ .

$$\begin{cases} u = u(\alpha, \beta) \\ v = v(\alpha, \beta) \end{cases} \quad \text{has inverse} \quad \begin{cases} \alpha = \alpha(u, v) \\ \beta = \beta(u, v) \end{cases} .$$

Then

$$\begin{aligned} \begin{pmatrix} du \\ dv \end{pmatrix} &= \begin{pmatrix} u_\alpha & u_\beta \\ v_\alpha & v_\beta \end{pmatrix} \begin{pmatrix} d\alpha \\ d\beta \end{pmatrix} = \frac{\partial(u, v)}{\partial(\alpha, \beta)} \begin{pmatrix} d\alpha \\ d\beta \end{pmatrix}. \\ \begin{pmatrix} \langle \varphi_u, \varphi_v \rangle & \langle \varphi_u, \varphi_v \rangle \\ \langle \varphi_v, \varphi_u \rangle & \langle \varphi_v, \varphi_v \rangle \end{pmatrix} &= \begin{pmatrix} \alpha_u & \beta_u \\ \alpha_v & \beta_v \end{pmatrix} \begin{pmatrix} \langle \psi_\alpha, \psi_\beta \rangle & \langle \psi_\alpha, \psi_\beta \rangle \\ \langle \psi_\beta, \psi_\alpha \rangle & \langle \psi_\beta, \psi_\beta \rangle \end{pmatrix} \begin{pmatrix} \alpha_u & \alpha_v \\ \beta_u & \beta_v \end{pmatrix}. \end{aligned}$$

This gives

$$\begin{aligned} (du, dv) \begin{pmatrix} \langle \varphi_u, \varphi_v \rangle & \langle \varphi_u, \varphi_v \rangle \\ \langle \varphi_v, \varphi_u \rangle & \langle \varphi_v, \varphi_v \rangle \end{pmatrix} \begin{pmatrix} du \\ dv \end{pmatrix} \\ = (d\alpha, d\beta) \underbrace{\begin{pmatrix} u_\alpha & u_\beta \\ v_\alpha & v_\beta \end{pmatrix}}_{\text{Id}} \underbrace{\begin{pmatrix} \alpha_u & \alpha_v \\ \beta_u & \beta_v \end{pmatrix}}_{\text{Id}} \begin{pmatrix} \langle \psi_\alpha, \psi_\beta \rangle & \langle \psi_\alpha, \psi_\beta \rangle \\ \langle \psi_\beta, \psi_\alpha \rangle & \langle \psi_\beta, \psi_\beta \rangle \end{pmatrix} \underbrace{\begin{pmatrix} \alpha_u & \alpha_v \\ \beta_u & \beta_v \end{pmatrix}}_{\text{Id}} \underbrace{\begin{pmatrix} u_\alpha & u_\beta \\ v_\alpha & v_\beta \end{pmatrix}}_{\text{Id}} \\ = (d\alpha, d\beta) \begin{pmatrix} \langle \psi_\alpha, \psi_\beta \rangle & \langle \psi_\alpha, \psi_\beta \rangle \\ \langle \psi_\beta, \psi_\alpha \rangle & \langle \psi_\beta, \psi_\beta \rangle \end{pmatrix} \begin{pmatrix} d\alpha \\ d\beta \end{pmatrix}. \end{aligned}$$

□

*Remark.* By this theorem, on a regular surface, to compute the 1st fundamental form, it suffices to work it out in a coordinate chart. As you will see, in this course and later in Riemannian Geometry course, there will be a lot of “local computation”.

**Example 2.6.2** (Plane).  $P \subset \mathbb{R}^3$  a plane through  $p_0 = (x_0, y_0, z_0)$ , consisting two orthonormal vectors  $w_1$  and  $w_2$ , viewed as vectors in  $\mathbb{R}^3$ . Then

$$\varphi(u, v) = p_0 + uw_1 + vw_2.$$

⇒

$$I = du^2 + dv^2.$$

Let  $v$  be a vector in  $P$ ,  $v = a\varphi_u + b\varphi_v = aw_1 + bw_2$ . Then

$$I(v, v) = (a, b) \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} a \\ b \end{pmatrix} = a^2 + b^2 = |v|^2.$$

**Example 2.6.3** (Cylinder).  $\varphi(u, v) = (\cos u, \sin u, v)$ ,  $\{0 < u < 2\pi, v \in \mathbb{R}\}$ .

Direct calculate shows

$$I = du^2 + dv^2.$$

**Question.** It looks both the plane and cylinder have the same 1st fundamental form. This means a vector at a point  $p \in P$  will have the same length when we “move” the point  $p$  and vector onto the cylinder (Think about the cylinder as gluing two edges of a paper). On the other hand, cylinder is clearly not the plane. What can you conclude?

(The difference lies in “topology”. There is non-shrinking circles on the cylinder. The plane and cylinder locally look the “same” (with the same measurement). But globally they are different).

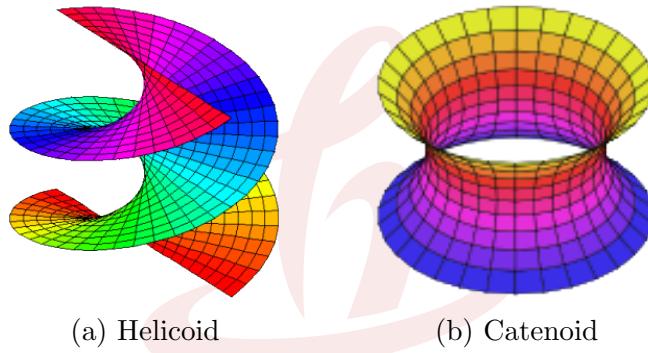
**Example 2.6.4.**  $\mathbb{S}^2 = \{x^2 + y^2 + z^2 = 1\}$ , compute the 1st fundamental form in three parametrizations introduced before. (Left as exercise)

**Example 2.6.5.** Helicoid and catenoid (from homework)

In your homework you have found local parametrizations of helicoid and catenoid

$$H(u, v) = (v \cos u, v \sin u, au)$$

$$C(\varphi, \theta) = (a \cosh \theta \cos \varphi, a \cosh \theta \sin \varphi, a\theta).$$



(1) Compute the 1<sup>st</sup> fundamental form of them.

$$I_H = (v^2 + a^2) du^2 + dv^2$$

$$I_C = (a^2 \cosh^2 \theta) d\varphi^2 + (a^2 \cosh^2 \theta) d\theta^2$$

(2) Show that there is a parametrization on the helicoid,  $\tilde{H}(\tilde{u}, \tilde{v})$ , such that

$$I_{\tilde{H}} = (a^2 \cosh^2 \tilde{v}) d\tilde{u}^2 + (a^2 \cosh^2 \tilde{v}) d\tilde{v}^2.$$

$$(u = \tilde{u}, v = a \sinh \tilde{v})$$

*Remark.* In both example 1 and example 3, we have seen that near a point, the two surfaces considered have the same 1<sup>st</sup> fundamental form (after a change of parametrization). Such property is called “local isometry”. We’ll make this definition more clear later.

- Application of the 1<sup>st</sup> fundamental form

(1) Arclength of a curve on  $S$ .

Note that for a vector  $v \in \mathbb{R}^2$ ,  $I(v, v) = |v|^2$ . Let  $\alpha(t): (0, t) \rightarrow S$  be a curve in  $S$  and  $\varphi: U \rightarrow S$ ,  $(u, v) \mapsto \varphi(u, v)$  be a local parametrization satisfying  $\alpha(t) \in \varphi(U)$ .

$$\begin{aligned}\implies \alpha(t) &= \varphi(u(t), v(t)). \\ \implies \alpha'(t) &= \varphi_u u'(t) + \varphi_v v'(t). \\ \implies |\alpha'(t)|^2 &= I(\alpha'(t), \alpha'(t)) = Eu_t^2 + 2Fu_tv_t + Gv_t^2.\end{aligned}$$

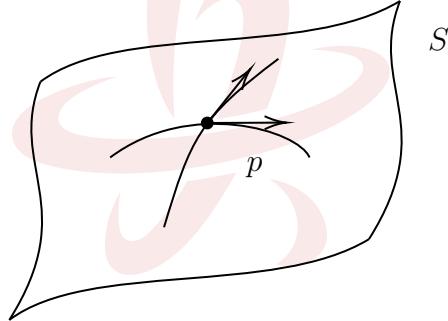
The arclength of  $\alpha(t)$  is defined by

$$\begin{aligned}s(t) &= \int_0^t |\alpha'(t)| dt = \int_0^t \sqrt{Eu_t^2 + 2Fu_tv_t + Gv_t^2} dt. \\ \implies ds &= \sqrt{Eu_t^2 + 2Fu_tv_t + Gv_t^2} dt. \\ \implies \left(\frac{ds}{dt}\right)^2 &= Eu_t^2 + 2Fu_tv_t + Gv_t^2. \\ \implies ds^2 &= Edu^2 + 2Fdudv + Gdv^2.\end{aligned}$$

This explains the “geometric meaning” of  $I$ , i.e. it measures the infinitesimal arclength.

(2) Angle between two curves intersecting at  $t_0$ .

Let  $\alpha: I \rightarrow S$ ,  $\beta: I \rightarrow S$  be two curves on  $S$ ,  $\alpha(t_0) = \beta(\bar{t}_0) = p \in S$ .



Define

$$\cos \theta = \frac{\langle \alpha'(t_0), \beta'(\bar{t}_0) \rangle_{\mathbb{R}^3}}{|\alpha'(t_0)| |\beta'(\bar{t}_0)|}.$$

**Question.** Given a parametrization  $\varphi(u, v)$ , we have two coordinate curve  $\varphi(u, v_0)$ ,  $\varphi(u_0, v)$ . What's the angle between them?

$$\begin{aligned}u\text{-curve: } \alpha(t) &= \varphi(u(t), c) \implies \alpha'(t) = \varphi_u u'. \\ v\text{-curve: } \beta(t) &= \varphi(c, v(t)) \implies \beta'(t) = \varphi_v v'. \\ \implies \cos \theta &= \frac{\langle \varphi_u u', \varphi_v v' \rangle}{|\varphi_u u'| |\varphi_v v'|} = \pm \frac{\langle \varphi_u, \varphi_v \rangle_{\mathbb{R}^3}}{|\varphi_u| |\varphi_v|} = \pm \frac{F}{\sqrt{EG}}.\end{aligned}$$

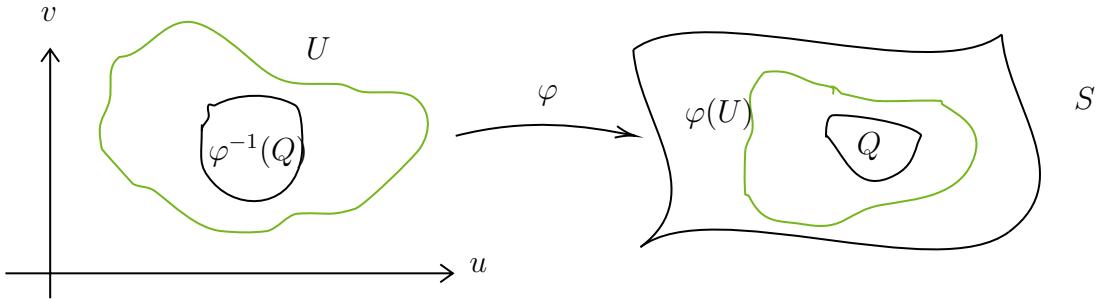
In particular, we conclude that

$$F = 0 \Leftrightarrow \text{Two coordinate curves are orthogonal},$$

and such parametrization is called an orthogonal parametrization. (e.g. For  $\mathbb{S}^2$ ,  $(\theta, \varphi)$  and the stereographic projection are two such parametrizations)

### (3) (Surface) Area.

Let  $S$  be a regular surface. Choose a parametrization  $\varphi: U \rightarrow S$ . Let  $Q \subset S$  be a bounded domain. Assume  $Q \subset \varphi(U)$ , so  $\varphi^{-1}(Q) \subset U$  is a bounded set in  $\mathbb{R}^2$ .



Let's assume the boundary of  $Q$  is a differentiable curve with singularities lying in a measure zero set.

**Definition 2.6.6** (Area of  $Q$ ).

$$Area(Q) = \iint_{\varphi(Q)} |\varphi_u \wedge \varphi_v| \, dudv \quad (\text{double integral in } \mathbb{R}^2).$$

Here, we give the definition in terms of a “parametrization”. However, the area of  $Q$  is a number only depending on  $Q$  itself. We should check that our definition does not depend on the parametrization.

**Claim:**  $Area(Q)$  defined above is independent of the choice of parametrizations.

*Proof.* (Left as exercise)

Let  $\psi(\alpha, \beta): V \rightarrow S$  be another parametrization. Let  $H = \psi^{-1} \circ \varphi$  be the change of parametrization,  $H(u, v) = (\alpha, \beta) \implies \varphi = \psi \circ H$ . We compute  $\iint_{\varphi(Q)} |\varphi_u \wedge \varphi_v| \, dudv$ .

By chain rule

$$\begin{pmatrix} \varphi_u \\ \varphi_v \end{pmatrix} = \frac{\partial(\alpha, \beta)}{\partial(u, v)} \begin{pmatrix} \psi_\alpha \\ \psi_\beta \end{pmatrix}.$$

$$\begin{aligned} \implies \varphi_u \wedge \varphi_v &= (\alpha_u \beta_v - \alpha_v \beta_u) \psi_\alpha \wedge \psi_\beta + (\alpha_v \beta_u - \alpha_u \beta_v) \psi_\beta \wedge \psi_\alpha \\ &= (\alpha_u \beta_v - \alpha_v \beta_u) \psi_\alpha \wedge \psi_\beta \\ &= \det \left( \frac{\partial(\alpha, \beta)}{\partial(u, v)} \right) \psi_\alpha \wedge \psi_\beta. \end{aligned}$$

$$\implies |\varphi_u \wedge \varphi_v| = \left| \det \left( \frac{\partial(\alpha, \beta)}{\partial(u, v)} \right) \right| |\psi_\alpha \wedge \psi_\beta|.$$

On the other hand,

$$\begin{pmatrix} du \\ dv \end{pmatrix} = \frac{\partial(u, v)}{\partial(\alpha, \beta)} \begin{pmatrix} d\alpha \\ d\beta \end{pmatrix}.$$

Thus, the change of infinitesimal area element is

$$\begin{aligned}
 dudv &= |\mathrm{d}u \wedge \mathrm{d}v| = \left| \det \left( \frac{\partial(u, v)}{\partial(\alpha, \beta)} \right) \right| |\mathrm{d}\alpha \wedge \mathrm{d}\beta| = \left| \det \left( \frac{\partial(u, v)}{\partial(\alpha, \beta)} \right) \right| \mathrm{d}\alpha \mathrm{d}\beta. \\
 \implies |\varphi_u \wedge \varphi_v| dudv &= |\psi_\alpha \wedge \psi_\beta| \mathrm{d}\alpha \mathrm{d}\beta. \\
 \implies \iint |\varphi_u \wedge \varphi_v| dudv &= \iint |\psi_\alpha \wedge \psi_\beta| \mathrm{d}\alpha \mathrm{d}\beta.
 \end{aligned}$$

□

*Remark.* By the 1<sup>st</sup> fundamental form

$$\begin{aligned}
 I &= E(\mathrm{d}u)^2 + 2F\mathrm{d}u \mathrm{d}v + G(\mathrm{d}v)^2 \\
 \implies \text{Area} &= \iint |\varphi_u \wedge \varphi_v| dudv = \iint \sqrt{EG - F^2} dudv.
 \end{aligned}$$

## 2.7 Gauss maps and the 2<sup>nd</sup> fundamental form

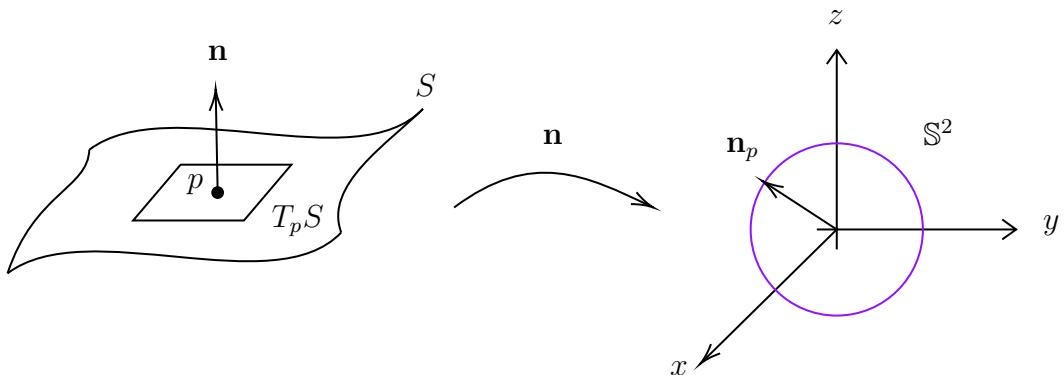
- Gauss maps.

**Question.** How is a regular surface curved in  $\mathbb{R}^3$ ?

Recall:  $S \subset \mathbb{R}^3$  is an oriented regular surface.  $\implies$  We can choose a unit vector field

$$\begin{aligned}
 \mathbf{n}: S &\rightarrow \mathbb{S}^2(1) \\
 p &\mapsto \mathbf{n}_p,
 \end{aligned}$$

is well-defined everywhere on  $S$ . Moreover,  $\mathbf{n}$  is a differentiable map with its image lying on the unit sphere, and we called the map to be the Gauss map.  $\mathbf{n}$  determines an orientation of  $S$ .



Let  $\varphi: U \rightarrow S$  be a local parametrization near  $p \in S$ , then

$$\mathbf{n} = \frac{\varphi_u \wedge \varphi_v}{|\varphi_u \wedge \varphi_v|}.$$

Let's compute the differential of the Gauss map at  $p$ .

$$\mathrm{d}\mathbf{n}_p: T_p S \rightarrow T_{\mathbf{n}_p} \mathbb{S}^2.$$

$\forall v \in T_p S$ , let  $\alpha(s)$  be the curve on  $S$  such that  $\alpha(0) = p$ ,  $\alpha'(0) = v$ .

$$\implies d\mathbf{n}_p(v) = \frac{d}{ds} \Big|_{s=0} \mathbf{n}(\alpha(s)) \text{ (changing rate of the Gauss map at } p \text{ along direction } v).$$

Note  $\langle \mathbf{n}(\alpha(s)), \mathbf{n}(\alpha(s)) \rangle = 1$ , taking derivation at  $s = 0$ :

$$\left\langle \frac{d}{ds} \Big|_{s=0} \mathbf{n}(\alpha(s)), \mathbf{n}_p \right\rangle = 0.$$

$$\implies d\mathbf{n}_p(v) = \frac{d}{ds} \Big|_{s=0} \mathbf{n}(\alpha(s)) \in T_p S.$$

**Definition 2.7.1** (The 2<sup>nd</sup> fundamental form).

- $\forall v \in T_p S$ , the 2<sup>nd</sup> fundamental form

$$II_p(v, v) = -\langle d\mathbf{n}_p(v), v \rangle_{\mathbb{R}^3}^{\textcolor{blue}{1}}.$$

- More generally  $\forall v, w \in T_p S$ ,

$$II_p: T_p S \times T_p S \rightarrow T_p \mathbb{R}$$

$$(v, w) \mapsto II_p(v, w) = -\langle d\mathbf{n}_p(v), w \rangle_{\mathbb{R}^3}.$$

$-d\mathbf{n}_p$  is also called the shape operator.

Before we explore  $II_p$ , let's compute the Gauss map's differential.

- Let  $\varphi(u, v)$  be a local parametrization. Any curve on  $S$  has parametrization

$$\alpha(t) = \varphi(u(t), v(t)) = (x(u(t), v(t)), y(u(t), v(t)), z(u(t), v(t))).$$

$$\implies \alpha'(0) = \varphi_u u'(0) + \varphi_v v'(0).$$

$$\begin{aligned} d\mathbf{n}_p(\alpha'(0)) &= \frac{d}{dt} \Big|_{t=0} \mathbf{n}(\alpha(t)) \\ &= \frac{d}{dt} \Big|_{t=0} \mathbf{n}(x(u(t), v(t)), y(u(t), v(t)), z(u(t), v(t))) \\ &= (\mathbf{n}_x x_u + \mathbf{n}_y y_u + \mathbf{n}_z z_u) u'(0) + (\mathbf{n}_x x_v + \mathbf{n}_y y_v + \mathbf{n}_z z_v) v'(0) \\ &= \mathbf{n}_u u'(0) + \mathbf{n}_v v'(0). \end{aligned}$$

On the other hand, by the linearity of  $d\mathbf{n}_p$ ,

$$d\mathbf{n}_p(\alpha'(0)) = u'(0)d\mathbf{n}_p(\varphi_u) + v'(0)d\mathbf{n}_p(\varphi_v).$$

---

<sup>1</sup>Thus,  $d\mathbf{n}_p: T_p S \rightarrow T_p S$  is a linear map, which is the directional derivation of  $\mathbf{n}$  along a tangent direction of  $S$ .



$$\implies \begin{cases} d\mathbf{n}_p(\varphi_u) = \mathbf{n}_u, \\ d\mathbf{n}_p(\varphi_v) = \mathbf{n}_v. \end{cases}$$

$$\begin{aligned} \langle d\mathbf{n}_p(\varphi_u), \varphi_u \rangle &= \langle \mathbf{n}_u, \varphi_u \rangle = \frac{\partial}{\partial u} \underbrace{\langle \mathbf{n}, \varphi_u \rangle}_{=0} - \langle \mathbf{n}, \varphi_{uu} \rangle \\ \langle d\mathbf{n}_p(\varphi_u), \varphi_v \rangle &= \langle \mathbf{n}_u, \varphi_v \rangle \\ &= \frac{\partial}{\partial u} \underbrace{\langle \mathbf{n}, \varphi_v \rangle}_{=0} - \langle \mathbf{n}, \varphi_{vu} \rangle \\ &= -\langle \mathbf{n}, \varphi_{vu} \rangle \\ \langle d\mathbf{n}_p(\varphi_v), \varphi_u \rangle &= \langle \mathbf{n}_v, \varphi_u \rangle \\ &= -\langle \mathbf{n}, \varphi_{uv} \rangle \text{ (Note that } \varphi_{uv} = \varphi_{vu} \text{ since } \varphi \text{ is smooth)} \\ \langle d\mathbf{n}_p(\varphi_v), \varphi_v \rangle &= \langle \mathbf{n}_v, \varphi_v \rangle = -\langle \mathbf{n}, \varphi_{vv} \rangle. \end{aligned}$$

Hence, we conclude that:

**Theorem 2.7.2.**  $\Pi_p(v, w) = \Pi_p(w, v)$ , i.e.  $\Pi_p$  is symmetric in  $v, w$ , and  $\Pi_p$  is a bilinear form.

*Remark.*

- (1) From the computation above, we see that  $d\mathbf{n}_p$  is self-adjoint, i.e.  $\langle d\mathbf{n}_p(v), w \rangle = \langle v, d\mathbf{n}_p(w) \rangle$ .
- (2) The 2<sup>nd</sup> fundamental form can be also defined as

$$\Pi_p(v, v) = \langle \mathbf{n}_p, \alpha''(0) \rangle,$$

where  $\alpha$  is a curve with  $\alpha'(0) = v$ .

**Exercise.** Check that this definition coincides with the previous one.

*Proof.* Along the curve  $\alpha(t) \in S$ ,  $\langle \mathbf{n}(\alpha(t)), \alpha'(t) \rangle = 0$ . Therefore,

$$\begin{aligned} 0 &= \frac{d}{dt} \langle \mathbf{n}(\alpha(t)), \alpha'(t) \rangle \\ &= \langle d\mathbf{n}_{\alpha(t)}(\alpha'(t), \alpha'(t)) \rangle + \langle \mathbf{n}(\alpha(t)), \alpha''(t) \rangle. \end{aligned}$$

□

Just as the 1<sup>st</sup> fundamental form, we write  $\Pi$  as

$$\Pi_p = e du^2 + 2f dudv + g dv^2,$$

where

$$\begin{aligned} e &= -\langle d\mathbf{n}_p(\varphi_u), \varphi_u \rangle = -\langle \mathbf{n}_u, \varphi_u \rangle = \langle \mathbf{n}, \varphi_{uu} \rangle \\ f &= -\langle d\mathbf{n}_p(\varphi_u), \varphi_v \rangle = -\langle \mathbf{n}_u, \varphi_v \rangle = \langle \mathbf{n}, \varphi_{uv} \rangle \\ ( &= -\langle d\mathbf{n}_p(\varphi_v), \varphi_u \rangle = -\langle \mathbf{n}_v, \varphi_u \rangle = \langle \mathbf{n}, \varphi_{vu} \rangle) \\ g &= -\langle d\mathbf{n}_p(\varphi_v), \varphi_v \rangle = -\langle \mathbf{n}_v, \varphi_v \rangle = \langle \mathbf{n}, \varphi_{vv} \rangle \end{aligned}$$

- Weingarten equations (linear representation of  $d\mathbf{n}$  in  $\{\varphi_u, \varphi_v\}$ )

We have seen  $d\mathbf{n}_p : T_p S \rightarrow T_{\mathbf{n}_p} \mathbb{S}^2$  has image actually lying in  $T_p S = \text{span}\{\varphi_u, \varphi_v\}$  in terms of a local parametrization  $\varphi(u, v)$ .

$$\implies \begin{cases} d\mathbf{n}_p(\varphi_u) = a_{11}\varphi_u + a_{12}\varphi_v \\ d\mathbf{n}_p(\varphi_v) = a_{21}\varphi_u + a_{22}\varphi_v \end{cases} \quad i.e. \quad \begin{cases} \mathbf{n}_u = a_{11}\varphi_u + a_{12}\varphi_v \\ \mathbf{n}_v = a_{21}\varphi_u + a_{22}\varphi_v \end{cases}$$

We would like to find out the matrix  $\begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix}$ .

Recall that

$$I_p = Edu^2 + 2Fdudv + Gdv^2,$$

where

$$E = \langle \varphi_u, \varphi_u \rangle, F = \langle \varphi_u, \varphi_v \rangle, G = \langle \varphi_v, \varphi_v \rangle.$$

Now we consider the matrix

$$\begin{pmatrix} \mathbf{n}_u \\ \mathbf{n}_v \end{pmatrix} \begin{pmatrix} \varphi_u & \varphi_v \end{pmatrix} = \begin{pmatrix} \langle \mathbf{n}_u, \varphi_u \rangle & \langle \mathbf{n}_u, \varphi_v \rangle \\ \langle \mathbf{n}_v, \varphi_u \rangle & \langle \mathbf{n}_v, \varphi_v \rangle \end{pmatrix}.$$

On the one hand, the R.H.S. is

$$\begin{pmatrix} -e & -f \\ -f & -g \end{pmatrix} = - \begin{pmatrix} e & f \\ f & g \end{pmatrix}.$$

On the other hand,

$$\text{R.H.S.} = \begin{pmatrix} a_{11}E + a_{12}F & a_{11}F + a_{12}G \\ a_{21}E + a_{22}F & a_{21}F + a_{22}G \end{pmatrix}$$

$$= \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix} \begin{pmatrix} E & F \\ F & G \end{pmatrix}.$$

$$\implies - \underbrace{\begin{pmatrix} e & f \\ f & g \end{pmatrix}}_{II} = \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix} \underbrace{\begin{pmatrix} E & F \\ F & G \end{pmatrix}}_I.$$

$$\begin{aligned} \implies \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix} &= - \begin{pmatrix} e & f \\ f & g \end{pmatrix} \begin{pmatrix} E & F \\ F & G \end{pmatrix}^{-1} \\ &= - \begin{pmatrix} e & f \\ f & g \end{pmatrix} \frac{1}{\det} \begin{pmatrix} G & -F \\ -F & E \end{pmatrix} \\ &= - \frac{1}{EG - F^2} \begin{pmatrix} e & f \\ f & g \end{pmatrix} \begin{pmatrix} G & -F \\ -F & E \end{pmatrix} \\ &= \frac{1}{EG - F^2} \begin{pmatrix} fF - eG & eF - fE \\ gF - fG & fF - gE \end{pmatrix}. \end{aligned} \tag{*}$$

The Weingarten equation is  $d\mathbf{n}_p \sim \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix}$ , i.e.

$$\begin{pmatrix} \mathbf{n}_u \\ \mathbf{n}_v \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix} \begin{pmatrix} \varphi_u \\ \varphi_v \end{pmatrix},$$

with  $\begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix}$  defined in (\*).

- ! For a regular surface  $S \subset \mathbb{R}^3$ , if we know the local parametrization  $\varphi(u, v)$  near a point  $p$ , then

$$I_p = Edu^2 + 2Fdudv + Gdv^2,$$

and

$$II_p = edu^2 + 2fdudv + gdv^2,$$

are fully understood with

$$\begin{pmatrix} E & F \\ F & G \end{pmatrix} = \begin{pmatrix} \langle \varphi_u, \varphi_u \rangle & \langle \varphi_u, \varphi_v \rangle \\ \langle \varphi_v, \varphi_u \rangle & \langle \varphi_v, \varphi_v \rangle \end{pmatrix},$$

and

$$\begin{pmatrix} e & f \\ f & g \end{pmatrix} = \begin{pmatrix} \langle \varphi_{uu}, \mathbf{n} \rangle & \langle \varphi_{uv}, \mathbf{n} \rangle \\ \langle \varphi_{vu}, \mathbf{n} \rangle & \langle \varphi_{vv}, \mathbf{n} \rangle \end{pmatrix}.$$

### Example 2.7.3.

(1) Plane:  $Ax + By + Cz + D = 0$

$$\mathbf{n} = \frac{(A, B, C)}{\sqrt{A^2 + B^2 + C^2}}$$

is a constant map. Thus,  $d\mathbf{n} = 0$  and  $II(v, v) = -\langle d\mathbf{n}(v), v \rangle = 0$ .

(2)  $\mathbb{S}^2(1) = \{x^2 + y^2 + z^2 = 1\}$ . At point  $(x, y, z)$ , the unit normal vector field is  $\mathbf{n}_{\pm} = \pm(x, y, z)$ , where  $\mathbf{n}_+$  means the outer normal vector, and  $\mathbf{n}_-$  the inner normal vector.

Let's consider  $\mathbf{n}_- = -(x, y, z)$ , let  $\alpha(t) = (x(t), y(t), z(t))$  be a curve on  $\mathbb{S}^2$ , then

$$d\mathbf{n}_-(\alpha'(t)) = \frac{d}{dt}\mathbf{n}_-(\alpha(t)) = -\frac{d}{dt}(x(t), y(t), z(t)) = -\alpha'(t).$$

$$\implies II(\alpha'(t), \alpha'(t)) = -\langle d\mathbf{n}_-(\alpha'(t)) \rangle = \langle \alpha'(t), \alpha'(t) \rangle = |\alpha'(t)|^2 \geq 0.$$

If we take  $\mathbf{n}_+$ , then

$$II(\alpha'(t), \alpha(t)) = -|\alpha'(t)|^2 \leq 0.$$

Hence, sign of the 2<sup>nd</sup> fundamental form depends on the choice of orientation (i.e. the unit normal).

(3) Helicoid (in which every point looks like a saddle point).

$$H(u, v) = (v \cos u, v \sin u, au)$$

$$H_u = (-v \sin u, v \cos u, a), \quad H_v = (\cos u, \sin u, 0).$$

$$H_{uu} = (-v \cos u, -v \sin u, 0), H_{uv} = (-\sin u, \cos u, 0), H_{vv} = (0, 0, 0).$$

$$\mathbf{n} = \left( -\frac{a \sin u}{\sqrt{a^2 + v^2}}, \frac{a \cos u}{\sqrt{a^2 + v^2}}, -\frac{v}{\sqrt{a^2 + v^2}} \right).$$

$$II = \frac{2a}{\sqrt{a^2 + v^2}} du dv,$$

i.e.

$$\begin{pmatrix} e & f \\ f & g \end{pmatrix} = \begin{pmatrix} 0 & \frac{2a}{\sqrt{a^2 + v^2}} \\ \frac{2a}{\sqrt{a^2 + v^2}} & 0 \end{pmatrix}, \quad \lambda = \pm \frac{a}{\sqrt{a^2 + v^2}} \text{ indefinite.}$$

(4) Cylinder.  $x^2 + y^2 = 1$

$$c(\theta, v) = (\cos \theta, \sin \theta, v).$$

$$c_\theta = (-\sin \theta, \cos \theta, 0), \quad c_v = (0, 0, 1).$$

$$\mathbf{n}_+ = (\cos \theta, \sin \theta, 0) \text{ (the outer normal)},$$

$$\mathbf{n}_- = (-\cos \theta, -\sin \theta, 0) \text{ (the inner normal)}.$$

$$c_{\theta\theta} = (-\cos \theta, -\sin \theta, 0), \quad c_{\theta v} = (0, 0, 0), \quad c_{vv} = (0, 0, 0).$$

$$\Rightarrow II_{\mathbf{n}_-} = d\theta^2 \sim \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}.$$

*Remark.* The cylinder and the plane have the same 1<sup>st</sup> fundamental form, but different 2<sup>nd</sup> fundamental form.

## 2.8 Geometric meaning of the 2<sup>nd</sup> fundamental form and curvatures

Recall:

- Gauss map

$$\vec{N}: S \rightarrow \mathbb{S}^2(1),$$

$$p \mapsto \vec{N}_p.$$

- $d\vec{N}_p: T_p S \rightarrow T_{\vec{N}(p)} \mathbb{S}^2(1) \simeq T_p S$ .

- $\forall v \in T_p S, II(v, v) = -\langle d\vec{N}_p(v), v \rangle = \langle \vec{N}_p, \alpha''(0) \rangle$ , where  $\alpha$  is a curve with  $\alpha(0) = p, \alpha'(0) = v$ .

(Note that at  $p$  along direction  $v$ , there are indefinitely many, curves passing through  $p$  with tangent vector  $v$ , each can be obtained by using a plane containing  $p, v$  to intersect with  $S$ ). However,  $II(v, v)$  only depends on  $\alpha'(0) = v$ .

Goal: Understanding how 2<sup>nd</sup> fundamental form reflects the surface is curved locally near a point.



### 2.8.1 Normal curvature

Let  $\alpha(s)$  be a regular curve parametrized by the arclength In  $S$ .

$$\implies \alpha'(s) = t(s), \quad |\alpha'(s)| = 1$$

$$\alpha''(s) = t'(s) = k(s)\mathbf{n}(s), \quad k(s) : \text{curvature of } \alpha(s), \quad \mathbf{n} : \text{unit normal vector of } \alpha(s)$$

$$\begin{aligned} \left\langle \alpha''(s), \vec{N}(\alpha(s)) \right\rangle &= \frac{d}{ds} \left\langle \underbrace{\alpha'(s)}_{\in T_{\alpha(s)} S} \vec{N}(\alpha(s)) \right\rangle - \left\langle \alpha'(s), \frac{d}{ds} \vec{N}(\alpha(s)) \right\rangle \\ &= - \left\langle \alpha'(s), d\vec{N}_{\alpha(s)}(\alpha'(s)) \right\rangle \\ &= II(\alpha'(s), \alpha'(s)) \end{aligned}$$

On the other hand,

$$\left\langle \alpha''(s), \vec{N}(\alpha(s)) \right\rangle = \left\langle k(s)\mathbf{n}(s), \vec{N}(s) \right\rangle = k(s) \cos \theta.$$

This is the projection of “curvature” of  $\alpha(s)$  on the normal vector of the surface. We call the value

$$k_{\mathbf{n}} = k(s) \cos \theta$$

to be the “normal curvature of curve  $\alpha(s)$ ”.

Hence, the 2<sup>nd</sup> fundamental form

$$II(\alpha'(s), \alpha'(s)) = \text{normal curvature of } \alpha(s) = k_{\mathbf{n}}.$$

But  $II(\alpha'(s), \alpha'(s))$  only depends on  $\alpha'(s)$  but not a particular curve. Hence, at  $p \in S$ , all curves passing through  $p$  with the same unit tangent vector  $v$  have the same normal curvature. A canonical choice of such curve is called the “normal section” which is a curve obtained by intersecting the plane  $\text{span}\{\underbrace{v}_{\text{unit}}, N\}$  with  $S$

$$\implies k_{\mathbf{n}} = \pm \text{curvature of normal section along direction } v.$$

$$\implies II(v, v) = \pm \text{curvature of normal section along direction } v.$$

**Exercise.** Compute  $k_{\mathbf{n}}$  in a local parametrization.

Let  $\alpha(s) = \varphi(u(s), v(s))$ ,  $\alpha'(s) = \varphi_u u'(s) + \varphi_v v'(s)$ , where  $s$  is the arclength parameter. Then,

$$\alpha''(s) = \varphi_{uu} (u'(s))^2 + 2\varphi_{uv} u'(s)v'(s) + \varphi_{vv} (v'(s))^2 + \underbrace{\varphi_u u''(s) + \varphi_v v''(s)}_{\text{tangential}}.$$

$$\begin{aligned} &\left\langle \alpha''(s), \vec{N}(\alpha(s)) \right\rangle \\ &= \left\langle \varphi_{uu}, \vec{N} \right\rangle (u'(s))^2 + 2 \left\langle \varphi_{uv}, \vec{N} \right\rangle u'(s)v'(s) + \left\langle \varphi_{vv}, \vec{N} \right\rangle (v'(s))^2 \\ &= e(u'(s))^2 + 2fu'(s)v'(s) + g(v'(s))^2. \end{aligned}$$

Therefore,

$$k_n(\alpha'(s)) = e(u'(s))^2 + 2fu'(s)v'(s) + g(v'(s))^2.$$

It's also interesting to obtain  $k_n$  in an arbitrary parametrization. Let  $\alpha(\tau)$  be some parameter,

$$\implies S = (\tau) \int_0^\tau |\alpha'(\tau)| d\tau, \quad \tau'(s) = \frac{1}{|\alpha'(\tau)|}.$$

$$\begin{aligned} \alpha'(s) &= \alpha'(\tau)\tau'(s), \\ \alpha''(s) &= \alpha''(\tau)(\tau'(s))^2 + \alpha'(\tau)\tau''(s). \end{aligned}$$

$$\begin{aligned} \langle \alpha''(s), \vec{N}(\alpha(\tau)) \rangle &= \langle \alpha''(\tau), \vec{N}(\alpha(\tau)) \rangle (\tau'(s))^2 \\ &= \frac{II(\alpha'(\tau), \alpha'(\tau))}{I(\alpha'(\tau), \alpha'(\tau))}. \end{aligned}$$

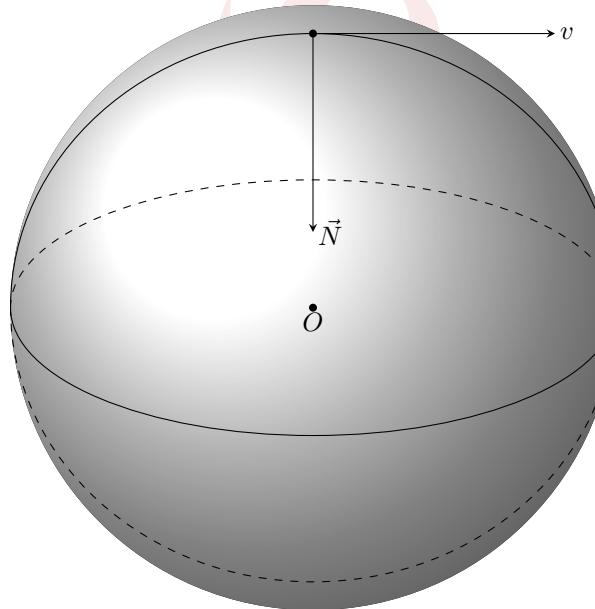
$$\therefore k_n(\alpha'(\tau)) = \frac{II(\alpha'(\tau), \alpha'(\tau))}{I(\alpha'(\tau), \alpha'(\tau))}.$$

! The normal curvature along direction  $v$  is  $II(v, v)$  tells us that how the surface is curved along direction  $v$  at  $p$ .

**Example 2.8.1.** Sphere:  $x^2 + y^2 + z^2 = 1$ .

Normal sections are the great circles of radius 1.

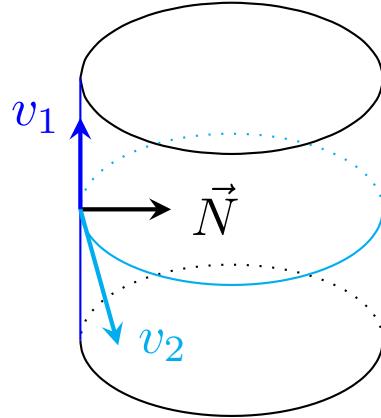
$$\therefore II(v, v) = 1, \quad \forall |v| = 1.$$



**Example 2.8.2.** Cylinder:  $x^2 + y^2 = 1$ .

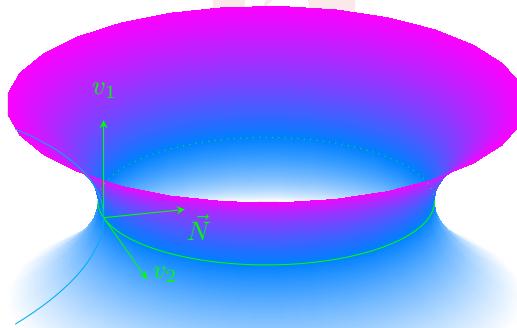
$\vec{N}$  : inner normal.

Let  $v_1$  be the unit normal along vertical lines.  $\Rightarrow$  normal section is just the line along  $v_1 \Rightarrow k_1 = 0$ . Let  $v_2$  be the unit normal parallel to  $xy$  plane.  $\Rightarrow$  normal section is a horizontal circle.  $\Rightarrow k_2 = 1$  (that is the curvature of a circle). As we move the horizontal circle to the vertical line (*i.e.*  $v_2 \rightarrow v_1$ ), the normal curvature is decreasing.



**Example 2.8.3.** Catenoid:  $\varphi(u, v) = (c \cosh \frac{v}{c} \cos u, c \cosh \frac{v}{c} \sin u, v)$

The normal section obtained by  $S \cap \text{span}\{v_1, \vec{N}\}$  is a catenary, with  $k_1 < 0$ . The normal section obtained by  $S \cap \text{span}\{v_2, \vec{N}\}$  is a circle, with  $k_2 > 0$ .



As you may notice, in example 2.8.1, all normal curvatures are the same at all points and along any direction. In example 2.8.2 and example 2.8.3, at any point there are extremal directions at which the normal curvature achieves the maximum and the minimum. Let's discuss more on these two special normal curvatures.

## 2.8.2 Principle curvature and principle direction

Since  $dN_p: T_p S \rightarrow T_p S$  is linear and symmetric (self-adjoint), for any orthonormal basis  $e_1, e_2$ ,

$$dN_p \begin{pmatrix} e_1 \\ e_2 \end{pmatrix} = \underbrace{\begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix}}_{\text{symmetric}} \begin{pmatrix} e_1 \\ e_2 \end{pmatrix}$$



$\implies \exists$  an orthonormal basis  $\tilde{e}_1, \tilde{e}_2$  of  $T_p S$  such that

$$dN_p \begin{pmatrix} \tilde{e}_1 \\ \tilde{e}_2 \end{pmatrix} = \begin{pmatrix} -k_1 & 0 \\ 0 & -k_2 \end{pmatrix} \begin{pmatrix} \tilde{e}_1 \\ \tilde{e}_2 \end{pmatrix} \quad (k_1 \geq k_2)$$

**Definition 2.8.4** (Principle curvature and principle direction).  $k_1$  and  $k_2$  above are called the principle curvature and  $\tilde{e}_1, \tilde{e}_2$  are called the principle directions at  $p$ .

*Remark.*  $k_1$  and  $k_2$  are the maximum and minimum values of the 2<sup>nd</sup> fundamental form  $II$  restricted on the unit vectors of  $T_p S$ .

*Proof.*

$$II(\tilde{e}_1, \tilde{e}_1) = -\langle dN_p(\tilde{e}_1), \tilde{e}_1 \rangle = \langle k_1 \tilde{e}_1, \tilde{e}_1 \rangle = k_1.$$

Similarly,  $II(\tilde{e}_2, \tilde{e}_2) = k_2$ .

For any unit vector  $v \in T_p S$ ,  $v = v_1 \tilde{e}_1 + v_2 \tilde{e}_2$ , with  $|v| = 1$ .

$$\begin{aligned} II(v, v) &= -\langle dN_p(v), v \rangle \\ &= -\langle v_1 dN_p(\tilde{e}_1) + v_2 dN_p(\tilde{e}_2), v_1 \tilde{e}_1 + v_2 \tilde{e}_2 \rangle \\ &= k_1 v_1^2 + k_2 v_2^2 = \begin{cases} k_1 + (k_1 - k_2)v_2^2 \leq k_1, \\ (k_1 - k_2)v_1^2 + k_2 \geq k_2. \end{cases} \end{aligned}$$

Hence,  $k_1$  and  $k_2$  are maximum and minimum values of normal curvature. Moreover,  $\forall$  unit vector  $v \in T_p S$  and  $e_1, e_2$  the principle direction, we can write

$$\begin{aligned} v &= \cos \theta e_1 + \sin \theta e_2, \\ k_n(v) &= k_1 \cos^2 \theta + k_2 \sin^2 \theta. \end{aligned}$$

The last is called “Euler formula”. □

**Definition 2.8.5** (Gaussian curvature & mean curvature). Follow the definition of principal curvature, we define

- Gaussian curvature:  $K = k_1 k_2$ .
- Mean curvature:  $H = \frac{k_1 + k_2}{2}$ .

*Remark.* (1) These two curvatures are very important in understanding the surface.

(2) Above definition is in terms of orthonormal basis  $\{e_1, e_2\}$  on  $T_p S$ , at each  $p \in S$ .

$$dN_p \begin{bmatrix} e_1 \\ e_2 \end{bmatrix} = \begin{bmatrix} -k_1 & 0 \\ 0 & -k_2 \end{bmatrix} \begin{bmatrix} e_1 \\ e_2 \end{bmatrix} \quad K \sim \det, H \sim \text{trace}.$$

**Exercise.** Find the expression of  $K$  and  $H$  in arbitrary parametrization. The answer is

$$K = \frac{\det II}{\det I} = \frac{eg - f^2}{EG - F^2}, \quad H = \frac{1}{2} \operatorname{tr}_I II = \frac{1}{2} \frac{eG - 2fF + gE}{EG - F^2}.$$



Once we know the Gaussian curvature  $K$  and mean curvature  $H$ , by the fact that  $K = \det A$ ,  $H = -\frac{1}{2} \operatorname{tr} A$ , we can write the characteristic polynomial of  $A$ :

$$\det(\lambda I - A) = \lambda^2 - \operatorname{tr} A \lambda + \det A = \lambda^2 + 2H\lambda + K.$$

Since the principal curvature  $k = -\lambda$ , we have

$$k^2 - 2Hk + K = 0.$$

And principal curvatures are:

$$k = H \pm \sqrt{H^2 - K}.$$

*Remark.*

- (1) The Gaussian curvature is an “intrinsic” curvature, it’s only determined by the surface itself. The Gaussian elegant theorem tell us that the Gaussian curvature is only determined by 1st fundamental form. This already sheds light on the Riemannian Geometry. (We’ll see the theorem later). The most beautiful result in surface theory is the Gauss-Bonnet’s theorem: If  $S$  is an oriented compact surface without boundary, then

$$\int_S K = 2\pi\chi(S) = 2\pi(2 - 2g).$$

- (2) The mean curvature is an “extrinsic curvature”. It depends on the ambient space. (Here, our ambient space is  $\mathbb{R}^3$ ). One of important problems in Differential Geometry is studying the surfaces with vanishing mean curvature. Such surface is called “minimal surface”. (We will explain “minimal” later). This problem heavily depends on PDE theory (of 2nd order elliptic type).

Here, let’s have a further understanding of principal curvature & principal direction from analysis point of view. We have seen:

- (1) Normal curvature at  $p \in S$ :

$$\begin{aligned} k_n: \mathbb{S}^1(T_p S) &\longrightarrow \mathbb{R} \\ v &\longmapsto k_n(v). \end{aligned}$$

- (2) Principal direction is at which  $k_n$  attains maximum / minimum.

- (3)  $\forall v$  not necessary a unit vector, then

$$k_n(v) = \frac{I_p(v, v)}{I_p(v, v)}.$$

Let  $v = v_1\varphi_1 + v^2\varphi_2$ , where  $\varphi(u^1, u^2)$  is a local parametrization. Then

$$k_n(v) = \frac{(v^1)e^2 + 2v^1v^2f + (v^2)^2g}{(v^1)^2E + 2v^1v^2F + (v^2)^2G}.$$

WLOG assume  $v^1 \neq 0$ ,  $\lambda = \frac{v^2}{v^1}$ , then

$$k_n(\lambda) = \frac{e + 2f\lambda + g\lambda^2}{E + 2F\lambda + G\lambda^2}.$$



(4) Since principal curvatures are critical values of  $k_n$ ,  $k'_n(\lambda) = 0$ ,

$$\iff (2f + 2g\lambda)(E + 2F\lambda + G\lambda^2) - (2F + 2G\lambda)(e + 2f\lambda + g\lambda^2) = 0. \quad (2.8.1)$$

i.e.

$$\frac{e + 2f\lambda + g\lambda^2}{E + 2F\lambda + G\lambda^2} = \frac{f + g\lambda}{F + G\lambda}.$$

Hence

$$k_n = \frac{f + g\lambda}{F + G\lambda}.$$

On the other hand, eq. (2.8.1) also implies

$$\begin{aligned} & (f + g\lambda)(E + F\lambda) + \lambda(f + g\lambda)(F + G\lambda) \\ &= (F + G\lambda)(e + f\lambda) + \lambda(F + G\lambda)(f + g\lambda). \end{aligned} \quad (2.8.2)$$

i.e.

$$\frac{f + g\lambda}{F + G\lambda} = \frac{e + f\lambda}{E + F\lambda}.$$

Hence

$$k_n = \frac{f + g\lambda}{F + G\lambda} = \frac{e + f\lambda}{E + F\lambda} \iff \text{principal curvature.}$$

Then

$$\begin{cases} f + g\lambda = k_n(F + G\lambda) \\ e + f\lambda = k_n(E + F\lambda) \end{cases} \implies \begin{cases} f - Fk_n = (Gk_n - g)\lambda \\ e - Ek_n = (Fk_n - f)\lambda \end{cases}.$$

This linear system has solution  $\lambda \iff$

$$\det \begin{bmatrix} e - k_n E & f - k_n F \\ f - k_n F & g - k_n G \end{bmatrix} = 0.$$

This gives an equation to solve  $k_n$ . To see the principal direction, i.e. solving  $\lambda$ ,

$$\begin{aligned} \text{eq. (2.8.2)} &\implies (gF - fG)\lambda^2 + (gE - eG)\lambda + (fE - eF) = 0 \\ &\iff \det \begin{bmatrix} \lambda^2 & -\lambda & 1 \\ E & F & G \\ e & f & g \end{bmatrix} = 0. \end{aligned}$$

Next, we would like to introduce several special points on a surface by using curvatures introduced previously.

**Definition 2.8.6** (Classification of points on surface).

A point  $p$  on a regular surface  $S$  is called a

- (1) Elliptic point, if  $K_p > 0$ . (All normal section have the same normal vectors)
- (2) Hyperbolic point, if  $K_p < 0$ . (There exist two normal sections with opposite normal vectors)
- (3) Parabolic point if  $K_p = 0$  but  $dN_p \neq 0$ . (One of principal directions is “flat”)
- (4) Planar point, if  $dN_p = 0$ , i.e.  $k_1 = k_2 = 0$ .



(5) Umbilical point, if  $k_1 = k_2$ .

*Remark.*

- (1) Apparently, umbilical points can only occur at elliptic point or planar point.
- (2) At umbilical points,  $\text{II} = kI$ .
- (3) On a minimal surface,  $H = 0 \implies k_1 = -k_2$ , so  $K \leq 0$ , and there is no elliptic point.

**Definition 2.8.7.**  $S$  is called totally umbilical, if all points are umbilical. For example, both plane and sphere are totally umbilical.

**Theorem 2.8.8.** *If  $S \hookrightarrow \mathbb{R}^3$  is totally umbilical and connected. Then  $S$  is either contained in a plane or a sphere.*

*Proof.* Umbilical  $\implies$  at each point,  $k_1 = k_2 = k$ , then  $\text{II}_p = kI_p$ .

Let  $\varphi(u, v)$  be a local parametrization near  $p$ . By Weingarten equation,

$$\begin{bmatrix} \mathbf{n}_u \\ \mathbf{n}_v \end{bmatrix} = A \begin{bmatrix} \varphi_u \\ \varphi_v \end{bmatrix} = \begin{bmatrix} -k & 0 \\ 0 & -k \end{bmatrix} \begin{bmatrix} \varphi_u \\ \varphi_v \end{bmatrix}, \quad A = \text{II} \cdot I^{-1}.$$

Hence

$$\begin{cases} \mathbf{n}_u = -k\varphi_u \\ \mathbf{n}_v = -k\varphi_v \end{cases} \implies \begin{cases} \mathbf{n}_{uv} = -k_v\varphi_u - k\varphi_{uv} \\ \mathbf{n}_{vu} = -k_u\varphi_v - k\varphi_{vu} \end{cases}.$$

So we must have

$$k_v\varphi_u = k_u\varphi_v.$$

$\varphi_u, \varphi_v$  linearly independent  $\implies k_u = k_v = 0$ . So  $k$  is constant on the chart.

Case 1:  $k = 0$ , then  $\mathbf{n}_u = \mathbf{n}_v = 0$ . Hence  $\mathbf{n}$  is a constant vector field. Then

$$\langle \varphi(u, v), \mathbf{n} \rangle$$

is constant since it has zero differentials. This shows  $S$  lie in a plane locally.

Case 2:  $k \neq 0$ , wlog assume  $k > 0$ , otherwise we can reverse the orientation. Then

$$\begin{cases} \varphi_u = -\frac{1}{k}\mathbf{n}_u \\ \varphi_v = -\frac{1}{k}\mathbf{n}_v \end{cases}.$$

So  $\varphi + \frac{1}{k}\mathbf{n}$  is constant. (Note  $\varphi$  is the position vector). Let  $c = \varphi + \frac{1}{k}\mathbf{n}$ . Then

$$|\varphi - c| = \frac{1}{k}.$$

This shows  $S$  lie in a sphere locally.

So far we proved the result only in a local coordinate chart. Since the surface is connected and smooth, one can easily use a topology (covering) argument to extend above result globally.  $\square$

*Remark.* So far, we can characterize  $\mathbb{S}^2(R)$  in  $\mathbb{R}^3$  in the following two ways geometrically:



(1)  $\mathbb{S}^2(R)$  = the set of points having the same distance  $R$  to a fixed point  $c$ . i.e.

$$|x - c| = R.$$

(2)  $\mathbb{S}^2(R)$  = all points are umbilical. i.e.  $\Pi = kI, k \neq 0$ .

Both of them are very useful in proving some surface is sphere.

*Remark.*  $H^2 - K = \frac{1}{4}(k_1 - k_2)^2 \geq 0$ . It vanishes at  $p$  when  $k_1 = k_2$ , i.e.  $p$  umbilical. Together with Gauss-Bonnet thm, we have

$$\int_S H^2 \geq \int_S K = 2\pi(2 - 2g)$$

on a closed oriented surface, with equality holds iff  $S$  is sphere. In fact, we can get a stronger integral inequality.

**Theorem 2.8.9** (Yau contest 2014). *For a closed (oriented) surface  $S \subset \mathbb{R}^3$ ,*

$$\int_S H^2 \geq 4\pi.$$

*Equality holds  $\iff S$  is a sphere.*

*Proof.* Recall the Gauss map  $\mathbf{n}: S \rightarrow \mathbb{S}^2(1)$ ,

$$d\mathbf{n} \begin{bmatrix} \varphi_u \\ \varphi_v \end{bmatrix} = A \begin{bmatrix} \varphi_u \\ \varphi_v \end{bmatrix}.$$

$$A = \Pi \cdot I^{-1} \implies K = \det A.$$

For  $S$  closed surface,  $\mathbf{n}$  is surjective to  $\mathbb{S}^2(1)$ . Hence

$$\int_S H^2 \geq \int_S |K| \geq \int_{\mathbb{S}^2} 1 = 4\pi.$$

(To see why  $\mathbf{n}$  is surjective, notice for any direction vector  $v_0$ , there is a point  $p \in S$  s.t.  $\langle p, v_0 \rangle$  maximal. For this point one can prove the normal vector coincident with  $v_0$ ).  $\square$

**Definition 2.8.10.**  $W(S) = \int_S H^2 d\sigma$  is called the Willmore energy of surface  $S$ .

Now we know  $W(S) \geq 4\pi$ , it's natural to ask what's the exact lower bounded of  $W(S)$  for given topology.

**Conjecture 2.8.11** (Willmore). *Given any smooth “immersed” torus  $T$  in  $\mathbb{R}^3$ ,*

$$W(T) \geq 2\pi.$$

This conjecture is settled in the case of “embedded” by Marques & Neves (2014 Annals). They also showed the equality holds iff the torus is obtained by the stereographic projection of the Clifford torus which is an “embedded” torus in  $\mathbb{R}^4$ .

$$\frac{1}{\sqrt{2}}\mathbb{S}^1 \times \frac{1}{\sqrt{2}}\mathbb{S}^1 = \left\{ \frac{1}{\sqrt{2}}(\cos \theta, \sin \theta, \cos \varphi, \sin \varphi) : 0 \leq \theta \leq 2\pi, 0 \leq \varphi \leq 2\pi \right\}.$$



**Conjecture 2.8.12** (Lawson, proved by Brendle). *Clifford torus is only minimally embedded torus in  $\mathbb{S}^3$ . (i.e. as a minimal surface in metric of  $\mathbb{S}^3$ ).*

Finally, we introduce some other geometric concepts in term of the 2nd fundamental form.

**Definition 2.8.13** (Curvature lines). The curvature lines are integral curves of principal directions:  $\gamma(s) \subset S$  s.t.  $\gamma'(s)$  is principal direction. i.e.

$$\mathbf{n}'(s) = \frac{d}{ds}\mathbf{n}(\gamma(s)) = -\lambda(s)\gamma'(s).$$

*Remark.* At an umbilical point, any normal section provides a principal direction, there are infinity many of them. However, if a point is not umbilical, i.e.  $k_1 \neq k_2$ , then we can find a local parametrization near  $p$ , s.t. coordinate curves are curvature lines which are orthogonal to each other.

**Exercise.** Let  $\varphi(u, v)$  be a local parametrization, show that coordinate curves are curvature lines  $\iff F = f = 0$ .

Let's derive an equation of curvature lines.

If  $\alpha(t) = \varphi(u(t), v(t))$  is a curvature line, then

$$d\mathbf{n}(\alpha'(t)) = -\lambda(t)\alpha'(t), \quad \text{while } \alpha'(t) = \varphi_u u'(t) + \varphi_v v'(t).$$

Then

$$\mathbf{n}_u u' + \mathbf{n}_v v' = -(\lambda \varphi_u u' + \lambda \varphi_v v').$$

Product with  $\varphi_u$  and  $\varphi_v$ , we get

$$\begin{cases} eu' + fv' = \lambda Eu' + \lambda Fv' \\ fu' + gv' = \lambda Fu' + \lambda Gv' \end{cases}.$$

Hence

$$\begin{cases} \frac{fF - eG}{EG - F^2}u' + \frac{gF - fG}{EG - F^2}v' = \lambda u' \\ \frac{eF - fE}{EG - F^2}u' + \frac{fF - gE}{EG - F^2}v' = \lambda v' \end{cases} \iff \begin{bmatrix} E & F \\ F & G \end{bmatrix}^{-1} \begin{bmatrix} e & f \\ f & g \end{bmatrix} = \lambda \text{Id}.$$

Eliminating  $\lambda$ , then

$$(fE - eF)(u')^2 + (gE - eG)u'v' + (gF - fG)(v')^2 = 0.$$

So  $\alpha(t)$  is curvature line  $\iff$

$$\det \begin{bmatrix} (v')^2 & -u'v' & (u')^2 \\ E & F & G \\ e & f & g \end{bmatrix} = 0.$$

**Example 2.8.14** (Catenoid). *Parametrization:  $(a \cosh \theta \cos \varphi, a \cosh \theta \sin \varphi, a\theta)$ .*

$$I = (a^2 \cosh^2 \theta) d\varphi^2 + (a^2 \cosh^2 \theta) d\theta^2$$

$$II = -d\varphi^2 + d\theta^2.$$

$\varphi(u, v_0)$  is curvature line  $\iff Ef - eF = 0$ ,

$\varphi(u_0, v)$  is curvature line  $\iff Fg - fG = 0$ .

$u$  curve  $\perp v$  curve  $\implies F = 0$ . Also  $EG > F^2$ , so  $E, G \neq 0$ , then  $f = 0$ .

Conversely if  $F = f = 0$ , then for  $u$  curve, i.e.  $v' = 0$ , clearly we have

$$\det \begin{bmatrix} 0 & 0 & (u')^2 \\ E & 0 & G \\ e & 0 & g \end{bmatrix} = 0.$$

Similarly for  $v$  curve. i.e.  $u, v$  curves are curvature lines.

**Definition 2.8.15** (Conjugate directions). Direction vectors  $v, w \in T_p S$  are called conjugate if

$$II(v, w) = 0 \quad (\iff \langle d\mathbf{n}_p, w \rangle = 0).$$

**Example 2.8.16.** (1) Tow principal directions at a non-umbilical point are always conjugate, since for a real symmetric matrix, eigenvector assigned to different eigenvalues are perpendicular.

(2)  $p \in S$  is a non-planar umbilical point, then any two orthogonal directions are conjugate.

(3)  $p \in S$  is a planar umbilical point, since  $d\mathbf{n} = 0$ , each direction is conjugate to other directions.

**Exercise.** Find a necessary and sufficient condition for two unit vectors are conjugate to each other.

**Definition 2.8.17** (Asymptotic direction and asymptotic curve).

If  $v \in T_p S$  s.t.  $II(v, v) = 0$ , then  $v$  is called asymptotic direction. The integral curve of asymptotic direction is called asymptotic curve.

*Remark.* (1) Asymptotic direction is conjugate to itself.

(2)  $II(v, v) = 0 \implies k_1 \cos^2 \alpha + k_2 \sin^2 \alpha = 0$ . So either  $\tan^2 \alpha = -\frac{k_1}{k_2}$  or  $\cot^2 \alpha = -\frac{k_2}{k_1}$ .  
 $\implies$  two values of  $\alpha$ .

**Exercise.** Let  $p$  be a hyperbolic point,  $\varphi(u, v)$  is a local parametrization, then  $\varphi(u, v_0)$  and  $\varphi(u_0, v)$  are asymptotic curves  $\iff e = g = 0$ .

**Definition 2.8.18** (Dupin indicatrix).

$$D_p = \{v \in T_p S : II(v, v) = \pm 1\} \subset T_p S.$$

*Remark.* Write  $v = v_1 e_1 + v_2 e_2 \in T_p S$ ,  $d\mathbf{n}_p(e_i) = -k_i e_i$ , then

$$II(v, v) = \pm 1 \iff k_1 v_1^2 + k_2 v_2^2 = \pm 1.$$

(1)  $K_p > 0$  ellipse in  $T_p S$ .

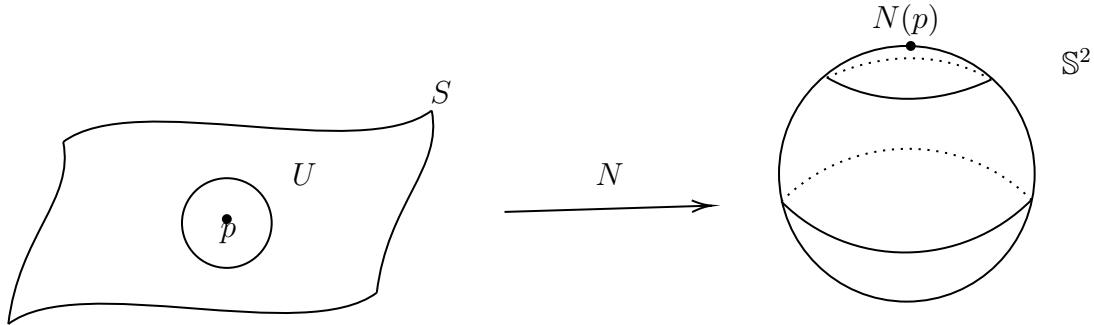
(2)  $K_p < 0$   $\implies$  hyperbolas in  $T_p S$ .

(3)  $K_p = 0$   $\implies$  crossing lines.

### 2.8.3 Geometric interpretation of Gauss curvature

Assume  $K_p \neq 0$ .

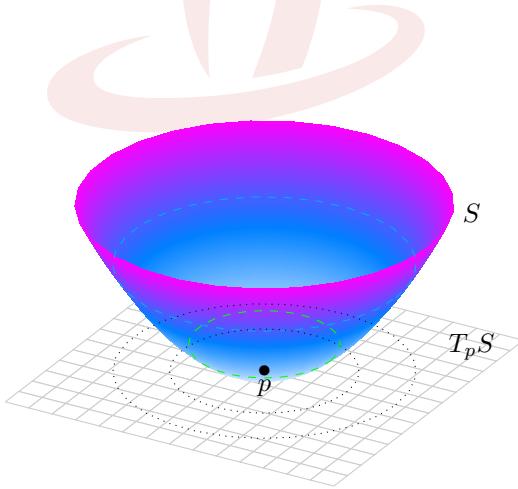
(a)  $p \in S$ ,  $U$  is a neighborhood of  $p$ .  $N: S \rightarrow \mathbb{S}^2$  is the Gauss map.



Let  $A = \text{Area of } U$ ,  $\delta A = \text{Area of } N(U)$ , then

$$|K(p)| = \lim_{A \rightarrow 0} \frac{\bar{A}}{A}. \quad (1)$$

(b)  $p \in T_p S = \text{tangent plane} \simeq \mathbb{R}^2$ . Consider a circle of radius  $r$  in  $T_p S$  and a “circle” of radius  $r$  on  $S$ .



Then

$$K(p) = \lim_{r \rightarrow 0} 3 \frac{2\pi r - c(r)}{\pi r^3}, \quad (2)$$

where  $c(r) = \text{circumference of the circle of radius } r \text{ on } S$ .

(c) Consider a disk around  $p$  of radius  $r$  in  $T_p S$ . Also consider a “disk” around  $p$  of radius  $r$  on  $S$ .

$$K(p) = \lim_{r \rightarrow 0} 12 \frac{\pi r^2 - A(r)}{\pi r^4}, \quad (3)$$

where  $A(r) = \text{Area of disk on } S$ .



*Remark.* From expression of eq. (2) and eq. (3), one can prove them by considering the Taylor's expansion of  $c(r)$  and  $A(r)$ . The proof of these two facts will be postponed after we step into intrinsic geometry.(Need Taylor's expansion of metric tensor)

*Proof.* Let  $F(u, v)$  be the local parametrization on  $U$ .

$$\Rightarrow \text{Area}(U) = \iint_{F^{-1}(U)} |F_u \wedge F_v| \, du \, dv,$$

then  $T_{N(p)}N(U) = \text{span}\{N_u, N_v\}$ ,

$$\bar{A} = \iint_{F^{-1}(U)} |N_u \wedge N_v| \, du \, dv.$$

Recall:  $dN \begin{pmatrix} F_u \\ F_v \end{pmatrix} = \begin{pmatrix} N_u \\ N_v \end{pmatrix} = A \begin{pmatrix} F_u \\ F_v \end{pmatrix}$ , where  $A$  is the Weingarten matrix.

$$\Rightarrow |N_u \wedge N_v| = |\det A| |F_u \wedge F_v| = |K| |F_u \wedge F_v|.$$

$$\begin{aligned} \frac{\bar{A}}{A} &= \frac{\iint |K| |F_u \wedge F_v| \, du \, dv}{\iint |F_u \wedge F_v| \, du \, dv} \\ &= \frac{|K(q)| |F_u \wedge F_v| (q) \text{Area}(F^{-1}(U))}{|F_u \wedge F_v| (\bar{q}) \text{Area}(F^{-1}(U))} \quad (\text{Middle value theorem}). \end{aligned}$$

As  $A \rightarrow 0$ ,  $q \rightarrow p$ ,  $\bar{q} \rightarrow p$ ,

$$\Rightarrow |K(p)| = \lim_{A \rightarrow 0} \frac{\bar{A}}{A}.$$

□

## 2.9 More Examples

**Exercise.** Graph  $z = h(x, y) = S$ .

(Recall: For a regular surface, by the implicit (inverse) function theorem, it can be written as a graph locally.)

In the HW 8, you may have computed

$$I = (1 + h_x^2) dx^2 + 2h_x h_y dx dy + (1 + h_y^2) dy^2$$

$$\begin{aligned} II &= \frac{h_{xx}}{\sqrt{1 + |\nabla h|^2}} dx^2 + 2 \frac{h_x h_y}{\sqrt{1 + |\nabla h|^2}} dx dy + \frac{h_{yy}}{\sqrt{1 + |\nabla h|^2}} dy^2. \\ N &= \frac{(-h_x, -h_y, 1)}{\sqrt{1 + |\nabla h|^2}}. \end{aligned}$$

$$K = \frac{h_{xx} h_{yy} - h_{xy}^2}{(1 + |\nabla h|^2)^2} = \frac{\det \nabla^2 h}{(1 + |\nabla h|^2)^2}.$$



$$2H = \frac{(1+h_x^2)h_{yy} - 2h_x h_y h_{xy} + (1+h_y^2)h_{xx}}{\left(1+|\nabla h|^2\right)^{\frac{3}{2}}}.$$

Note that the last term equals

$$\operatorname{div}_{\mathbb{R}^2} \left( \frac{\nabla h}{\sqrt{1+|\nabla h|^2}} \right) = \sum_{i,j=1}^2 L^{ij} (\nabla f) \nabla_i \nabla_j h,$$

where

$$L^{ij} (\nabla f) = \frac{1}{\sqrt{1+|\nabla h|^2}} \left( \delta_{ij} - \frac{\nabla_i h \nabla_j h}{1+|\nabla h|^2} \right).$$

Let  $p \in S$ , and assume  $p$  is the origin in  $\mathbb{R}^3$ , and  $N$  agrees with the unit normal of  $z$ -axis

$$h_x = h_y = 0 \text{ at } p.$$

$$e = h_{xx}(0,0), f = h_{xy}(0,0), g = h_{yy}(0,0).$$

Hessian of  $h$  at  $p$  is

$$\begin{pmatrix} h_{xx}(0,0) & h_{xy}(0,0) \\ h_{yx}(0,0) & h_{yy}(0,0) \end{pmatrix}.$$

Hence, at  $p$

$$II = \operatorname{Hess} h.$$

Moreover, at  $p$

$$\partial H = \delta h.$$

As an application, we give a geometric interpretation of the Dupin indicatrix.

Claim: If  $p \in S$  is not a planar point, consider the intersection of a plane parallel to  $T_p S$  with  $S$ , and the plane is close enough to  $T_p S$ , then the obtained curve is approximated by the Dupin indicatrix.

*Proof.* Since we only care about local behavior at  $p$ , W.L.O.G assume near  $p$ , the surface is parametrized by the graph  $z = h(x, y)$ , such that  $p$  is the origin and  $z$ -axis is the normal direction and  $x$ -axis,  $y$ -axis are principal directions. Let the intersection curve be  $h(x, y) = \epsilon$ , for sufficiently small  $\epsilon$ . Consider the Taylor's expansion of  $h(x, y)$  at  $p$

$$\begin{aligned} h(x, y) &= h(0, 0) + h_x(0, 0)x + h_y(0, 0)y \\ &\quad + \frac{1}{2} \left( h_{xx}(0, 0)x^2 + \underbrace{2h_{xy}(0, 0)}_{=0(\text{principal direction})} xy + h_{yy}(0, 0)y^2 \right) \\ &\quad + \text{Remainder} \\ &= \frac{1}{2} \begin{pmatrix} x & y \end{pmatrix} \begin{pmatrix} h_{xx}(0, 0) & 0 \\ 0 & h_{yy}(0, 0) \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} + \text{Remainder}, \end{aligned}$$

□

---

<sup>2</sup>A basic observation one should make is how  $K$  and  $H$  depend on the 2<sup>nd</sup> derivative of  $h$ .

where

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

Hence, the intersection curve is given by

$$\frac{1}{2} (h_{xx}(0,0)x^2 + h_{yy}(0,0)y^2) + R = \epsilon.$$

Note: in the 2<sup>nd</sup> fundamental form  $II f = 0$ , and in the 1<sup>st</sup> fundamental form  $I F = 0$ , then at  $p$  one has

$$\begin{cases} k_1 = \frac{e}{E} = h_{xx}(0,0) \\ k_2 = \frac{g}{G} = h_{yy}(0,0) \end{cases}$$

using  $k_i = H \pm \sqrt{H^2 - K}$ . Then,  $k_1 x^2 + k_2 y^2 = 2\epsilon$  can be viewed as the 1<sup>st</sup> order approximation of the intersection curve. Renormalized it, then

$$k_1 \bar{x}^2 + k_2 \bar{y}^2 = 1,$$

is just the Dupin indicatrix.

**Exercise.** Surface of revolution.

Let  $\alpha(s) = (\varphi(s), 0, \psi(s))$  be a regular curve, with  $\varphi(s) > 0$  and  $s \in (a, b)$  is the arclength parametrization.  $\Rightarrow (\varphi'(s))^2 + (\psi'(s))^2 = 1 \Rightarrow \varphi' \varphi'' + \psi' \psi'' = 0$ . Rotate it about  $z$ -axis

$$\Rightarrow \alpha(\theta, s) = (\varphi(s) \cos \theta, \varphi(s) \sin \theta, \psi(s)), 0 < \theta < 2\pi.$$

$$\begin{aligned} I &= ds^2 + \varphi(s)^2 d\theta^2 \\ II &= (\psi' \varphi'' - \psi'' \varphi') ds^2 - \varphi \psi' d\theta^2. \end{aligned}$$

$\therefore F = f = 0$ ,  $\therefore$   $s$ -curve and  $\theta$ -curve are curvature lines.

$$K = \frac{e}{E} \frac{g}{G} = -\frac{\varphi''}{\varphi}, H = \frac{1}{2} \left( \frac{e}{E} + \frac{g}{G} \right).$$

Since principal curvatures satisfy  $\lambda^2 - 2\lambda H + K = 0$ .

$$\Rightarrow \lambda_1 = \frac{e}{E} = -\frac{\varphi''}{\varphi}, \lambda_2 = \frac{g}{G} = \psi' \varphi'' - \psi'' \varphi'.$$

The mean curvature is

$$H = \frac{1}{2} \frac{-\psi' + \varphi (\psi' \varphi'' - \psi'' \varphi')}{\varphi}.$$

**Question** (Homework). (1) Assume  $K = 1$ ,  $\lim_{s \rightarrow 0^+} \alpha(s) = (0, 0, 1)$ ,  $\alpha(\frac{\pi}{2}) = (1, 0, 0)$ ,  $s \in (0, \pi)$ . Describe the surface and determine the 1<sup>st</sup> fundamental form ( $ds^2 + \sin^2 s d\theta^2$ ).

(2) Assume  $K = 0$ ,  $\lim_{s \rightarrow 0^+} \alpha(s) = (0, 0, 1)$ ,  $\alpha(1) = (\frac{\sqrt{2}}{2}, 0, \sqrt{2}2)$ ,  $s \in (0, \infty)$ , answer the same question as in (1) ( $ds^2 + \frac{1}{2} s^2 d\theta^2$ ).

(3) Assume  $H = 0$ ,  $\alpha(0) = (1, 0, 0)$ ,  $\alpha(1) = (\sqrt{2}, 0, \arcsin(1))$ ,  $s > 0$ , answer the question in (1). ( $\alpha(s) = (\sqrt{1+s^2}, 0, \arcsin s)$ ,  $I = ds^2 + (1+s^2)^2 d\theta^2 \sim$  Catenoid).

**Exercise** (Ruled surface). A line passing through a point  $\alpha_0 \in \mathbb{R}^3$  with direction  $v \in \mathbb{R}^3$  can be written as

$$\ell(t) = \alpha_0 + tv.$$

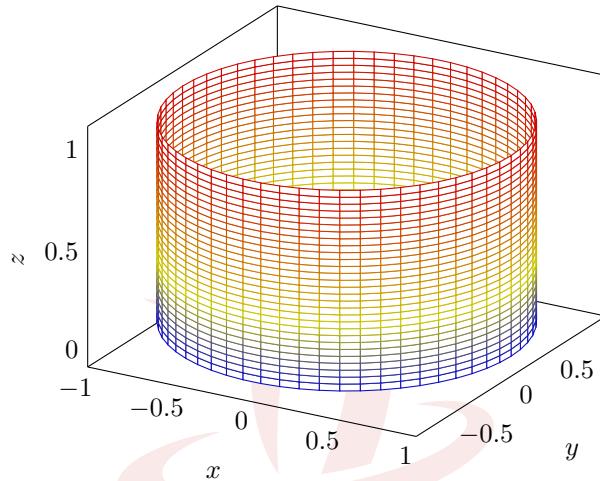
Now we let  $\alpha_0, v$  are two vector-valued functions, i.e.  $\alpha(s), v(s)$ , then the collection of lines form a surface

$$R(s, t) = \alpha(s) + tv(s).$$

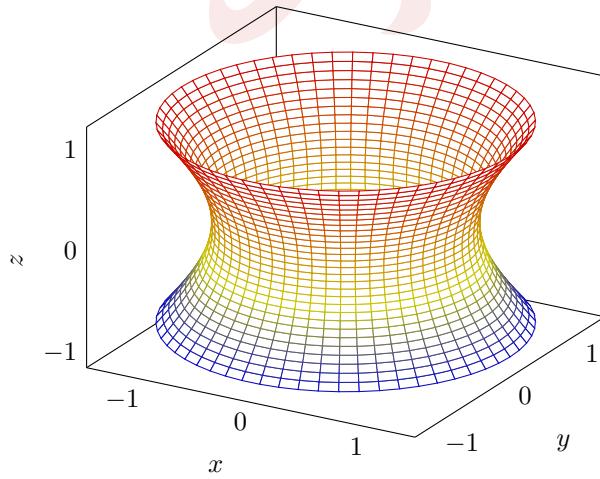
Surfaces with such parametrization is called the ruled surfaces, where  $\alpha(s)$  is called the base curve of  $S$  and  $v(s)$  is called the director curve.

*Remark.* Ruled surface may contain singular points.

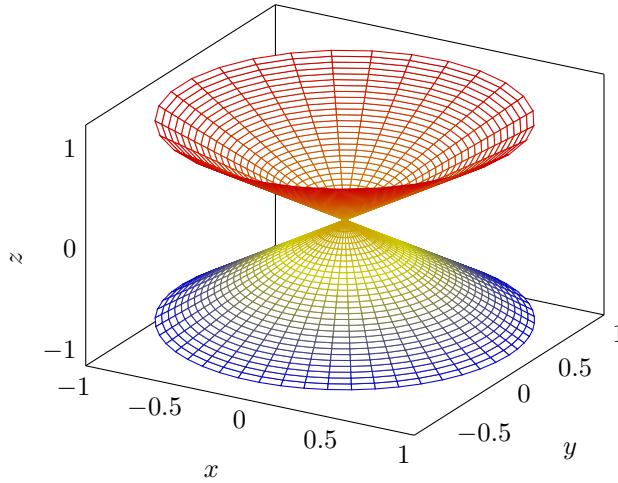
**Example 2.9.1.**  $R(s, t) = \alpha(s) + te_3$ .  $\alpha(s)$  is the circle on  $x - y$  plane,  $e_3 = (0, 0, 1)$ . ( $x^2 + y^2 = 1$ )



**Example 2.9.2.**  $R(s, t) = \alpha(s) + t(\alpha'(s) + e_3)$ , where  $\alpha(s)$  and  $e_3$  are the same as before.



**Example 2.9.3.**  $R(s, t) = 0 + t(u(s) + e_3)$ , where  $u(s) = (\cos \theta, \sin \theta, 0)$



In the following discussion, we assume the ruled surface  $S$

$$R(s, t) = \alpha(s) + tv(s), |v(s)| = 1, v'(s) \neq 0 \forall s.$$

Direct computation shows:

$$\begin{aligned} I &= |\alpha_s + tv_s|^2 ds^2 + 2 \langle \alpha_s, v \rangle dsdt + dt^2 \\ N &= \frac{\alpha_s \wedge v + tv_s \wedge v}{|\alpha_s \wedge v + tv_s \wedge v|} \\ II &= e ds^2 + 2f dsdt. \end{aligned}$$

Hence,

$$K = -\frac{f^2}{\det I} \leq 0.$$

Note that

$$\begin{aligned} f &= \langle R_{st}, N \rangle \\ &= v_s \cdot \frac{\alpha_s \wedge v + tv_s \wedge v}{|\alpha_s \wedge v + tv_s \wedge v|} \\ &= \frac{(v_s, \alpha_s, v)}{|R_s \wedge R_t|}. \end{aligned}$$

**Definition 2.9.4.**  $S$  is called developable on “flat” surface if  $(v_s, v, \alpha_s) \equiv 0$ . In this case  $K = 0$ .

*Remark.* Physically, a developable surface can be flattened onto a plane without “stretching” or “compressing”, but allowing unfolding or cutting along a line. Later, we’ll see on page 414, section 5-8 in Do Carmo: If on a developable surface  $S$ , all lines can be extended on both sides, the surface can only be a plane or a cylinder.

*Remark.* On a non-cylindrical ruled surface  $S$ , i.e.

$$R(s, t) = \alpha(s) + tv(s), v'(s) \neq 0 \forall s,$$

one can choose a spherical base curve  $\beta(s)$  such that

$$R(s, t) = \beta(s) + tv(s),$$

where  $\langle \beta'(s) + v'(s) \rangle = 0$ , such curve is called the line of striction. Points on the line of striction is called the central points of the ruled surface.

**Example 2.9.5.** In example 2.9.2,  $\alpha(s)$  is the line of striction.

**Exercise.** Find the line of restriction  $(\beta(s) - \alpha(s) - \frac{\langle \alpha', v' \rangle}{|v'|^2} v)$ . Then  $R(s, u) = \beta(s) + uv(s)$ .  
 Hence, if we let  $\lambda = \frac{\langle \beta', v, v' \rangle}{|v'|^2}$ , then  $K = -\frac{\lambda^2}{(\lambda^2 + u^2)^2}$ .

**Exercise** (Homework). Prove that there are no closed smooth minimal surface in  $\mathbb{R}^2$ .

*Proof.* On a closed surface, there must exist an elliptic point, at which  $k > 0$ , this contradicts to minimal surface.  $\square$

**Theorem 2.9.6.** (1) If a surface of revolution  $M$  is minimal, then  $M$  is contained in either a plane or a catenoid.

(2) If a ruled surface  $M$  is minimal, then  $M$  is contained in either a plane or a helicoid.

*Proof.* See homework.  $\square$

## 2.10 Isometries between surfaces

From this lecture on, we'll study the intrinsic geometry of a regular surface. More precisely, we'll see how the 1<sup>st</sup> fundamental form determines the geometry.

- $S_1, S_2$  are regular Surfaces,  $f: S_1 \rightarrow S_2$ .

- (1)  $f$  is isomorphism (1-1 and onto) (of sets)  $\Leftrightarrow S_1$  and  $S_2$  are identified as sets.
- (2)  $f$  is homeomorphism ( $f$  is an isomorphism +  $f$  and  $f^{-1}$  continuous)  $\Leftrightarrow S_1$  and  $S_2$  are identified as topological spaces.
- (3)  $f$  is diffeomorphism ( $f$  is a homeomorphism +  $f, f^{-1}$  are smooth)  $\Leftrightarrow S_1$  and  $S_2$  are identified with considering smooth structures on them.
- (4)  $f$  is isometry  
 $\Leftrightarrow f$  is a diffeomorphism and  $f$  preserves the arclength, area, angles, ... (everything defined by the 1<sup>st</sup> fundamental form).

**Definition 2.10.1** (Isometry).  $\varphi: S_1 \rightarrow S_2$  is a diffeomorphism between regular surfaces. If  $\forall p \in S_1, v_1, v_2 \in T_p S$

$$\langle v_1, v_2 \rangle_p = \langle d\varphi_p(v_1), d\varphi_p(v_2) \rangle, \quad (1)$$

which is equivalent to saying that  $\varphi$  preserves the 1<sup>st</sup> fundamental form, then we say  $\varphi$  is an isometry.

**Definition 2.10.2** (Local isometry).  $\varphi: S_1 \rightarrow S_2$  is called a local isometry, if  $\forall p \in S_1, \exists$  a neighborhood  $U$  of  $p$  such that  $\varphi|_U$  is an isometry.

**Example 2.10.3.** Catenoid and helicoid are only locally isometric to each other but not global isometric. In fact the helicoid is simply connected, but the catenoid is not (since it comes from revolution).

*Remark.* Isometry implies local isometry, however the converse is false.

**Example 2.10.4.**  $(\mathbb{R}^2, dx^2 + dy^2)$  and the cylinder  $(\cos u, \sin u, v), du^2 + dv^2$  are only local isometric to each other, but not “globally” isometric.

(The local isometry map is just the local parametrization of cylinder:

$$\varphi: (u, v, 0) \rightarrow (\cos u, \sin u, v).$$

Clearly,  $\mathbb{R}^2$  and the cylinder are not diffeomorphic to each other, since the cylinder has a non-shrinkable loop.)

**Exercise.** The condition in eq. (1) is equivalent to

$$\forall w \in T_p S, \quad |w|_p = |d\varphi_p(w)|_{\varphi(p)}. \quad (2)$$

*Proof.* eq. (1)  $\Rightarrow$  eq. (2), obviously.

eq. (2)  $\Rightarrow$  eq. (1), let  $w = v_1 + v_2$ , then

$$|w|_p^2 = |d\varphi_p(w)|_{\varphi(p)}^2, \quad |v_1|_p^2 = |d\varphi_p(v_1)|_{\varphi(p)}^2, \quad |v_2|_p^2 = |d\varphi_p(v_2)|_{\varphi(p)}^2$$

$$\Rightarrow \langle v_1, v_2 \rangle_p = \langle d\varphi_p(v_1), d\varphi_p(v_2) \rangle.$$

□

*Remark.* If  $\varphi: S_1 \rightarrow S_2$  is a local isometry.  $\forall p \in S_1$ , let  $U$  be a coordinate patch of  $p$  and  $\varphi|_U: U \rightarrow \varphi(U)$  is a diffeomorphism given by

$$\varphi(u, v) = (\tilde{u}, \tilde{v}).$$

$$I_1 = \begin{pmatrix} du & dv \end{pmatrix} \begin{pmatrix} E & F \\ F & G \end{pmatrix} \begin{pmatrix} du \\ dv \end{pmatrix}$$

$$I_2 = \begin{pmatrix} d\tilde{u} & d\tilde{v} \end{pmatrix} \begin{pmatrix} \tilde{E} & \tilde{F} \\ \tilde{F} & \tilde{G} \end{pmatrix} \begin{pmatrix} d\tilde{u} \\ d\tilde{v} \end{pmatrix}.$$

Note

$$\begin{aligned} \begin{pmatrix} d\tilde{u} \\ d\tilde{v} \end{pmatrix} &= \frac{\partial(\tilde{u}, \tilde{v})}{\partial(u, v)} \begin{pmatrix} du \\ dv \end{pmatrix} = J_\varphi \begin{pmatrix} du \\ dv \end{pmatrix} \\ &\Rightarrow \begin{pmatrix} E & F \\ F & G \end{pmatrix} = J_\varphi^\top \begin{pmatrix} \tilde{E} & \tilde{F} \\ \tilde{F} & \tilde{G} \end{pmatrix} J_\varphi. \end{aligned}$$

**Proposition 2.10.5.**  $U \subset \mathbb{R}^2$ , assume  $\gamma_1(U) \subset S_1$ ,  $\gamma_2(U) \subset S_2$  are two local parametrizations of  $S_1$  and  $S_2$  such that

$$E_1 = E_2, \quad F_1 = F_2, \quad G_1 = G_2,$$

then  $\varphi = \gamma_2 \circ \gamma_1^{-1}$  is a local isometry.

*Proof.*  $\gamma_1, \gamma_2$  are local parametrizations  $\Rightarrow \varphi = \gamma_2 \circ \gamma_1^{-1}$  is a local diffeomorphism. It suffices to show  $\forall p \in U, w \in T_p U$

$$I_p(w, w) = I_{\varphi(p)}(d\varphi_p(w), d\varphi_p(w)).$$

Let  $w = \alpha'(0) \in T_p S$  for a curve  $\alpha(t) \in S_1$ ,  $\alpha(t) = \gamma_1(u(t), v(t))$

$$\Rightarrow w = \frac{\partial \gamma_1}{\partial u} u'(0) + \frac{\partial \gamma_1}{\partial v} v'(0)$$

$$I_p(w, w) = E_1 u'(0)^2 + 2F_1 u'(0)v'(0) + G_1 v'(0)^2.$$

Since

$$d\varphi_p(w) = \frac{d}{dt} \Big|_{t=0} \varphi \circ \alpha(t) = \frac{\partial \gamma_2}{\partial u} u'(0) + \frac{\partial \gamma_2}{\partial v} v'(0),$$

$$\therefore I_{\varphi(p)}(d\varphi_p(w), d\varphi_p(w)) = E_2 u'(0)^2 + 2F_2 u'(0)v'(0) + G_2 v'(0)^2.$$

By assumption,  $I_p(w, w) = I_{\varphi(p)}(d\varphi_p(w), d\varphi_p(w))$ .  $\square$

*Remark.* For two (local) isometric surfaces  $S_1$  and  $S_2$ , the 1<sup>st</sup> fundamental forms might look quite different in the given parametrization. But we can always find a coordinate change on one of them to get the desired isometry between them. (Such coordinate change gives the isometry on the surface to itself)

**Exercise.** In your homework 6, you have checked the catenoid and the with

$$C(u, v) = (a \cosh v \cos u, a \cosh v \sin u, av), \quad 0 < u < 2\pi, \quad -\infty < v < +\infty$$

and the helicoid with

$$H(\bar{u}, \bar{v}) = (\bar{v} \cos \bar{u}, \bar{v} \sin \bar{u}, a\bar{u}), \quad 0 < \bar{u} < 2\pi, \quad -\infty < \bar{v} < +\infty$$

are local isometric, and the local isometry is

$$\varphi(u, v) = (\bar{u}, \bar{v}), \quad \bar{u} = u, \quad \bar{v} = a \sinh v.$$

*Remark.* If  $\varphi: S_1 \rightarrow S_2$  is an isometry,  $\varphi$  preserves distance, length, angle, area et.c.

We often use another weaker equivalent condition, i.e. a diffeomorphism only preserving angle.

**Definition 2.10.6.** A diffeomorphism  $\varphi: S_1 \rightarrow S_2$  is called a conformal map if  $\forall p \in S_1$ ,  $v_1, v_2 \in T_p S_1$ , we have

$$\langle d\varphi_p(v_1), d\varphi_p(v_2) \rangle = \lambda^2(p) \langle v_1, v_2 \rangle_p,$$

where  $\lambda^2$  is a nowhere vanishing smooth function on  $S_1$  and  $S_1$  is said to be conformal to  $S_2$ .

**Definition 2.10.7** (Locally conformal).  $\varphi: S_1 \rightarrow S_2$  is called a locally conformal map, if  $\forall \exists$  a neighborhood  $U$  of  $p$  such that  $\varphi|U$  is a conformal map.

**Proposition 2.10.8.**  $\varphi: S_1 \rightarrow S_2$  is a locally conformal map if and only if  $\varphi$  is an angle preserving smooth map.

*Proof.* See homework.  $\square$

*Remark.* (1) Angle-preserving is a geometric description of (locally) conformal condition.  
In reality, it's more convenient to use definition.



(2) Conformal is also an equivalent relation on regular surfaces.

**Example 2.10.9.** In HW 6, you have checked that stereographic map

$$\begin{aligned}\pi_N: \mathbb{S}^2 - N &\rightarrow \mathbb{R}^2 \\ (x, y, z) &\mapsto \left( \frac{x}{1-z}, \frac{y}{1-z} \right),\end{aligned}$$

is a locally conformal map. Recall

$$\begin{aligned}ds_{\mathbb{S}^2}^2 &= \frac{4}{(1+u^2+v^2)^2} (du^2 + dv^2) \\ &= \frac{4}{(1+u^2+v^2)^2} ds_{\mathbb{R}^2}^2\end{aligned}$$

**Definition 2.10.10** (Locally conformal flat). A regular surface is called locally conformally flat, if  $\forall p \in S \exists$  neighborhood  $U$  of  $p$  such that  $U$  is conformally equivalent to an open subset of  $\mathbb{R}^2$ , i.e. on  $U$  the first fundamental form of  $S$  is

$$I_U = \lambda^2 I_{\mathbb{R}^2}$$

for a non-vanishing smooth function.

A remarkable result in surface theory is:

**Theorem 2.10.11.** Any regular surface is locally conformally flat.

In practice, this is very useful. The theorem tells that  $\forall p \in S$ , we can choose a local parametrization near  $p$  such that

$$ds^2 = \lambda^2 ds_{\mathbb{R}^2}^2 = \lambda^2 (dx^2 + dy^2).$$

Such parametrization is called Isothermal parametrization. Hence, the study of geometry on  $S$  (which is determined by the 1<sup>st</sup> fundamental form) becomes the study of function  $\lambda$ .

*Proof.* (Skip) (Reference: S.S. Chern, 1955, proceedings, An elementary proof of the existence of isothermal parameters on a surface). The proof is reduced to solving some complex valued differential equations  $\square$

*Remark.* Later, in Riemannian Geometry course, you'll see there is a “mysterious” curvature (Weyl) tensor to characterize the “locally conformally flat” condition, i.e.

$$\text{Weyl tensor } \equiv 0 \Leftrightarrow \text{Locally conformally flat.}$$

However, Weyl tensor is always zero on a manifold of dimension 2 and 3.

*Remark.* (1) In surface theory, conformal map is closely related to the complex analysis.

(2) In higher dimensional Riemannian Geometry, there is a branch called conformal geometry.

Yamabe Problem:

(1) Let  $(M, g)$  be a close Riemannian manifold with  $\dim M \geq 3$ . Does there exist a Riemannian metric  $\tilde{g}$  such that  $\tilde{g} = \lambda^2 g$  and the “scalar curvature” of  $\tilde{g}$  is a constant  $c$ ? ( $c < 0$  and  $c = 0$  are solved.  $c > 0$  remains open)

(2) In  $\dim = 2$ , this question is equivalent to finding a metric with constant Gaussian curvature on a closed surface under the conformal change.

# Chapter 3

## Intrinsic geometry

**Definition 3.0.1.**

$$\begin{aligned}\nabla: \Gamma(TM) \times \Gamma(TM) &\rightarrow \Gamma(TM) \\ (X, Y) &\mapsto \nabla_X Y\end{aligned}$$

is called the affine connection on  $M$ .

Fact: There are many such affine connections!

In practice, we need local expressions of  $\nabla_V W$ . Let  $(x^1, \dots, x^n)$  be a local coordinate on  $U \subset M$ ,  $V = V^i \frac{\partial}{\partial x^i}$ ,  $W = W^i \frac{\partial}{\partial x^i}$ , then

$$\begin{aligned}\nabla_V W &= \nabla_{V^i \frac{\partial}{\partial x^i}} \left( W^j \frac{\partial}{\partial x^j} \right) \\ &= V^i \nabla_{\frac{\partial}{\partial x^i}} \left( W^j \frac{\partial}{\partial x^j} \right) \\ &= V^i \left( \left( \nabla_{\frac{\partial}{\partial x^i}} W^j \right) \frac{\partial}{\partial x^j} + W^j \nabla_{\frac{\partial}{\partial x^i}} \frac{\partial}{\partial x^j} \right) \\ &= V^i \left( \frac{\partial W^j}{\partial x^i} \frac{\partial}{\partial x^j} + W^j \boxed{\nabla_{\frac{\partial}{\partial x^i}} \frac{\partial}{\partial x^j}} \right).\end{aligned}$$

**Definition 3.0.2.** On  $U$ , we define the Christoffel symbol by

$$\nabla_{\frac{\partial}{\partial x^i}} \frac{\partial}{\partial x^j} = \Gamma_{ij}^k \frac{\partial}{\partial x^k}.$$

(Here, one should compare this definition with the Christoffel symbol introduced in the study of equation of motion in previous lectures).

$$\Rightarrow \nabla_V W = V^i \left( \frac{\partial W^j}{\partial x^i} + W^k \Gamma_{ki}^j \right) \frac{\partial}{\partial x^j}.$$

Conventionally, we define

$$\nabla_i W^j = \frac{\partial W^j}{\partial x^i} + \Gamma_{ik}^j W^k$$

- $\nabla_i W^j$ : Taking covariant derivative of  $j$ -th component of  $W$  along the  $i$ -th coordinate direction.



- $\frac{\partial W^j}{\partial x^i}$ : Euclidean derivative.
- $\Gamma_{ik}^j W^k$ : Correction term.

This notion is frequently used in geometry references.

Again, because there are tons of selection of affine connections, this yields many choices of  $\Gamma_{ij}^k$ ! After we introduce the Riemannian metric, we shall see there is a unique affine connection compatible with the Riemannian metric.

**Definition 3.0.3** (Riemannian metric). Let  $M$  be a smooth manifold. A Riemannian metric on  $M$  is a smooth map

$$g: \Gamma(TM) \times \Gamma(TM) \rightarrow C^\infty(M),$$

such that  $\forall X, Y, Z \in \Gamma(TM), f \in C^\infty(M)$  there is the following

- (1)  $g(X, Y) = g(Y, X)$ .(symmetry)
- (2)  $g(X, X) \geq 0$ , and equality achieves iff  $X = 0$ . (positive definite)
- (3)  $g(fX + Y, Z) = f \cdot g(X, Z) + g(Y, Z)$ .( $C^\infty$  linearity)

$(M, g)$  is called a Riemannian manifold.

*Remark.* At each  $p \in M$ ,  $g$  defines an inner product  $g_p$  on  $T_p M$ . If we choose a coordinate chart near  $p$  with local coordinate  $(x^1, \dots, x^n)$ , the local expression of  $g$  is written as

$$g = g_{ij} dx^i dx^j,$$

where  $g_{ij} = g\left(\frac{\partial}{\partial x^i}, \frac{\partial}{\partial x^j}\right)$ .

**Example 3.0.4.** The 1<sup>st</sup> fundamental form on  $M$  is a Riemannian metric.

Using the Riemannian metric  $g$ , we can define the length, area, angle, etc.

**Definition 3.0.5.** (1)  $X \in \Gamma(TM), |X| = \sqrt{g(X, X)}$ .

(2) The volume density on  $(M, g)$  is defined as

$$dV = \sqrt{\det(g_{ij})} dx^1 \wedge \dots \wedge dx^n.$$

(3) The volume of a bounded region  $B$  is

$$V(B) = \int_B 1 dV$$

With the Riemannian metric introduced, we can uniquely determine an affine connection compatible with the Riemannian metric.

**Theorem 3.0.6.** Let  $(M, g)$  be a Riemannian manifold, then there is a unique affine connection  $\nabla: \Gamma(TM) \times \Gamma(TM) \rightarrow \Gamma(TM)$  satisfying following conditions:  $\forall X, Y, Z$

- (1)  $\nabla_Z (g(X, Y)) = g(\nabla_Z X, Y) + g(X, \nabla_Z Y)$ .(Compatible with metric  $g$ )<sup>1</sup>



(2)  $\nabla_X Y - \nabla_Y X = [X, Y].$  (*Torsion free*)

The connection  $\nabla$  is called Levi-Civita connection.

Locally, take  $X = \frac{\partial}{\partial x^i}, Y = \frac{\partial}{\partial x^j}, Z = \frac{\partial}{\partial x^k}$

$$(1) \Rightarrow \frac{\partial g_{ij}}{\partial x^k} = \Gamma_{ki}^l g_{lj} + \Gamma_{kj}^l g_{li}$$

$$(2) \Rightarrow \Gamma_{ij}^k = \Gamma_{ji}^k.$$

**Exercise.** Show that

$$\Gamma_{ij}^k = \frac{1}{2} g^{kl} \left( \frac{\partial g_{jl}}{\partial x^i} + \frac{\partial g_{il}}{\partial x^j} - \frac{\partial g_{ij}}{\partial x^l} \right)$$

This is just the same expression as we see on.

So far, we have defined 1<sup>st</sup> order derivatives (Lie derivative, covariant derivative) on functions and vector fields. Next we shall consider 2<sup>nd</sup> order derivatives of a function and vector fields. In particular, non-commutative nature of 2<sup>nd</sup> order derivative on vector fields will be captured by the “curvature”.

Let's assume  $\nabla$  to be the Levi-Civita connection from now on.

- Recall we have defined tangent bundle.  $TM = \bigcup_{p \in M} T_p M$  is the collection of all tangent vector spaces. As a vector space,  $T_p M$  is isomorphic to  $\mathbb{R}^n$ . Let  $T_p^* M = \{ \text{all covectors at } p \}$ . We also let  $T^* M = \bigcup_{p \in M} T_p^* M = \bigcup_p \{(p, \alpha) | \alpha \in T_p^* M\}$ . Similar to the  $TM$ , one can endow a smooth structure on  $T^* M$  such that it's a smooth manifold of dimension  $2 \dim M$ . We shall also call an element of  $\Gamma(T^* M)$  a differential 1-form, where  $\Gamma(T^* M)$  is the collection of all global covectors.

- We have introduced

$$\begin{aligned} \nabla: \Gamma(TM) \times C^\infty(M) &\rightarrow C^\infty(M) \\ (X, f) &\mapsto \nabla_X f. \end{aligned}$$

This map induces

$$\nabla f: \Gamma(TM) \rightarrow C^\infty(M).$$

At each point  $p \in M$  this map is

$$X \mapsto \nabla_X f = \nabla f(X).$$

$$\nabla f(p): T_p M \rightarrow \mathbb{R} \Rightarrow \nabla f(p) \in T_p^* M \Rightarrow \nabla f \in \Gamma(T^* M).$$

*Remark.* If  $(x^1, \dots, x^n)$  is local coordinate at  $p$ .  $T_p M = \text{span}\{\frac{\partial}{\partial x^1}, \dots, \frac{\partial}{\partial x^n}\}$ , then  $T_p^* M = \text{span}\{dx^1, \dots, dx^n\}$ ,  $dx^i \left( \frac{\partial}{\partial x^j} \right) = \delta_j^i$

$$\Rightarrow \nabla f(p) = \frac{\partial f}{\partial x^i} dx^i = \nabla_i f \cdot dx^i. \quad (\nabla_i f = \frac{\partial f}{\partial x^i})$$

**Definition 3.0.7.** The gradient vector field of  $f$ , written as  $\text{grad}f = \text{grad}_g f$  is defined as  $\forall X \in \Gamma(TM)$

$$g(\text{grad}f, X) = \nabla_X f = \nabla f(X).$$

---

<sup>1</sup>(1) is also equivalent to  $\nabla g = 0$ . (We shall talk about this later)

Locally,

$$\text{grad}f = g^{ij} \frac{\partial f}{\partial x^j} \frac{\partial}{\partial x^i} = \nabla^i f \frac{\partial}{\partial x^i}.$$

**Definition 3.0.8** (Hessian of  $f$ ).

$$\nabla \nabla f: \Gamma(TM) \times \Gamma(TM) \rightarrow C^\infty(M)$$

$$(X, Y) \mapsto \nabla \nabla f(X, Y).$$

Where  $\nabla \nabla f(X, Y) = (\nabla_X \nabla f)(Y)^2 = \nabla_X (\nabla f(Y)) - \nabla f(\nabla_X Y) = X(Yf) - (\nabla_X Y)f$ .

Locally:

$$\begin{aligned} \nabla \nabla f \left( \frac{\partial}{\partial x^i}, \frac{\partial}{\partial x^j} \right) &= \frac{\partial}{\partial x^i} \left( \frac{\partial f}{\partial x^j} \right) - \nabla_{\frac{\partial}{\partial x^i}} \frac{\partial}{\partial x^j} f \\ &= \frac{\partial^2 f}{\partial x^i \partial x^j} - \Gamma_{ij}^k \frac{\partial f}{\partial x^k}. \end{aligned}$$

*Remark.* (1) We conventionally write  $\nabla \nabla f(\frac{\partial}{\partial x^i} \frac{\partial}{\partial x^j}) = \nabla_i \nabla_j f$ , i.e.

$$\nabla_i \nabla_j f = \frac{\partial^2 f}{\partial x^i \partial x^j} - \Gamma_{ij}^k \frac{\partial f}{\partial x^k}.$$

- $\nabla_i \nabla_j f$ : tensor component.
- $\frac{\partial^2 f}{\partial x^i \partial x^j}$ : Euclidean Hessian.
- $\Gamma_{ij}^k \frac{\partial f}{\partial x^k}$  Correction.

(2)  $\nabla_i \nabla_j f = \nabla_j \nabla_i f$ . (Symmetric in  $i$  and  $j$ )

(3) In tensor notation we write this as

$$\nabla \nabla f = (\nabla_i \nabla_j f) dx^i dx^j.$$

**Definition 3.0.9** (Laplacian of  $f$ ).  $\Delta f = \text{trace}(\nabla(\text{grad}f))$ .

Locally,  $\text{grad}f = \nabla^i f \frac{\partial}{\partial x^i} \Rightarrow \nabla(\text{grad}f) = \nabla_j \nabla^i f dx^j \otimes \frac{\partial}{\partial x^i}$ .

$$\begin{aligned} \Delta f &= \nabla_i \nabla^i f = g^{ij} \nabla_i \nabla_j f \\ &= g^{ij} \left( \frac{\partial^2 f}{\partial x^i \partial x^j} - \Gamma_{ij}^k \frac{\partial f}{\partial x^k} \right). \end{aligned}$$

**Exercise.** Show that

$$\Delta f = \frac{1}{\sqrt{\det g}} \frac{\partial}{\partial x^i} \left( \sqrt{\det g} \cdot g^{ij} \frac{\partial f}{\partial x^j} \right).$$

---

<sup>2</sup>Note that here we haven't defined the covariant derivative of a 1-form

Note that the expression of R.H.S follows from “integration by parts”, i.e.  $\forall h \in C_c^\infty(M)$ ,

$$\int_M h \Delta f \sqrt{g} dx = - \int_M \langle \nabla h, \nabla f \rangle \sqrt{g} dx.$$

Next, we consider taking 2<sup>nd</sup> order derivative of a vector field  $Z$  along two different vector fields  $X$  and  $Y$ . Let's do a general local computation.(The following computation should be very familiar with you)

$$\text{Let } X = X^i \frac{\partial}{\partial x^i}, Y = Y^j \frac{\partial}{\partial x^j}, Z = Z^k \frac{\partial}{\partial x^k}$$

$$\begin{aligned} & \Rightarrow \nabla_X \nabla_Y Z = \nabla_X (\nabla_Y Z) \\ &= \nabla_X \left( \left( Y^j \nabla_j Z^k \right) \frac{\partial}{\partial x^k} \right) \\ &= \left( X^i \nabla_i Y^j \nabla_j Z^k + X^i Y^j \nabla_j \nabla_i Z^k \right) \frac{\partial}{\partial x^k} \\ & \nabla_Y \nabla_X Z = \left( Y^j \nabla_j X^i \nabla_i Z^k + X^i Y^j \nabla_j \nabla_i Z^k \right) \frac{\partial}{\partial x^k} \\ \\ & \Rightarrow \nabla_X \nabla_Y Z - \nabla_Y \nabla_X Z \\ &= X^i Y^j \left( \nabla_i \nabla_j Z^k - \nabla_j \nabla_i Z^k \right) \frac{\partial}{\partial x^k} + \left( \nabla_{\nabla_X Y} Z^k - \nabla_{\nabla_Y X} Z^k \right) \frac{\partial}{\partial x^k} \\ &= X^i Y^j \left( \nabla_i \nabla_j Z^k - \nabla_j \nabla_i Z^k \right) \frac{\partial}{\partial x^k} + \left( \nabla_{[X,Y]} Z^k \right) \frac{\partial}{\partial x^k}. \\ & \therefore \nabla_X \nabla_Y Z - \nabla_Y \nabla_X Z - \nabla_{[X,Y]} Z = X^i Y^j \left( \nabla_i \nabla_j Z^k - \nabla_j \nabla_i Z^k \right) \frac{\partial}{\partial x^k}. \end{aligned}$$

**Definition 3.0.10.** The (1,3) Riemannian curvature tensor is defined by a map

$$R: \Gamma(TM) \times \Gamma(TM) \times \Gamma(TM) \rightarrow \Gamma(TM)$$

$$(X, Y, Z) \mapsto R(X, Y)Z$$

$$R(X, Y)Z = \nabla_X \nabla_Y Z - \nabla_Y \nabla_X Z - \nabla_{[X, Y]} Z$$

Locally,

$$R \left( \frac{\partial}{\partial x^i}, \frac{\partial}{\partial x^j} \right) \frac{\partial}{\partial x^k} = R_{ij}{}^l \frac{\partial}{\partial x^l}$$

**Exercise.** (1) Check  $R$  is  $C^\infty$  in  $X, Y, Z$ .

(2) Find a local expression for  $R_{ij}{}^l$  in terms of Christoffel symbols.

Computation: take  $X = \frac{\partial}{\partial x^i}$ ,  $Y = \frac{\partial}{\partial x^j}$ ,  $Z = \frac{\partial}{\partial x^k}$ ,

$$\begin{aligned} R \left( \frac{\partial}{\partial x^i}, \frac{\partial}{\partial x^j} \right) \frac{\partial}{\partial x^k} &= \nabla_i \nabla_j \frac{\partial}{\partial x^k} - \nabla_j \nabla_i \frac{\partial}{\partial x^k} \\ &= \nabla_i \left( \Gamma_{jk}^l \frac{\partial}{\partial x^l} \right) - \nabla_j \left( \Gamma_{ik}^l \frac{\partial}{\partial x^l} \right) \\ &= \left( \partial_i \Gamma_{jk}^l \right) \frac{\partial}{\partial x^l} + \Gamma_{jk}^l \Gamma_{il}^p \frac{\partial}{\partial x^p} - \partial_j \Gamma_{ik}^l \frac{\partial}{\partial x^l} - \Gamma_{ik}^l \Gamma_{jl}^p \frac{\partial}{\partial x^p} \\ &= \left( \partial_i \Gamma_{jk}^l + \Gamma_{jk}^p \Gamma_{ip}^l - \partial_j \Gamma_{ik}^l - \Gamma_{ik}^p \Gamma_{jp}^l \right) \frac{\partial}{\partial x^l} \\ &= \left( \color{blue}{\partial_i \Gamma_{jk}^l - \partial_j \Gamma_{ik}^l + \Gamma_{jk}^p \Gamma_{ip}^l - \Gamma_{ik}^p \Gamma_{jp}^l} \right) \frac{\partial}{\partial x^l} \end{aligned}$$



Notation:  $R\left(\frac{\partial}{\partial x^i}, \frac{\partial}{\partial x^j}\right) \frac{\partial}{\partial x^k} = R_{ij}{}^l{}_k \frac{\partial}{\partial x^l}$ .

$$R_{ij}{}^l{}_k = \partial_i \Gamma_{jk}^l - \partial_j \Gamma_{ik}^l + \Gamma_{jk}^p \Gamma_{ip}^l - \Gamma_{ik}^p \Gamma_{jp}^l$$

**Definition 3.0.11.** The (0,4) Riemannian curvature tensor is defined as

$$Rm : \Gamma(TM) \times \Gamma(TM) \times \Gamma(TM) \times \Gamma(TM) \rightarrow C^\infty(M)$$

$$(X, Y, W, Z) \mapsto Rm(X, Y, W, Z) = g(R(X, Y), Z, W)$$

$$\begin{aligned} \text{Locally, } R_{ijkl} &= R\left(\frac{\partial}{\partial x^i}, \frac{\partial}{\partial x^k}, \frac{\partial}{\partial x^l}, \frac{\partial}{\partial x^j}\right) = g\left(R\left(\frac{\partial}{\partial x^i}, \frac{\partial}{\partial x^j}\right) \frac{\partial}{\partial x^k}, \frac{\partial}{\partial x^l}\right) = g\left(R_{ij}{}^p{}_k \frac{\partial}{\partial x^p}, \frac{\partial}{\partial x^l}\right) = \\ &R_{ij}{}^p{}_k g_{pl} \\ &\Rightarrow R_{ijkl} = R_{ij}{}^p{}_k g_{pl} \text{ (pull-down the 3rd index),} \\ &\Rightarrow R_{ij}{}^p{}_k = R_{ijkl} g^{lp} \text{ (lift-up the 3rd index).} \end{aligned}$$

*Remark.* For a pair of vector fields  $X, Y$ ,  $R(X, Y) = [\nabla_X, \nabla_Y] - \nabla_{[X, Y]}$  is an antisymmetric (in  $X$  and  $Y$ ) operator from  $\Gamma(TM) \rightarrow \Gamma(TM)/$

$$\Rightarrow R(X, Y) \in End(\Gamma(TM)) = \Gamma(T^*M \otimes TM).$$

**Definition 3.0.12.** At  $p \in M$ , let  $\pi$  be a 2-plane generated by  $v, w \in T_p W$ , the sectional curvature of  $\pi$  is

$$K_p(\pi) = \frac{Rm(v, w, v, w)}{\|v \wedge w\|^2},$$

where  $\|v \wedge w\|^2 = g(v, v)g(w, w) - g(v, w)^2$ . (Area of  $\pi$ )

Important properties of (0,4) Riemannian curvature tensor:

- (1)  $Rm(X, Y, W, Z) = -Rm(Y, X, W, Z)$ .
- (2)  $Rm(X, Y, W, Z) + Rm(Y, Z, W, X) + Rm(Z, X, W, Y) = 0$  This is called the 1<sup>st</sup> Bianchi identity.
- (3)  $Rm(X, Y, W, Z) = Rm(W, Z, X, Y)$ .

Locally,

$$(a) -R_{jikl} \stackrel{(1)}{=} R_{ijkl} \stackrel{(3)}{=} R_{klij} \stackrel{(1)}{=} -R_{lkij} \stackrel{(3)}{=} -R_{ijkl}.$$

$$(b) R_{ijlk} + R_{jklj} + R_{kilj} = 0.$$

*Remark.* There are also 2<sup>nd</sup> Bianchi identity:

$$\nabla_U R(X, Y, V, W) + \nabla_V R(X, Y, W, U) + \nabla_W R(X, Y, U, V) = 0,$$

and contracted 2<sup>nd</sup> Bianchi identity:

$$\nabla_X \underbrace{Ric(X, Y)}_{\text{Ricci curvature}} = \frac{1}{2} \nabla_Y \underbrace{S}_{\text{Scalar curvature}}.$$

We are not going to use these two important Bianchi identities in this course.

**Theorem 3.0.13.** *In 2-d, the sectional curvature is just the Gaussian curvature.*

*Proof.* (1) We have seen there are 4 Gaussian equations

$$Kg_{11} = \partial_2\Gamma_{11}^2 - \partial_1\Gamma_{12}^2 + \Gamma_{2p}^2\Gamma_{11}^p - \Gamma_{1p}^2\Gamma_{12}^p = R_{21}{}^2{}_1$$

$$Kg_{12} = \partial_1\Gamma_{12}^1 - \partial_2\Gamma_{11}^1 + \Gamma_{1p}^1\Gamma_{12}^p - \Gamma_{2p}^1\Gamma_{11}^p = R_{12}{}^1{}_1$$

$$Kg_{21} = \partial_2\Gamma_{12}^2 - \partial_1\Gamma_{22}^2 + \Gamma_{2p}^2\Gamma_{12}^p - \Gamma_{1p}^2\Gamma_{22}^p = R_{21}{}^2{}_2$$

$$Kg_{22} = \partial_1\Gamma_{22}^1 - \partial_2\Gamma_{12}^1 + \Gamma_{1p}^1\Gamma_{22}^p - \Gamma_{2p}^1\Gamma_{12}^p = R_{12}{}^1{}_2$$

(2)

$$R_{21}{}^2{}_1 = R_{21p1}g^{p2} = \underbrace{R_{2111}}_0 g^{12} + R_{2121}g^{22} = R_{1212}g^{22}$$

$$R_{12}{}^1{}_1 = R_{12p1}g^{p1} = \underbrace{R_{1211}}_0 g^{11} + R_{1221}g^{21} = -R_{1212}g^{21}$$

$$R_{21}{}^2{}_2 = R_{21p2}g^{p2} = R_{2112}g^{12} + \underbrace{R_{2122}}_0 g^{22} = -R_{1212}g^{12}$$

$$R_{12}{}^1{}_2 = R_{12p2}g^{p1} = R_{1212}g^{11} + \underbrace{R_{1222}}_0 g^{21} = -R_{1212}g^{11}$$

(1) and (2)  $\Rightarrow$

$$K \begin{pmatrix} g_{11} & g_{12} \\ g_{12} & g_{22} \end{pmatrix} = R_{1212} \begin{pmatrix} g^{22} & -g^{12} \\ -g^{12} & g^{11} \end{pmatrix}. \quad (\star)$$

Note  $g^{11} = \frac{1}{\det g}g_{22}$ ,  $g^{12} = -\frac{1}{\det g}g_{12}$ ,  $g^{22} = \frac{1}{\det g}g_{11}$

$$K \begin{pmatrix} g_{11} & g_{12} \\ g_{12} & g_{22} \end{pmatrix} = R_{1212} \cdot \frac{1}{\det g} \begin{pmatrix} g_{11} & g_{12} \\ g_{12} & g_{22} \end{pmatrix}.$$

i.e.

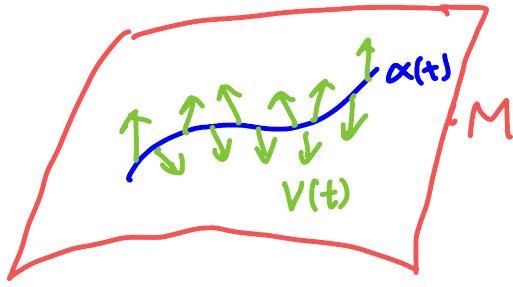
$$K = \frac{R_{1212}}{\det g}.$$

□

Note:  $R_{1212} = R \left( \frac{\partial}{\partial 1}, \frac{\partial}{\partial 2}, \frac{\partial}{\partial 1}, \frac{\partial}{\partial 2} \right)$ ,  $\det = g_{11}g_{22} - g_{12}^2 =$  Area of plane generated by  $\{\frac{\partial}{\partial x^1}, \frac{\partial}{\partial x^2}\}$ .

### 3.1 Parallel transportation and Geodesics

Let  $(M, g)$  be an n-dimensional Riemannian manifold,  $v \in \Gamma(TM)$  is a smooth vector field.  $\alpha(t) \subset M$  is a regular curve on  $M$ . Let  $v(t) = v|_{\alpha(t)}$  be the restriction of  $V$  on the curve.



We can take “derivatives” of  $V(t)$  along  $\alpha(t)$ , denoted as  $\frac{DV(t)}{dt}$ . To understand this, we shall compute this locally. Let  $(x^1, \dots, x^n)$  be a local coordinate, write  $\alpha(t) = ((x^1(t), \dots, x^n))$ ,  $V(t) = V^i(t) \frac{\partial}{\partial x^i}$ ,  $\dot{\alpha}(t) = \dot{x}^i(t) \frac{\partial}{\partial x^i}$ .

$$\begin{aligned}\frac{DV(t)}{dt} &= \frac{D}{dt} \left( V^i(t) \frac{\partial}{\partial x^i} \right) = \dot{V}^i(t) \frac{\partial}{\partial x^i} + V^i(t) \nabla_{\dot{\alpha}(t)} \frac{\partial}{\partial x^i} \\ &= \dot{V}^i(t) \frac{\partial}{\partial x^i} + V^i(t) \dot{x}^j(t) \nabla_{\frac{\partial}{\partial x^j}} \frac{\partial}{\partial x^i} = \dot{V}^i(t) \frac{\partial}{\partial x^i} + V^i(t) \dot{x}^j(t) \Gamma_{ji}^k \frac{\partial}{\partial x^k} \\ &= \left( V^i(t) + \Gamma_{jk}^i \dot{x}^j(t) V^k(t) \right) \frac{\partial}{\partial x^i}\end{aligned}$$

i.e.

$$\frac{DV(t)}{dt} = \left( \left( V^i(t) + \Gamma_{jk}^i \dot{x}^j(t) V^k(t) \right) \right) \frac{\partial}{\partial x^i} \quad (\star)$$

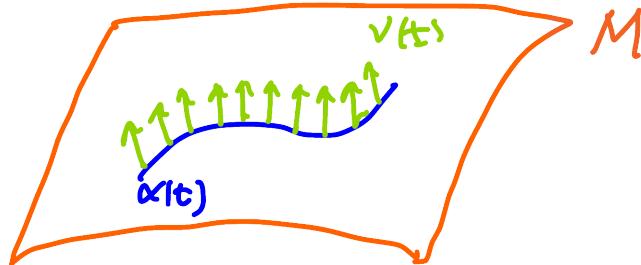
*Remark.* Let  $S$  be a regular surface in  $\mathbb{R}^3$ ,  $\alpha(t) \in S$  is a regular curve.  $V$  is a smooth vector field on  $S$ .  $V|_{\alpha(t)}$  is a vector field along  $\alpha(t)$ . We can also view  $V(t)$  as a vector field in  $\mathbb{R}^3$ . Take the usual derivative of  $V(t)$  in  $\mathbb{R}^3$ , i.e.  $\frac{dV(t)}{dt}$ , and let  $\frac{DV(t)}{dt}$  = tangential part of  $\frac{dV(t)}{dt}$  on  $S$ , i.e. taking the projection of  $\frac{dV(t)}{dt}$  on  $TS$  at each point.

**Exercise.** Check: this definition coincides with  $\star$ .

(Hint: using the equation of motion of coordinate frame.)

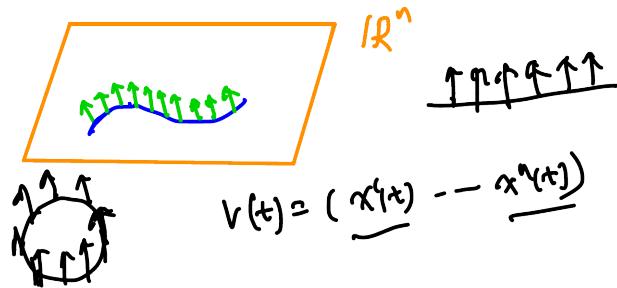
**Definition 3.1.1** (parallel vector field). (1) A vector field  $V$  along a curve  $\alpha(t): I \rightarrow M$  is called parallel if

$$\frac{DV(t)}{dt} = 0.$$

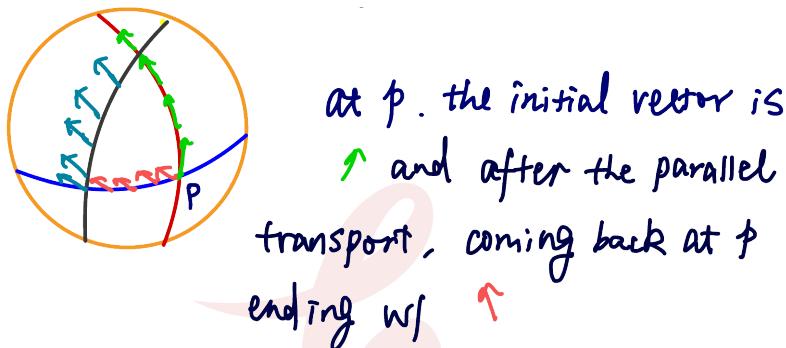


(2) In general, we call a vector field  $V$  to be parallel, if  $\nabla V = 0$ . Equivalently, along any curve  $\alpha(t)$  in  $M$ ,  $\frac{DV(t)}{dt} = 0$ .

**Example 3.1.2.** (1) In  $\mathbb{R}^n$ ,  $\frac{DV(t)}{dt} = 0 \Rightarrow V$  is a constant vector field along the curve.



(2)  $\mathbb{S}^2$ , the tangent vector field of a great circle is a parallel vector field along this circle (Green arrows).



Let  $\alpha(\theta)$  be the great circle, after a rotation we assume

$$\alpha(\theta) = (\cos \theta, \sin \theta, 0)$$

to be the equator. The tangent vector field of  $\alpha(\theta)$  is

$$\alpha'(\theta) = (-\sin \theta, \cos \theta, 0).$$

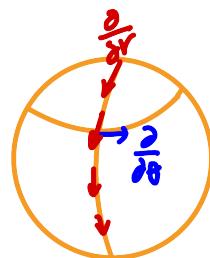
$$\Rightarrow \frac{d\alpha'(t)}{dt} = -\alpha(\theta) = \text{normal field of } \mathbb{S}^2.$$

$$\Rightarrow \alpha''(\theta) \text{ has no projection part on } T\mathbb{S}^2, \text{ i.e. } \frac{D\alpha'(t)}{dt} = 0.$$

*Remark.* The 1<sup>st</sup> fundamental form on  $\mathbb{S}^2$  is

$$ds^2 = dr^2 + \sin^2 r d\theta^2.$$

At each point  $p$ ,  $T_p S = \text{span}\{\frac{\partial}{\partial r}, \frac{\partial}{\partial \theta}\}$ .



Fixing  $\theta$ , then  $\frac{\partial}{\partial r}$  is the tangent vector field of the great circle, then

$$\frac{D}{dr} \left( \frac{\partial}{\partial r} \right) = \nabla_{\frac{\partial}{\partial r}} \frac{\partial}{\partial r} = \Gamma_{rr}^r \frac{\partial}{\partial r} + \Gamma_{rr}^\theta \frac{\partial}{\partial \theta},$$

where

$$\Gamma_{rr}^r = \frac{1}{2} g^{rk} \left( \frac{\partial g_{rk}}{\partial r} + \frac{\partial g_{rk}}{\partial r} - \frac{\partial g_{rr}}{\partial x^k} \right) = \frac{1}{2} g^{rr} \frac{\partial g_{rr}}{\partial r} = 0.$$

$$\Gamma_{rr}^\theta = \frac{1}{2} g^{\theta\theta} \left( \frac{\partial g_{r\theta}}{\partial r} + \frac{\partial g_{r\theta}}{\partial r} - \frac{\partial g_{rr}}{\partial \theta} \right) = 0$$

$\Rightarrow \frac{D}{dr} \frac{\partial}{\partial r} = 0 \Rightarrow \frac{\partial}{\partial r}$  is parallel along itself.

If we compute

$$\frac{D}{d\theta} \frac{\partial}{\partial \theta} = \nabla_{\frac{\partial}{\partial \theta}} \frac{\partial}{\partial \theta} = \Gamma_{\theta\theta}^r \frac{\partial}{\partial r} + \Gamma_{\theta\theta}^\theta \frac{\partial}{\partial \theta} = -\sin r \cos r \frac{\partial}{\partial r}.$$

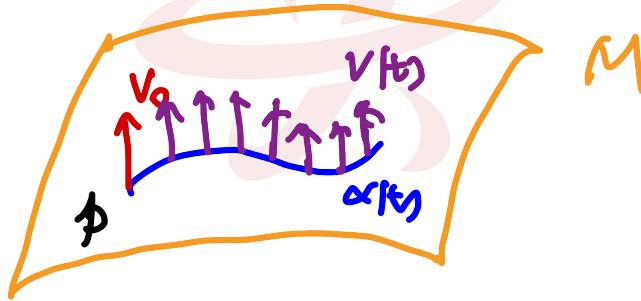
Hence,

$$\frac{D}{d\theta} \frac{\partial}{\partial \theta} = 0 \iff r = \frac{\pi}{2}.$$

Facts:

$$\frac{DV(t)}{dt} = 0 \iff \dot{V}^i(t) + \Gamma_{jk}^i(t) \dot{x}^j(t) V^k(t) = 0.$$

This is the 1<sup>st</sup> order linear O.D.E. system of  $V(t)$ . Hence, given a curve  $\alpha(t)$ , let  $p \in \alpha(t)$ ,  $v_0 \in T_p M$ , then by the Solution to the Cauchy problem, there is a unique parallel vector field  $V(t)$  along  $\alpha(t)$  such that  $V(0) = v_0$ .

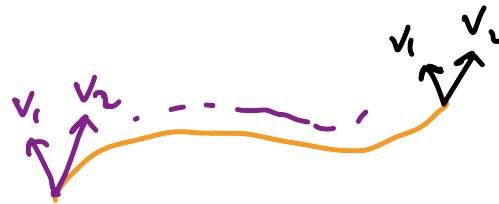


Consider  $p, q \in M$ , let  $\alpha(t): [0, 1] \rightarrow M$  such that  $\alpha(0) = p, \alpha(1) = q, v_0 \in T_p M$ , and  $V(t)$  is the parallel vector field along  $\alpha(t)$  with  $V(0) = v_0$ , then  $V(1) \in T_q M$  is called the parallel transportation of  $v_0$  at  $q$ .

**Proposition 3.1.3.** Let  $V_1, V_2$  be two parallel vector fields along a curve  $\alpha(t)$ , then  $\langle V_1, V_2 \rangle$  is a constant along  $\alpha(t)$ .

*Proof.*  $\frac{d}{dt} \langle V_1(t), V_2(t) \rangle = \left\langle \frac{dV_1(t)}{dt}, V_2(t) \right\rangle + \left\langle \frac{dV_2(t)}{dt}, V_1(t) \right\rangle = 0.$   $\square$

**Corollary 3.1.4.** The parallel transport along a curve does not change the length or angle of original vectors.

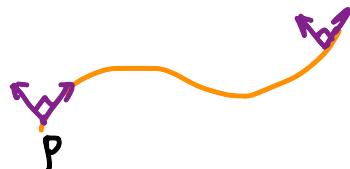


In particular, the map

$$P_{\alpha(1)}: T_p M \rightarrow T_q M$$

is a linear isometry.

*Remark.* The advantage of parallel transport is helping us choose an orthonormal frame along a curve  $\alpha(t)$ . At  $T_p M$ , choose orthonormal basis  $\{E_1, \dots, E_n\}$  and parallel transport  $E_i$  along  $\alpha$ , then at each point of the curve  $\{E_1(t), \dots, E_n(t)\}$  is an orthonormal basis of  $T_{\alpha(t)} M$ .



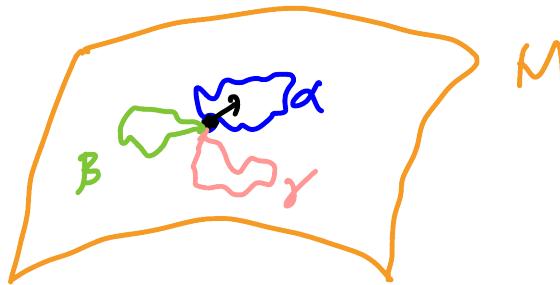
For any vector field  $V(t)$  along  $\alpha(t)$ ,  $V(t) = V^i(t)E_i(t)$ ,

$$\begin{aligned} \frac{DV(t)}{dt} &= \frac{D}{dt} (V^i(t)E_i(t)) = \dot{V}^i(t)E_i(t) + V^i(t) \underbrace{\frac{DE_i(t)}{dt}}_{=0}. \\ \frac{DV(t)}{dt} &= \dot{V}^i(t)E_i(t). \end{aligned}$$

*Remark.*  $\forall p \in M$ , let  $\alpha$  be a piecewise smooth **closed** curve passing through  $p$ , then the parallel transport  $P_\alpha: T_p M \rightarrow T_p M$  yields a linear isometry of  $T_p M$ . If  $\beta$  is another piecewise **closed** curve passing through  $p$ , we have another linear isometry  $P_\beta$ .

### Definition 3.1.5.

$$\text{Hol}_p(M, g) = \{P_\alpha: T_p M \rightarrow T_p M, \alpha: \text{closed curve passing through } p\}.$$



This set has a group structure given by composition of parallel transport.  $\text{Hol}_p(M, g)$  is called the Holonomy group of  $M$  at  $p$ . In fact, it's a Lie group. Note that  $\text{Hol}(M, g)$  relies on the Riemannian metric  $g$ .

! The classification of Holonomy group is useful to understand the classification of Riemannian manifold (metric). Details can be found in Peter Peterson's Riemannian Geometry book p.388.

**Definition 3.1.6 (Geodesics).**  $\gamma(t)$  is a parametrized curve in  $M$ , if

$$\frac{D}{dt}\dot{\gamma}(t) = 0 \iff \nabla_{\dot{\gamma}(t)}\dot{\gamma}(t) = 0 \text{ or simply } \nabla_{\dot{\gamma}}\dot{\gamma}.$$

i.e.  $\dot{\gamma}(t)$  is a parallel vector field along  $\gamma(t)$ , then we call  $\alpha(t)$  a geodesic.

*Remark.* By definition,  $\langle \dot{\gamma}(t), \dot{\gamma}(t) \rangle$  is constant, after reparametrization,  $\gamma(t) = \gamma(s), s = ct$  is the arclength parameter,  $\therefore$  a curve  $\alpha(s)$  with arclength parameter is a geodesic iff  $\frac{D}{ds}(\alpha'(s)) = 0$ .

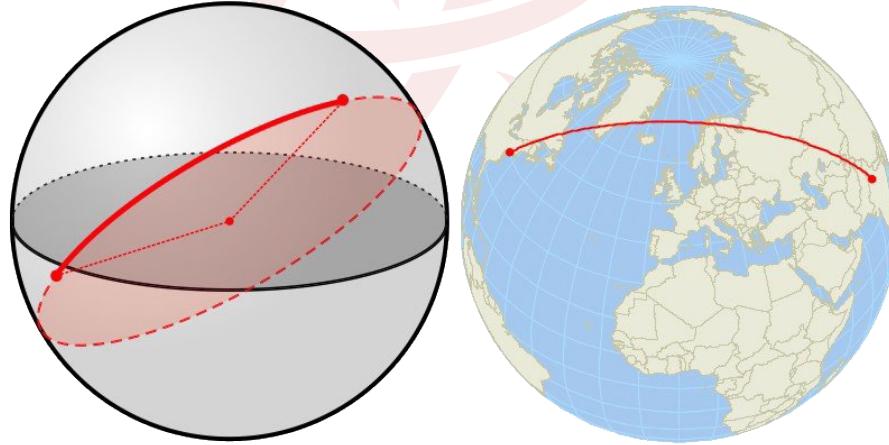
## Geodesics on surfaces

Let  $S$  be a regular surface in  $\mathbb{R}^3$ . Let  $\alpha(s)$  be a geodesic on  $S$  with arclength parameter. Then  $\alpha''(s)$  (in  $\mathbb{R}^3$ ) has the following decomposition

$$\begin{aligned} \alpha''(s) &= \frac{D}{ds}(\alpha'(s)) + \left\langle \alpha''(s), \vec{N}(\alpha(s)) \right\rangle \vec{N} \\ &= \left\langle \alpha''(s), \vec{N}(\alpha(s)) \right\rangle \vec{N} \\ &= k_n(s) \vec{N}. \end{aligned}$$

$\therefore \alpha(s)$  is a geodesic  $\iff$  principal normal  $\vec{n}(s)$  is parallel to the normal of surface  $\vec{N}$ . Note normal section is a geodesic, but geodesic may not be a normal section.

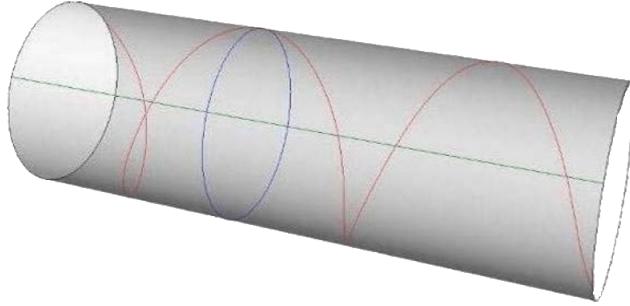
(1)  $\mathbb{S}^2$ . Great circles are geodesics.



(2) On Cylinder,  $x^2 + y^2 = 1$ ,

---

<sup>3</sup>Recall that  $k_n(s) = II(\alpha'(s), \alpha'(s))$ .



The red curve is a geodesic, but not a normal section

consider the local parametrization

$$\gamma(u, v) = (\cos u, \sin u, v)$$

⇒ lines, horizontal circles, and helix curve  $(\cos as, \sin as, bs)$  are all geodesics.

## 3.2 Quick introduction to tensor and tensor field

- (I) Let  $V$  be a vector space,  $\dim V = n$ .  $V^*$  be the covector space = {all linear functionals  $\alpha: V \rightarrow \mathbb{R}$ }. The pairing is given by

$$\begin{aligned} V^* \times V &\rightarrow \mathbb{R} \\ (\alpha, v) &\mapsto \alpha(v) \end{aligned}$$

- A covariant  $l$ -tensor on  $V$  is a multilinear map

$$\omega: V \times \dots \times V \rightarrow \mathbb{R}. \quad (1)$$

A contravariant  $k$ -tensor is a multilinear map

$$X: V^* \times \dots \times V^* \rightarrow \mathbb{R}. \quad (2)$$

A tensor of  $(k, l)$  type ( $k$ -contravariant,  $l$ -covariant) is a multilinear map

$$T: V^* \times \dots \times V^* \times V \times \dots \times V \rightarrow \mathbb{R}. \quad (3)$$

Let

$$\begin{aligned} \bigotimes^l V^* &= \{\text{all covariant } l\text{-tensors}\} \Rightarrow \omega \text{ in (1)} \in \bigotimes^l V^* \\ \bigotimes^k V &= \{\text{all contravariant } k\text{-tensors}\} \Rightarrow X \text{ in (2)} \in \bigotimes^k V \\ \mathcal{T}^{(k,l)}(V) &= \{\text{all } (k, l)\text{-type tensors}\} \Rightarrow T \in \mathcal{T}^{(k,l)}(V) \end{aligned}$$

- Next we talk about the tensor product. Let  $T \in \mathcal{T}^{(k,l)}(V)$ ,  $S \in \mathcal{T}^{(p,q)}(V)$ , then  $T \otimes S \in \mathcal{T}^{(k+p, l+q)}(V)$  is defined as

$$\begin{aligned} T \otimes S &\left( \omega^1, \dots, \omega^{k+p}; X_1, \dots, X_{l+q} \right) \\ &= T \left( \omega^1, \dots, \omega^k; X_1, \dots, X_l \right) S \left( \omega^{k+1}, \dots, \omega^{k+p}; X_{l+1}, \dots, X_{l+q} \right). \end{aligned}$$

Let  $V = \text{span}\{E_1, \dots, E_n\}$ ,  $V^* = \text{span}\{\alpha^1, \dots, \alpha^n\}$  with  $\alpha^i(E_j) = \delta_j^i$ , or equivalently  $E_j(\alpha^i) = \delta_j^i$ .

Then

$$(1) \Rightarrow \omega = \omega_{i_1, i_2, \dots, i_l} \alpha^{i_1} \otimes \dots \otimes \alpha^{i_l}.$$

Moreover,

$$\begin{aligned} \omega(E_{j_1}, \dots, E_{j_l}) &= \omega_{i_1, i_2, \dots, i_l} \alpha^{i_1} \otimes \dots \otimes \alpha^{i_l} (E_{j_1} \otimes \dots \otimes E_{j_l}) \\ &= \omega_{i_1, i_2, \dots, i_l} \alpha^{i_1}(E_{j_1}) \cdots \alpha^{i_l}(E_{j_l}) \\ &= \omega_{i_1, i_2, \dots, i_l} \delta_{j_1}^{i_1} \cdots \delta_{j_l}^{i_l} = \omega_{j_1 \dots j_l}. \end{aligned}$$

$$(2) \Rightarrow X = X^{i_1 \dots i_k} E_{i_1} \otimes \dots \otimes E_{i_k}.$$

$$(3) \Rightarrow T = T^{i_1 \dots i_k}_{j_1 \dots j_l} E_{i_1} \otimes \dots \otimes E_{i_k} \otimes \alpha^{j_1} \otimes \dots \otimes \alpha^{j_l}.$$

(II) On manifold  $M$ , we have introduced

- $TM = \coprod_{p \in M} T_p M$  the tangent bundle.
- $T^*M = \coprod_{p \in M} T_p^* M$  cotangent bundle.

Now, we define  $(k, l)$ -tensor bundle

$$\mathcal{T}^{(k,l)} M = \coprod_{p \in M} \mathcal{T}_p^{(k,l)} M,$$

where  $\mathcal{T}_p^{(k,l)} M$  is the space of all  $(k, l)$ -tensors on  $T_p M$ . A tensor field  $T$  is a smooth map

$$\begin{aligned} T: M &\rightarrow \mathcal{T}^{(k,l)} M \\ p &\mapsto T_p \in \mathcal{T}_p^{(k,l)} M. \end{aligned}$$

Let  $(x^1, \dots, x^n)$  be a local coordinate, then

$$T = T^{i_1 \dots i_k}_{j_1 \dots j_l} \frac{\partial}{\partial x^{i_1}} \otimes \dots \otimes \frac{\partial}{\partial x^{i_k}} \otimes dx^{j_1} \otimes \dots \otimes dx^{j_l}.$$

!  $T(\alpha^1, \dots, \alpha^k; X_1, \dots, X_l)$  is  $C^\infty$ -linear in each variable  $\alpha^i$  and  $X_j$ .

### 3.3 Induced Riemannian metric

- Let  $(M, g)$  be a Riemannian manifold. Let  $p \in M$ , and around  $p$  we have a local coordinate  $(x^1, \dots, x^n)$
- $T_p M = \text{span} \left\{ \frac{\partial}{\partial x^1}, \dots, \frac{\partial}{\partial x^n} \right\}$ ,  $T_p^* M = \text{span} \{dx^1, \dots, dx^n\}$ . Moreover,

$$dx^i \left( \frac{\partial}{\partial x^j} \right) = \delta_j^i.$$

---

<sup>4</sup>Tensor is ordered!



- The Riemannian metric at  $p$  is

$$g_p: T_p M \times T_p M \rightarrow \mathbb{R}$$

$$(V, W) \mapsto g_p(V, W)$$

For a non-zero vector  $V \in T_p M$ , this induces a linear map

$$\varphi_V: T_p M \rightarrow \mathbb{R}$$

$$W \mapsto \varphi_V(W)$$

i.e.  $\varphi_V \in T_p^* M = \{\text{all linear functionals on } T_p M\}$ . In particular, let  $V = \frac{\partial}{\partial x^i}$ ,  $\forall W = \frac{\partial}{\partial x^j}$

$$\varphi_{\frac{\partial}{\partial x^i}} \left( \frac{\partial}{\partial x^j} \right) = g \left( \frac{\partial}{\partial x^i}, \frac{\partial}{\partial x^j} \right) = g_{ij}.$$

Hence, as an element in  $T_p^* M$ , we can write

$$\varphi_{\frac{\partial}{\partial x^i}} = g_{ij} dx^j.$$

- Discussions above says that we have a linear isomorphism

$$\varphi: T_p M \rightarrow T_p^* M$$

$$V \mapsto \varphi_V$$

- Let  $\psi: T_p^* M \rightarrow T_p M$  be the inverse of  $\varphi$ , then

$$T_p M \xrightarrow{\varphi} T_p^* M \xrightarrow{\psi} T_p M$$

$$\frac{\partial}{\partial x^i} \mapsto g_{ij} dx^j \mapsto \frac{\partial}{\partial x^i}$$

$$\text{i.e. } \psi(g_{ij} dx^j) = g_{ij} \psi(dx^j) = \frac{\partial}{\partial x^i} \Rightarrow \psi(dx^j) = \underbrace{g^{ij}}_{\text{inverse of } (g_{ij})} \frac{\partial}{\partial x^i}.$$

Moreover, for any covector  $\alpha = \alpha_j dx^j$

$$\psi(\alpha_j dx^j) = \alpha_j g^{ij} \frac{\partial}{\partial x^i}$$

### Definition 3.3.1. (1)

$$\varphi: T_p M \rightarrow T_p^* M$$

$$v \mapsto \varphi(v) = (v^i g_{ij}) dx^j$$

is called index-lowered down, usually denoted by  $\varphi(v) = v_b$ .<sup>5</sup>

---

<sup>5</sup>flat for “flat” in music.

(2)

$$\psi: T_p^*M \rightarrow T_p M$$

$$\alpha \mapsto \psi(\alpha) = (\alpha_i g^{ij}) \frac{\partial}{\partial x^j}$$

is called index-lifted up, denoted by  $\psi(\alpha) = \alpha^\sharp$ .<sup>6</sup>

- The linear isomorphism  $\sharp$  enables us to extend the Riemannian metric on  $T^*M$ , i.e.  $\forall p \in M$

$$\begin{aligned} \tilde{g}: T_p^*M \times T_p^*M &\rightarrow \mathbb{R} \\ (\alpha, \beta) &\mapsto \tilde{g}(\alpha, \beta) \end{aligned}$$

such that

$$\tilde{g}(\alpha, \beta) := g(\alpha^\sharp, \beta^\sharp).$$

In local coordinate,  $\alpha = \alpha_i dx^i, \beta = \beta_j dx^j$

$$\begin{aligned} \tilde{g}(\alpha, \beta) &= g\left(\alpha_i g^{ik} \frac{\partial}{\partial x^k}, \beta_j g^{jl} \frac{\partial}{\partial x^l}\right) = \alpha_i g^{ik} \beta_j g^{jl} g\left(\frac{\partial}{\partial x^k}, \frac{\partial}{\partial x^l}\right) \\ &= \alpha_i g^{ik} \underbrace{\beta_j g^{jl}}_{\delta_k^j} g_{kl} = \alpha_i \beta_j g^{ij}. \end{aligned}$$

i.e.  $\tilde{g}(\alpha, \beta) = g^{ij} \alpha_i \beta_j$ . In particular,  $\tilde{g}(dx^i, dx^j) = g^{ij}$ .

In general, we can extend the Riemannian metric to any tensor of the same type, i.e.  $\forall S, T$  are two  $p, q$  tensors, locally

$$S = S_{j_1 \dots j_q}^{i_1 \dots i_p} \frac{\partial}{\partial x^{i_1}} \otimes \dots \otimes \frac{\partial}{\partial x^{i_p}} \otimes dx^{j_1} \otimes \dots \otimes dx^{j_q}.$$

$$T = T_{j_1 \dots j_q}^{i_1 \dots i_p} \frac{\partial}{\partial x^{i_1}} \otimes \dots \otimes \frac{\partial}{\partial x^{i_p}} \otimes dx^{j_1} \otimes \dots \otimes dx^{j_q}.$$

Then  $\tilde{g}(S, T) := S_{j_1 \dots j_q}^{i_1 \dots i_p} T_{l_1 \dots l_q}^{k_1 \dots k_p} g_{i_1 k_1} g_{i_2 k_2} \dots g_{i_p k_p} g^{j_1 l_1} \dots g^{j_q l_q}$ .

**Example 3.3.2.** (1) If  $S = S_{ij} dx^i \otimes dx^j$ ,  $T = T_{pq} dx^p \otimes dx^q$ , then

$$\tilde{g}(S, T) = S_{ij} T_{pq} g^{ip} g^{jq}.$$

(2)  $\nabla f = df = f_i dx^i$ ,  $\text{grad } f = g^{ij} f_j \frac{\partial}{\partial x^i}$ .

$$\Rightarrow \begin{cases} |\nabla f|^2 = g(f_i dx^i, f_j dx^j) = g^{ij} f_i f_j, \\ |\text{grad } f|^2 = g^{ij} f_j g^{kl} f_l g_{ik} = g^{ij} f_i f_j. \end{cases} \Rightarrow |\nabla f|^2 = |\text{grad } f|^2.$$

(3) From (1),  $\text{Hess } f = \nabla_i \nabla_j f dx^i \otimes dx^j$ ,<sup>7</sup>

$$\Rightarrow |\text{Hess } f|^2 = g^{ik} g^{jl} \nabla_i \nabla_j f \nabla_k \nabla_l f.$$

---

<sup>6</sup>  $\sharp$  for “sharp” in music

<sup>7</sup> Recall that  $\nabla_i \nabla_j f = \frac{\partial^2 f}{\partial x^i \partial x^j} - \Gamma_{ij}^k \frac{\partial f}{\partial x^k}$ .

## 3.4 Bochner formula in 2-dimensional Riemannian manifold

**Theorem 3.4.1.** Let  $(S, g)$  be a 2-dimensional Riemannian manifold,  $f \in C^3(S)$ , then

$$\frac{1}{2}\Delta|\nabla f|^2 = |\nabla\nabla f|^2 + \langle \nabla(\Delta f), \nabla f \rangle + K|\nabla f|^2.$$

*Remark.* (1) In your homework, you have shown that on the Euclidean space

$$\frac{1}{2}\Delta|\nabla f|^2 = |\nabla\nabla f|^2 + \langle \nabla(\Delta f), \nabla f \rangle.$$

(2) On a general Riemannian manifold, the Bochner formula is

$$\frac{1}{2}\Delta|\nabla f|^2 = |\nabla\nabla f|^2 + \langle \nabla(\Delta f), \nabla f \rangle + \text{Ric}(\nabla f, \nabla f).$$

*Proof.*

$$\begin{aligned} \Delta|\nabla f|^2 &= g^{ij}\nabla_i\nabla_j\left(g^{kl}\nabla_kf\nabla_lf\right) \\ &= g^{ij}g^{kl}\left(\nabla_i\nabla_j\nabla_kf\nabla_lf + \nabla_i\nabla_j\nabla_lf\nabla_kf + \nabla_i\nabla_lf\nabla_j\nabla_kf + \nabla_i\nabla_kf\nabla_j\nabla_lf\right) \\ &= 2g^{ij}g^{kl}\nabla_i\nabla_j\nabla_kf\nabla_lf + 2g^{ij}g^{kl}\nabla_i\nabla_kf\nabla_j\nabla_lf \\ &= 2|\nabla\nabla f|^2 + 2g^{ij}g^{kl}\nabla_i\nabla_kf\nabla_j\nabla_lf. \end{aligned}$$

To further compute R.H.S., we take geodesic polar coordinate

$$ds^2 = dr^2 + G(r, \theta)d\theta^2 \Rightarrow g^{-1} = \begin{pmatrix} 1 & 0 \\ 0 & \frac{1}{G} \end{pmatrix}.$$

$$\begin{aligned} g^{ij}g^{kl}\nabla_i\nabla_k\nabla_jf \cdot \nabla_lf &= g^{kl}\nabla_i\nabla_k\nabla^i f \nabla_lf \\ &= \nabla_i\nabla_1\nabla^i f \cdot \nabla_1f + \frac{1}{G}\nabla_i\nabla_2\nabla^i f \nabla_2f \\ &= \nabla_1\nabla_1\nabla^1 f \cdot \nabla_1f + \nabla_2\nabla_1\nabla^2 f \cdot \nabla_1f + \frac{1}{G}(\nabla_1\nabla_2\nabla^1 f \nabla_2f + \nabla_2\nabla_2\nabla^2 f \nabla_2f) \end{aligned}$$

(1)

$$\begin{aligned} \nabla_2\nabla_1(\nabla^2 f) \cdot \nabla_1f &= \nabla_1\nabla_2(\nabla^2 f) \cdot + R_{21}{}^2{}_i \nabla^i f \nabla_1f \\ &= \nabla_1\nabla_2(\nabla^2 f) \cdot \nabla_1f + R_{212i}g^{22}\nabla^i f \nabla_1f \\ &= \nabla_1\nabla_2\nabla^2 f \cdot \nabla_1f + R_{2121}\frac{1}{G}\nabla^1 f \nabla_1f. \end{aligned}$$

(2)

$$\begin{aligned}\nabla_1 \nabla_2 \nabla^1 f \cdot \nabla_2 f &= \nabla_2 \nabla_1 \nabla^1 f \cdot \nabla_2 f + R_{12}{}^1{}_i \nabla^i f \nabla_2 f \\ &= \nabla_2 \nabla_1 \nabla^1 f \cdot \nabla_2 f + R_{1212} \nabla^2 f \nabla_2 f.\end{aligned}$$

Note that  $R_{1212} = R_{2121}$  and  $K = \frac{R_{1212}}{G}$ .

$$\begin{aligned}&g^{kl} \nabla_i \nabla_k \nabla^i f \cdot \nabla_l f \\ &= \underbrace{\nabla_1 \nabla_1 \nabla^1 f \nabla_1 f}_{(1)} + \underbrace{\nabla_1 \nabla_2 \nabla^2 f \nabla_1 f}_{(2)} + K \nabla^1 f \nabla_1 f \\ &\quad + \underbrace{\frac{1}{G} (\nabla_2 \nabla_1 \nabla^1 f \nabla_2 f + \nabla_2 \nabla_2 \nabla^2 f \nabla_2 f)}_{(1)} + \underbrace{K \nabla^2 f \nabla_2 f}_{(2)} \\ &= \nabla_1 (\Delta f) \nabla_1 f + \frac{1}{G} (\nabla_2 (\Delta f) \nabla_2 f) + K |\nabla f|^2 \\ &= \langle \nabla(\Delta f), \nabla f \rangle + K |\nabla f|^2.\end{aligned}$$

Hence,  $\frac{1}{2} \Delta |\nabla f|^2 = |\nabla \nabla f|^2 + \langle \nabla(\Delta f), \nabla f \rangle + K |\nabla f|^2$ .  $\square$

To obtain interesting geometry results, it (Bochner formula) needs to combine with analysis tools, one of such tools is the following maximum principle.

**Theorem 3.4.2** (Hopf-Calabi: Maximum principle).

- $(M, g)$  is a connected Riemannian manifold.
- $f: M \rightarrow \mathbb{R}$ :  $C^\infty$  subharmonic function, i.e.  $\Delta_g f \geq 0$ .

$\Rightarrow f$  attains no maximum unless it's constant.

The proof is based on the standard maximum principle in the P.D.E. theory. We'll show, if  $f$  attains maximum at  $p \in M$ , then  $f$  must be a constant. (Again, we'll consider the  $\dim M = 2$  case in the following, and in higher dimension arguments are similar.)

**Step 1** (Strong version) If  $\Delta f > 0$ , then  $f$  has no local maximum.

*Proof.* If  $f$  attains local max at  $p \in M$ , then  $\nabla f(p) = 0$  and  $\nabla \nabla f \leq 0 \Rightarrow \Delta f(p) \leq 0$ .  $\square$

**Step 2** (Weak version) If  $\Delta f \geq 0$ , and  $f$  attains global maximum at  $p$ , then  $f$  is constant.

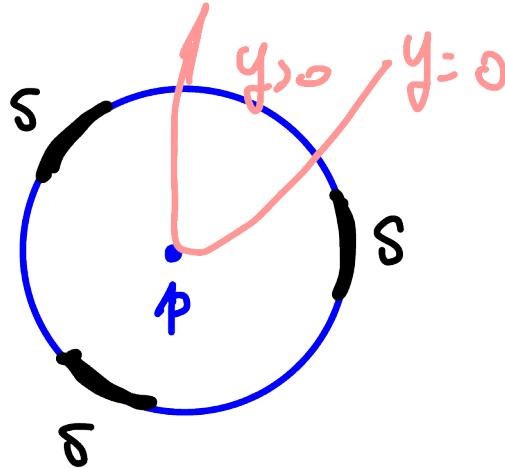
*Proof.* (By perturbation method) If  $f$  attains global maximum at  $p$ , then  $p$  is also a local maximum of  $f$ . Assume  $f$  is not a constant in any neighborhood of  $p$ , then we may choose a sufficient small coordinate ball (geodesic ball)  $B$  of  $p$  such that

$$S = \{x \in \partial B \mid f(x) \geq f(p) - 1\}^8$$

(You can choose 1 here after replacing  $f$  by some  $\lambda f$ ) is a proper subset of  $\partial B$  (i.e. there must be some  $\bar{q} \in \partial B$ ,  $f(\bar{q}) < f(p)$ ).

---

<sup>8</sup>This is modified slightly by the TA.



By a suitable choice of coordinate  $(x, y)$ , we can further assume  $p$  lies on  $y = 0$  and  $S$  lies on  $\{y < 0\}$ . Consider coordinate  $y(q)$  for  $\forall q \in B_p(r)$ , then  $y$  is a smooth function on  $\bar{B}$ .

Note that

- (1)  $y(p) = 0$ , and  $y < 0$  on  $S$ .
- (2)  $|\nabla y|^2 = |g^{22}| \neq 0$  (By positive-definiteness).
- (3)  $|\Delta y| = |g^{ij}\Gamma_{ij}^2| \leq A$  for some constant  $A > 0$ .

Let  $h = e^{cy} - 1$  for  $c \gg 1$ , then

- (1)  $h(p) = 0$ .
- (2)  $\Delta h = ce^{cy} (c|\nabla y|^2) + \Delta y$ . Note that  $|\Delta y| \leq A$ ,  $|\nabla y| \neq 0$ , we can choose  $c$  sufficiently large such that

$$\Delta h > 0 \text{ on } \bar{B}.$$

- (3)  $h < 0$  on  $S$ .

Now consider a perturbation of  $f$

$$f_\epsilon = f + \epsilon h, 0 < \epsilon \ll 1.$$

Then

- (1)  $f_\epsilon(p) = f(p) + \epsilon h(p) = f(p)$ .
- (2)  $\Delta f_\epsilon = \Delta f + \epsilon \Delta h > 0$  on  $\bar{B}$ .
- (3)  $f_\epsilon$  must attain maximum inside  $B$ . Since  $\forall x \in \partial B$ , if  $x$  lies in  $S = \{x | f(x) \geq f(p) - 1\}$ , note that  $p$  is a local maximum, and  $S \subset \{y < 0\}$ , then

$$f_\epsilon < f_\epsilon(p) \text{ on } S.$$

If  $x \in \partial B - S$ , i.e.  $f(x) < f(p) - 1$ , take  $\epsilon$  sufficiently small such that  $|\epsilon h(x)| < 1$  on  $\partial B$ , then one has

$$f_\epsilon(x) < f_\epsilon(p) \text{ on } \partial B - S.$$

This contradicts the strong maximum principle.

□

**Exercise** (Maximum principle in 1-dimensional calculus). *Show that*

- (1)  $x \in \mathbb{R}$ ,  $f''(x) > 0$ , then  $f$  has no upper bound.
- (2)  $x \in \mathbb{R}$ ,  $f''(x) \geq 0$ , if  $\exists x_0 \in \mathbb{R}$  such that  $f(x_0) = A = \max f(x)$ , then  $f(x) = A$  for all  $x \in \mathbb{R}$ .

### 3.5 Induced covariant derivative on tensor fields

Let  $\nabla$  be the LeviCivita connection on  $(M, g)$ , then for  $\forall$  vector field  $X \in \Gamma(TM)$ , the covariant derivative  $\nabla_X$  is

$$\nabla_X : \Gamma(TM) \rightarrow \Gamma(TM)$$

$$Y \mapsto \nabla_X Y$$

and locally

$$\nabla_{\frac{\partial}{\partial x^i}} \frac{\partial}{\partial x^j} = \Gamma_{ij}^k \frac{\partial}{\partial x^k}.$$

Since  $T^*M$  is the dual bundle of  $TM$ , we can extend  $\nabla_X$  on  $T^*M$  as

$$\nabla_X : \Gamma(T^*M) \rightarrow \Gamma(T^*M)$$

$$\omega \mapsto \nabla_X \omega$$

such that  $\forall Y \in \Gamma(TM)$

$$(\nabla_X \omega)(Y) = \nabla_X (\omega(Y)) - \omega(\nabla_X Y).$$

Locally,  $\Gamma(T^*M) = \text{span}\{dx^1, \dots, dx^n\}$

$$\begin{aligned} \left( \nabla_{\frac{\partial}{\partial x^i}} dx^j \right) \left( \frac{\partial}{\partial x^k} \right) &= \nabla_{\frac{\partial}{\partial x^i}} \left( dx^j \left( \frac{\partial}{\partial x^k} \right) \right) - dx^j \left( \nabla_{\frac{\partial}{\partial x^i}} \frac{\partial}{\partial x^k} \right) \\ &= -dx^j \left( \Gamma_{ik}^p \frac{\partial}{\partial x^p} \right) \\ &= -\Gamma_{ik}^j. \end{aligned}$$

$\Rightarrow \boxed{\nabla_{\frac{\partial}{\partial x^i}} dx^j = -\Gamma_{ik}^j dx^k}$ . Now, let  $T$  be a  $p, q$ -tensor

$$T = T^{i_1 \dots i_p}_{j_1 \dots j_q} \frac{\partial}{\partial x^{i_1}} \otimes \dots \otimes \frac{\partial}{\partial x^{i_p}} \otimes dx^{j_1} \otimes \dots \otimes dx^{j_q}.$$

Then

$$\begin{aligned}
 \nabla_k T &= \nabla_k \left( T_{j_1 \dots j_q}^{i_1 \dots i_p} \frac{\partial}{\partial x^{i_1}} \otimes \dots \otimes \frac{\partial}{\partial x^{i_p}} \otimes dx^{j_1} \otimes \dots \otimes dx^{j_q} \right) \\
 &= \partial_k T_{j_1 \dots j_q}^{i_1 \dots i_p} \frac{\partial}{\partial x^{i_1}} \otimes \dots \otimes \frac{\partial}{\partial x^{i_p}} \otimes dx^{j_1} \otimes \dots \otimes dx^{j_q} \\
 &\quad + \sum_{\alpha=1}^p T_{j_1 \dots j_q}^{i_1 \dots i_\alpha \dots i_p} \frac{\partial}{\partial x^{i_1}} \otimes \dots \otimes \nabla_k \left( \frac{\partial}{\partial x_\alpha^{i_\alpha}} \right) \otimes \dots \otimes \frac{\partial}{\partial x^{i_p}} \otimes dx^{j_1} \otimes \dots \otimes dx^{j_q} \\
 &\quad + \sum_{\beta=1}^q T_{j_1 \dots j_\beta \dots j_q}^{i_1 \dots i_p} \frac{\partial}{\partial x^{i_1}} \otimes \dots \otimes \frac{\partial}{\partial x^{i_p}} \otimes dx^{j_1} \otimes \dots \otimes \nabla_k \left( dx^{j_\beta} \right) \otimes \dots \otimes dx^{j_q} \\
 &= \partial_k T_{j_1 \dots j_q}^{i_1 \dots i_p} \frac{\partial}{\partial x^{i_1}} \otimes \dots \otimes \frac{\partial}{\partial x^{i_p}} \otimes dx^{j_1} \otimes \dots \otimes dx^{j_q} \\
 &\quad + \sum_{\alpha=1}^p T_{j_1 \dots j_q}^{i_1 \dots \gamma \dots i_p} \Gamma_{k\gamma}^{i_\alpha} \frac{\partial}{\partial x^{i_1}} \otimes \dots \otimes \frac{\partial}{\partial x^{i_p}} \otimes dx^{j_1} \otimes \dots \otimes dx^{j_q} \\
 &\quad - \sum_{\beta=1}^q T_{j_1 \dots \theta \dots j_q}^{i_1 \dots i_p} \Gamma_{kj_\beta}^\theta \frac{\partial}{\partial x^{i_1}} \otimes \dots \otimes \frac{\partial}{\partial x^{i_p}} \otimes dx^{j_1} \otimes \dots \otimes dx^{j_q}.
 \end{aligned}$$

$$\therefore \nabla_k T = \left( \partial_k T_{j_1 \dots j_q}^{i_1 \dots i_p} + \sum_{\alpha=1}^p T_{j_1 \dots j_q}^{i_1 \dots \gamma \dots i_p} \Gamma_{k\gamma}^{i_\alpha} \right. \\
 \left. - \sum_{\beta=1}^q T_{j_1 \dots \theta \dots j_q}^{i_1 \dots i_p} \Gamma_{kj_\beta}^\theta \right) \frac{\partial}{\partial x^{i_1}} \otimes \dots \otimes \frac{\partial}{\partial x^{i_p}} \otimes dx^{j_1} \otimes \dots \otimes dx^{j_q},$$

or

$$\nabla_k T_{j_1 \dots j_q}^{i_1 \dots i_p} = \partial_k T_{j_1 \dots j_q}^{i_1 \dots i_p} + \sum_{\alpha=1}^p T_{j_1 \dots j_q}^{i_1 \dots \gamma \dots i_p} \Gamma_{k\gamma}^{i_\alpha} - \sum_{\beta=1}^q T_{j_1 \dots \theta \dots j_q}^{i_1 \dots i_p} \Gamma_{kj_\beta}^\theta$$