

Geometry of Curves and Surfaces*

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1 Introduction

The study of the geometry of curves and surfaces involves three main components.

1.1 Curves

A curve is a smooth map $\gamma : [a, b] \rightarrow \mathbb{R}^n$, here we consider when $n \in \{2, 3\}$, where $\gamma'(t) \neq 0$ for $t \in [a, b]$. With curves in \mathbb{R}^2 referred to as planar curves and curves in \mathbb{R}^3 referred to as space curves.

Exercise 1.1.1. Why do we need $\gamma'(t) \neq 0$ for $t \in [a, b]$.

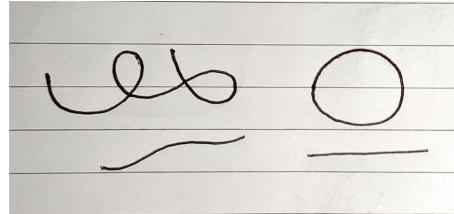
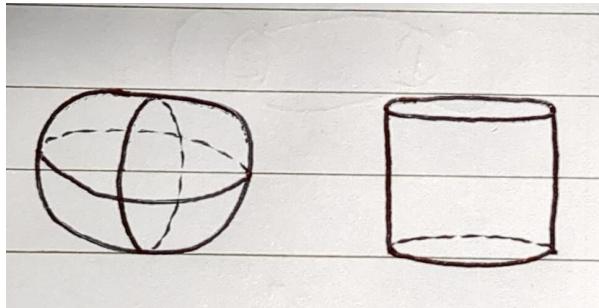


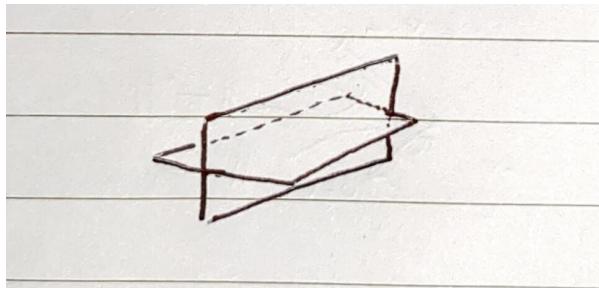
Figure 1.1.1: Examples of curves.

1.2 Surface

A subset $S \subseteq \mathbb{R}^3$ is a surface if locally it looks like \mathbb{R}^2 .



(a) The surface on the left is the surface of a 3-dimensional sphere. When the sphere has radius one this surface is denoted S^2 . The surface on the right is the surface of a cylinder. When the cylinder has radius r this surface is denoted C_r .



(b) These intersecting planes provide an example of something that is not a surface.

Figure 1.2.1: Examples and non-examples of surfaces.

1.3 Geometry

Geometry is the study of geometric notions such as lengths, angles, area, volumes and so forth. Whereas topology is the study of shapes where these geometric notions are not present. In geometry, a map between geometrical

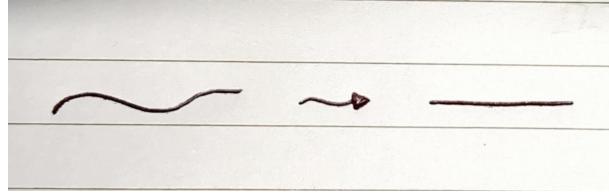


Figure 1.4.2: The extrinsic curvature of a planar curve.

objects that preserves these geometric notions is known as an isometry.

1.4 Curvature

A recurring focus of study is curvature of which there are different types, namely intrinsic and extrinsic curvature. Roughly speaking, an intrinsic property is preserved under isometries, whereas an extrinsic property is dependent on the context.

Example 1.4.1.

1. A cylinder is not intrinsically curved. One can cut down a side of a cylinder and roll it out flat whilst preserving geometric notions on the surface such as lengths, angles and areas. The process of transforming the cylinder into a plane is an example of an isometry.
2. A sphere has intrinsic curvature as no isometry removes its curvature. That is, it cannot be flattened without disturbing geometric properties such as length, angles and areas on the surface.

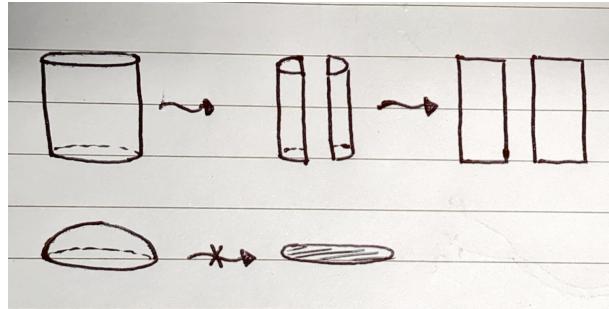


Figure 1.4.1: The extrinsic curvature of a cylinder and the intrinsic curvature of a sphere in terms of the existence of isometries.

Intrinsic curvature is absent when speaking about planar curves, every planar curve is intrinsically flat, Figure 1.4.2. Given a curve, we can stretch it out to a flat line. However, curves can exhibit extrinsic curvature. Intuitively, extrinsic planar curvature should say that a straight line has zero curvature, whereas a circle should have a non-zero constant curvature. More generally, a circle of radius r_1 should have more curvature than a circle of radius r_2 when $r_1 < r_2$. For example, we can define the curvature of a circle of radius r to be $\frac{1}{r}$, with a straight line being thought of as a circle with infinite radius. Using the idea that general planar curves can be approximated by circles, even of infinite radius, leads to the following definition of the curvature of a planar curve.

Definition 1.4.2 (Informal). A planar curve $\gamma : [a, b] \rightarrow \mathbb{R}^2$ has curvature $\kappa_\gamma : [a, b] \rightarrow \mathbb{R}$ where $\kappa_\gamma(p)$ is given by the curvature of the circle which best approximates γ at p .

Remark 1.4.3.

1. The curvature of a planar curve γ at a point p can be thought of as the failure of γ to be a straight line.
2. For space curves, we have an additional geometrical notion referred to as torsion, which can be thought of as the failure of the curve to lie in a plane.

The curvature of a surface is more nuanced. Let $S \subseteq \mathbb{R}^3$ be a surface with $p \in S$ and \mathbf{n} the normal to S at p . We can then consider the plane containing the normal and p . The intersection of this plane with S produces a curve for which we can talk about curvature. Therefore, with this perspective, we are considering an extrinsic curvature.

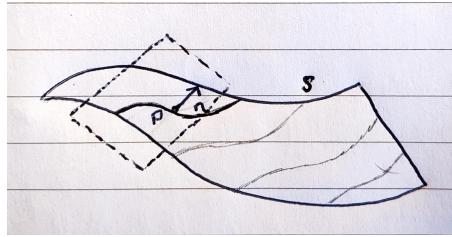


Figure 1.4.3: The curvature of the surface using an intersecting plane.

The principal curvature of $\kappa_1(p)$ and $\kappa_2(p)$ of S at p are the minimum and maximum values of the curvature of the intersecting curves between S and the planes that pass through p .

Example 1.4.4.

1. For the surface S^2 we have $\kappa_1(p) = \kappa_2(p) = 1$ for all $p \in S^2$.
2. For the surface C_r we have $\kappa_1(p) = 0$ and $\kappa_2(p) = \frac{1}{r}$ for all $p \in C_r$.

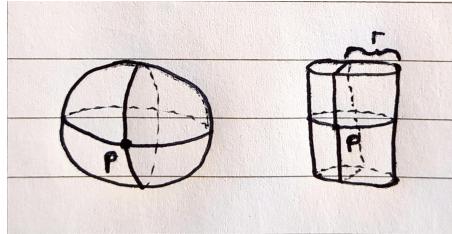


Figure 1.4.4: The intersecting planes resulting the principal components on S^2 , left, and C_r , right.

Theorem 1.4.5 (Gauss Theorema Egregium). *Let $S \subseteq \mathbb{R}^3$, the quantity $K(p) = \kappa_1(p)\kappa_2(p)$ is an intrinsic property of the surface S .*

Remark 1.4.6. *The function $K_S : S \rightarrow \mathbb{R}$ referred to in Theorem 1.4.5 is known as the Gauss curvature of S .*

Example 1.4.7.

1. For S^2 we have $K_{S^2} \equiv 1$.
2. For C_r we have $K_{C_r} \equiv 0$.

Corollary 1.4.8. *The surface S^2 is not isometric to the plane.*

Proof. As C_r is isometric to the plane by Theorem 1.4.5 it follows that $K_P \equiv 0$, where P is a plane. Therefore, $K_P \neq K_{S^2}$ and so S^2 is not isometric to P by Theorem 1.4.5. \square

1.5 Geodesics

Geodesics are curves in a surface S that are as straight as possible. For example, on the cylinder, a geodesic should have the property that under an isometry to the plane they map to straight lines. On S^2 , all geodesics are great circles, which are circles on a plane which passes through the origin.

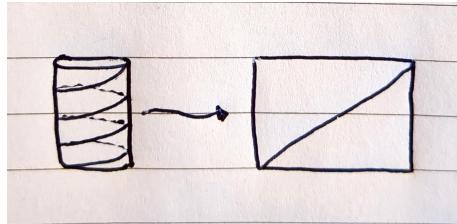


Figure 1.5.1: An illustration of how the geodesic of a cylinder transforms into a straight line under the cut and roll isometry discussed previously.

1.6 Geometry and Topology

Questions between geometry and topology arise naturally and are important in many applications such as solving partial differential equations. For example, a question one may ask is whether we can embed S^2 , as a topological space, into \mathbb{R}^3 such that the Gauss curvature of the resulting surface is non-positive. Similarly, one may ask if there is an embedding of S^2 into \mathbb{R}^3 which contains non-intersecting geodesics.

Theorem 1.6.1 (Gauss-Bonnet). *Let $S \subseteq \mathbb{R}^3$ be a compact orientable surface. Then*

$$\int_S K dA_S = 2\pi\chi(S),$$

where $\chi(S)$ is the Euler characteristic of S as a topological surface.

Example 1.6.2. *For S^2 we have $\chi(S^2) = 2$. Therefore,*

$$\int_{S^2} K dS^2 = 4\pi > 0.$$

Therefore, S^2 cannot be embedded into \mathbb{R}^3 such that $K \leq 0$.

1.7 Solution to Exercises

Exercise 1.1.1

Solution. Ensuring $\gamma'(t) \neq 0$ for all $t \in [a, b]$ means that the tangent at any point along the curve is well-defined. More specifically, for a curve $\gamma : [a, b] \rightarrow \mathbb{R}^n$, the tangent to the curve at the point $\gamma(t_0)$ is $\varphi : \mathbb{R} \rightarrow \mathbb{R}^n$ where

$$s \mapsto \gamma(t_0) + s\gamma'(t_0).$$

\square

2 Curves

2.1 Regular Curves

The map $\langle \cdot, \cdot \rangle : \mathbb{R}^n \times \mathbb{R}^n \rightarrow \mathbb{R}$ will be the Euclidean dot product, that is

$$\langle x, y \rangle = \sum_{i=1}^n x_i y_i.$$

The Euclidean norm will thus be

$$|x| = \sqrt{\langle x, x \rangle} = \sqrt{\sum_{i=1}^n x_i^2},$$

which provides a notion of length for \mathbb{R}^n .

Definition 2.1.1. A parameterised curve in \mathbb{R}^n is a smooth map $\gamma : I \rightarrow \mathbb{R}^n$, where $I \subseteq \mathbb{R}$ is an interval. Moreover, γ is regular if $|\gamma'(t)| \neq 0$ for all $t \in I$.

Remark 2.1.2.

1. Here we will only be concerned with $n = 2$ and $n = 3$, which we refer to as a planar curve and a space curve respectively.
2. Note that a curve can either refer to a regular parameterisation $\gamma : I \rightarrow \mathbb{R}^n$ or the image of a regular parameterisation, namely $\gamma([a, b]) \subset \mathbb{R}^n$. The former interpretation is akin to thinking of the curve as the trajectory of a particle that is always in motion. Whilst the latter is a subset of \mathbb{R}^n whose properties such as length we will be interested in.

Example 2.1.3.

1. A straight line segment given by $\gamma_1 : [0, 1] \rightarrow \mathbb{R}^2$ where $\gamma_1(t) = (2t - 1, 3t + 2)$.
2. A circle with radius $r > 0$ given by $\gamma_2 : [0, 2\pi] \rightarrow \mathbb{R}^2$ where $\gamma_2(t) = (r \cos(t), r \sin(t))$.
3. A helix given by $\gamma_3 : [0, 6\pi] \rightarrow \mathbb{R}^3$ where $\gamma_3(t) = (\cos(t), \sin(t), t)$.
4. Curves can be self-intersecting, $\gamma_4 : \mathbb{R} \rightarrow \mathbb{R}^2$ where $\gamma_4(t) = (t^3 - 4t, t^2 - 4)$.
5. The Folium of Descartes is the curve $\gamma_5 : (-1, \infty) \rightarrow \mathbb{R}^2$ where $\gamma_5(t) = \left(\frac{3t}{1+t^3}, \frac{3t^2}{1+t^3} \right)$. This curve is injective but not homeomorphic to its image.
6. We make the distinction between regular and non-regular curves as regular curves have well-defined tangents at each point whereas non-regular curves do not. The curve $\gamma_6 : \mathbb{R} \rightarrow \mathbb{R}^2$ given by $\gamma_6(t) = (t^3, t^2)$ is a parameterised curve but it is not regular as $\gamma_6'(0) = (0, 0)$. Note that $\gamma_6(\mathbb{R}) = \{(x, y) \in \mathbb{R}^2 : y = x^{\frac{2}{3}}\}$ has a cusp at the origin.

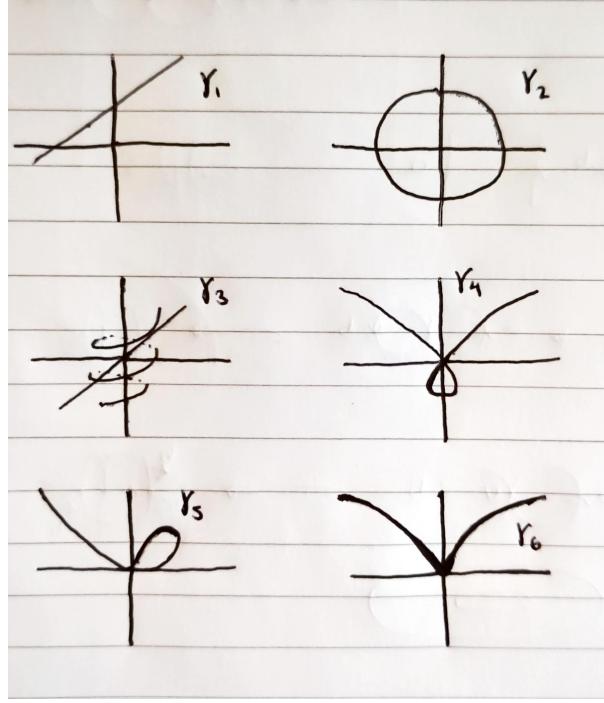


Figure 2.1.1: Illustrations of the curves stated in Example 2.1.3

Definition 2.1.4. Let γ represent a regular curve. Then the tangent line to ϕ at $\phi(t_0)$ is given by

$$\{\gamma(t_0) + \gamma'(t_0)s : s \in \mathbb{R}\}.$$

Example 2.1.5. Being smooth is not sufficient to ensure that a tangent line is well-defined. Consider $\alpha : (-1, 1) \rightarrow \mathbb{R}^3$ given by

$$\alpha(t) = \begin{cases} \left(\exp\left(-\frac{1}{t^2}\right), \exp\left(-\frac{1}{t^2}\right), 0\right) & t > 0 \\ (0, 0, 0) & t = 0 \\ \left(-\exp\left(-\frac{1}{t^2}\right), \exp\left(-\frac{1}{t^2}\right), 0\right) & t < 0. \end{cases}$$

Then α is smooth, however, the tangent line to α at $\alpha(0)$ is not well-defined at $\alpha'(0) = (0, 0, 0)$.

Definition 2.1.6. Let $J, I \subseteq \mathbb{R}$ be intervals. If $f : J \rightarrow I$ is a diffeomorphism, that is $f'(t) \neq 0$ for every $t \in J$, and $\gamma : I \rightarrow \mathbb{R}^n$ is a regular curve then $\gamma \circ f : J \rightarrow \mathbb{R}^n$ is a reparameterisation of γ .

Remark 2.1.7. It is clear that a reparameterisation as given in Definition 2.1.6 is a regular curve.

Most properties of interest are invariant under reparameterisation.

2.2 Length

Let $\gamma : [a, b] \rightarrow \mathbb{R}^n$ be a regular curve and consider the partition

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

Then the length of γ denoted $L(\gamma)$ is approximated by

$$L(\gamma) \approx \sum_{i=0}^{n-1} |\gamma(t_{i+1}) - \gamma(t_i)| \approx \sum_{i=0}^{n-1} |\gamma'(t_i)| |t_{i+1} - t_i|,$$

where the second approximation comes from the mean value theorem. The approximation becomes better as the partition becomes finer.

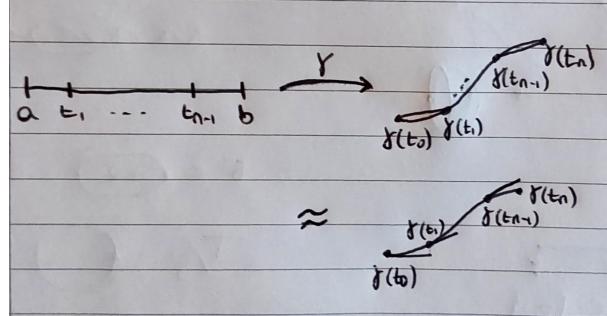


Figure 2.2.1: Approximating the length of a curve by using line segments between points of a partition.

Definition 2.2.1. The length of a regular curve $\gamma : [a, b] \rightarrow \mathbb{R}^n$ is given by

$$L(\gamma) = \int_a^b |\gamma'(t)| dt.$$

Example 2.2.2. Using Definition 2.2.1 we can find the length of a few of the curves from Example 2.1.3.

1. $L(\gamma_1) = \int_0^1 |(2, 3)| dt = \sqrt{13}.$
2. $L(\gamma_2) = \int_0^{2\pi} |(-r \sin(t), r \cos(t))| dt = \int_0^{2\pi} r dt = 2\pi r.$
3. $L(\gamma_3) = \int_0^{6\pi} |(-\sin(t), \cos(t), 1)| dt = 6\sqrt{2}\pi.$

Proposition 2.2.3. The length of a regular curve $\gamma : I \rightarrow \mathbb{R}^n$ is independent of the parameterisation. That is,

$$L(\gamma) = L(\gamma \circ f),$$

where f is a reparameterisation as given by Definition 2.1.6.

Proof. Let $\gamma : [a, b] \rightarrow \mathbb{R}^n$ be a regular curve, with $f : [c, d] \rightarrow [a, b]$ a smooth function such that $f'(s) \neq 0$ for all $s \in [c, d]$ and $f([c, d]) = [a, b]$. Then $\psi := \gamma \circ f : [c, d] \rightarrow \mathbb{R}^n$ is a reparameterisation of $\gamma([a, b])$. Since $f'(s) \neq 0$ for all $s \in [c, d]$ and f' is continuous on $[c, d]$ it follows that $f' > 0$ on $[c, d]$ or $f' < 0$ on $[c, d]$. Without loss of generality suppose that $f' > 0$ on $[c, d]$ such that $f(c) = a$ and $f(d) = b$. With $\gamma(t) = (x_1(t), \dots, x_n(t))$ we have

$$\begin{aligned} |\psi'(s)| &= |(\gamma \circ f)'(s)| \\ &= |((x_1 \circ f)'(s), \dots, (x_n \circ f)'(s))| \\ &= |(x'_1(f(s))f'(s), \dots, x'_n(f(s))f'(s))| \\ &= |f'(s)| |(x'_1(f(s)), \dots, x'_n(f(s)))| \\ &= |f'(s)| |\gamma'(f(s))|. \end{aligned}$$

Therefore,

$$\begin{aligned}
\ell(\psi([c, d])) &= \int_c^d |\psi'(s)| \, dt \\
&= \int_c^d f'(s) |\gamma'(f(s))| \, dt \\
&\stackrel{t=f(s)}{=} \int_{f(c)}^{f(d)} |\gamma'(t)| \, dt \\
&= \int_a^b |\gamma'(t)| \, dt \\
&= \ell(\gamma([a, b])).
\end{aligned}$$

□

Definition 2.2.4. A regular curve $\gamma : [a, b] \rightarrow \mathbb{R}^n$ is parameterised by arc length if $|\gamma'(t)| = 1$ for all $t \in (a, b)$.

Remark 2.2.5.

1. With the interpretation that a curve traces the trajectory of a non-stationary particle, the arc parameterisation ensures that the particle moves at a unit speed along the curve. Consequently, the arc length parameterisation is also referred to as the unit speed parameterisation.
2. Note that if a regular curve $\gamma : [a, b] \rightarrow \mathbb{R}^n$ is parameterised by arc length, the $L(\gamma) = b - a$.
3. The arc-length parameterisation of a regular curve is not unique. In particular, one can reverse the direction of an arc-length parameterisation and obtain a different arc-length parameterisation.

Proposition 2.2.6. Any regular curve $\gamma : [a, b] \rightarrow \mathbb{R}^n$ can be parameterised by arc length.

Proof. Let $\gamma : [a, b] \rightarrow \mathbb{R}^n$ be a regular curve. Let $h : [a, b] \rightarrow \mathbb{R}^n$ be given by

$$t \mapsto \int_a^t |\gamma'(u)| \, du + c.$$

As $\gamma'(u)$ exists and is continuous for all $u \in [a, b]$, the function h is well-defined with $h(a) = c$ and $h(b) = \ell(\gamma([a, b])) + c =: d$. Moreover,

$$h'(t) = |\gamma'(t)|, \tag{2.2.1}$$

which implies that h has a non-zero derivative at every point $t \in [a, b]$. In particular, this means that $h : [a, b] \rightarrow [c, d]$ has a well-defined inverse. Let $f : [c, d] \rightarrow [a, b]$ be the inverse of $h : [a, b] \rightarrow [c, d]$, which we note is smooth with a non-zero derivative. Thus we can consider the reparameterisation $\psi := \gamma \circ f : [c, d] \rightarrow \mathbb{R}^n$. As $h \circ f = \text{id}_{[c, d]}$ we have $h'(f(t))f'(t) = 1$, and as the derivatives are non-zero we deduce that

$$|f'(t)| = \frac{1}{|h'(f(t))|}. \tag{2.2.2}$$

Using (2.2.1) and (2.2.2) it follows that

$$|\psi'(t)| = |\gamma'(f(t))f'(t)| = |h'(f(t))| \frac{1}{|h'(f(t))|} = 1.$$

Therefore, ψ is an arc-length parameterisation of $\gamma : [a, b] \rightarrow \mathbb{R}^n$.

□

2.3 Curvature

Recall that regular curves are intrinsically flat, that is they are locally isometric to a straight line. Therefore, the curvature of a curve always refers to an extrinsic property.

Definition 2.3.1. Let $\gamma : [0, l] \rightarrow \mathbb{R}^n$ be a regular curve parameterised by arc length. The geodesic curvature of γ at $\gamma(t)$ is

$$k(t) := |\gamma''(t)|.$$

The curvature vector is given by $\mathbf{k}(t) = \gamma''(t)$.

Lemma 2.3.2. Geodesic curvature and curvature vector of a regular curve are independent of the arc length parameterisation of the curve.

Proof. Let γ be a regular curve parameterised by arc length. Let $\psi = \gamma \circ f$ be an arc length parameterisation of γ . Then

$$1 = |\psi'(t)| = |\gamma'(f(t))| |f'(t)| = |f'(t)|.$$

Thus,

$$f(t) = \pm t + c$$

for some constant c . Therefore, $\psi(t) = \gamma(\pm t + c)$ and so

$$\psi''(t) = \gamma''(t).$$

□

Example 2.3.3. Let $\gamma : [0, 2\pi] \rightarrow \mathbb{R}^2$ be given by

$$\gamma(t) = (R \cos(t), R \sin(t)).$$

Note that $|\gamma'(t)| = R$ and thus γ is not parameterised by arc length. Let

$$h(t) := \int_0^t |\gamma'(s)| \, ds = tR,$$

and so set

$$f(t) := \frac{t}{R}.$$

Then with

$$\psi(t) = \gamma \circ f(t) = \left(R \sin\left(\frac{t}{R}\right), R \cos\left(\frac{t}{R}\right) \right)$$

we note that $|\psi'(t)| = 1$, and so ψ is parameterised by arc length. Hence, we can write

$$\mathbf{k}(t) = \left(-\frac{1}{R} \cos\left(\frac{t}{R}\right), -\frac{1}{R} \sin\left(\frac{t}{R}\right) \right)$$

and $k(t) = \frac{1}{R}$. This corresponds to our osculating circle heuristic developed previously.

Proposition 2.3.4. Let $\gamma : I \rightarrow \mathbb{R}^n$ be a regular curve parameterised by arc length. Then $k(t) = 0$ for all $t \in I$ if and only if γ is a straight line.

Proof. Note that $k \equiv 0$ if and only if $\gamma'' \equiv 0$ which happens if and only if $\gamma = at + b$ for some $a, b \in \mathbb{R}^n$. □

Remark 2.3.5. The curve must be parameterised by arc length in Proposition 2.3.4. Consider $\gamma : [0, 1] \rightarrow \mathbb{R}^2$ given by $\gamma(t) = (0, e^t)$. Then $\gamma([0, 1])$ is a straight line, however,

$$\gamma''(t) = (0, e^t) \neq (0, 0).$$

Indeed,

$$|\gamma'(t)| = e^t,$$

which is not equal to one for all t .

Exercise 2.3.6. Let $\gamma : (a, b) \rightarrow \mathbb{R}^2$ be a regular curve parameterised by arc length, with $k_\gamma(t_0) > 0$ for some $t_0 \in (a, b)$. For $v \in \mathbb{R}^2$, let

$$C_v := \{p \in \mathbb{R}^2 : |p - v| = |\gamma(t_0) - v|\}$$

and $f_v : (a, b) \rightarrow \mathbb{R}^2$ be given by

$$f_v(t) = |\gamma(t) - v|^2.$$

1. Show that C_v is tangent to γ at t_0 if and only if $f'_v(t_0) = 0$.
2. Show that there exists a $v \in \mathbb{R}^2$ such that $f'_v(t_0) = f''_v(t_0) = 0$ with C_v having a radius of $\frac{1}{k_\gamma(t_0)}$.

Remark 2.3.7. Note that C_v from Exercise 2.3.6 is a circle that passes through $\gamma(t_0)$. Thus statement 2 of Exercise 2.3.6 says that the tangential circle that best approximates the curve γ at t_0 has radius $\frac{1}{k_\gamma(t_0)}$, which relates to our osculating circle heuristic developed previously.

Proposition 2.3.8. For any regular curve $\gamma : [a, b] \rightarrow \mathbb{R}^n$, for every $t \in [a, b]$, the curvature vector $\mathbf{k}(t)$ is perpendicular to the tangent vector $\gamma'(t)$ to the curve $\gamma([a, b])$ at $\gamma(t)$.

Proof. As γ is parameterised by arc length we have $\langle \gamma'(t), \gamma'(t) \rangle = 1$ for all $t \in [a, b]$, thus $\frac{d}{dt} \langle \gamma'(t), \gamma'(t) \rangle = 0$ for all $t \in [a, b]$. On the other hand,

$$\frac{d}{dt} \langle \gamma'(t), \gamma'(t) \rangle = \langle \gamma''(t), \gamma'(t) \rangle + \langle \gamma'(t), \gamma''(t) \rangle = 2 \langle \mathbf{k}(t), \gamma'(t) \rangle.$$

Therefore, $\langle \mathbf{k}(t), \gamma'(t) \rangle = 0$ for all $t \in [a, b]$ which means that $\mathbf{k}(t)$ is perpendicular to the tangent line of $\gamma([a, b])$ at $\gamma(t)$. \square

Remark 2.3.9.

1. For planar curves, the curvature vector can point in one of two directions whilst still being orthogonal to the tangent vector, Figure 2.3.1. The direction of the curvature vector points depends on the direction in which the arc length parameterisation is given.
2. Returning to the interpretation that a curve is the trajectory of a particle, we noted that with an arc length parameterisation, the particle travels at unit speed along this trajectory. Thus acceleration is only experienced in the centripetal direction, that is the direction orthogonal to its motion. Hence, the curvature gives the acceleration of the particle and thus can be thought of as being responsible for changing the direction of the curve.

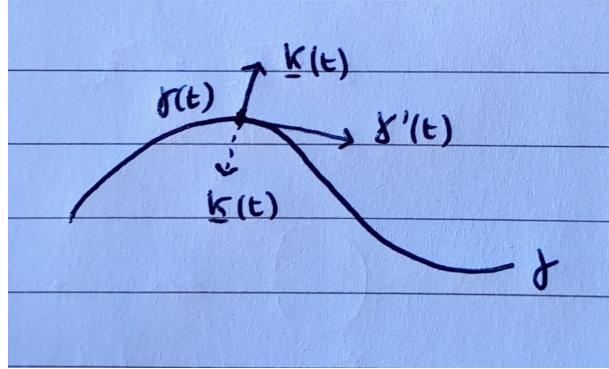


Figure 2.3.1: The tangent vector and curvature vector for a regular curve in \mathbb{R}^2 .

Proposition 2.3.10. Let $\gamma : [a, b] \rightarrow \mathbb{R}^3$ be a regular curve parameterised by arc length, and suppose that $|\gamma(t)|$ achieves its maximum value at some $t_0 \in (a, b)$. Then,

$$|k(t_0)| \geq \frac{1}{|\gamma(t_0)|}.$$

Proof. Consider the function $f : [a, b] \rightarrow \mathbb{R}$ given by

$$f(t) = \langle \gamma(t), \gamma(t) \rangle.$$

Then

$$f'(t) = 2 \langle \gamma(t), \gamma'(t) \rangle$$

and

$$\begin{aligned} f''(t) &= 2 \langle \gamma(t), \gamma''(t) \rangle + 2 \langle \gamma'(t), \gamma'(t) \rangle \\ &= 2 \langle \gamma(t), \gamma''(t) \rangle + 2 \end{aligned}$$

where the second equality follows as γ is parameterised by arc length. Then as $f(t_0)$ is a maximum, and t_0 is an interior point to (a, b) , it follows that $f''(t_0) \leq 0$. Thus,

$$2 \langle \gamma(t_0), \gamma''(t_0) \rangle + 2 \leq 0. \quad (2.3.1)$$

In particular, it must be the case that $\langle \gamma(t_0), \gamma''(t_0) \rangle < 0$, and so

$$\langle \gamma(t_0), \gamma''(t_0) \rangle = -|\langle \gamma(t_0), \gamma''(t_0) \rangle|.$$

Thus, (2.3.1) becomes

$$1 \leq |\langle \gamma(t_0), \gamma''(t_0) \rangle|.$$

Using the Cauchy-Schwartz inequality it follows that

$$1 \leq |\gamma(t_0)| |\gamma''(t_0)| = |\gamma(t_0)| |k(t_0)|.$$

Upon rearrangement we arrive at

$$|k(t_0)| \geq \frac{1}{|\gamma(t_0)|}.$$

□

2.4 Frenet Frames

Let $\gamma : [a, b] \rightarrow \mathbb{R}^3$ be a regular curve parameterised by arc length for which we suppose that $k_\gamma(t) \neq 0$ for every $t \in [a, b]$.

Definition 2.4.1. Let $\gamma : [a, b] \rightarrow \mathbb{R}^3$ be a regular curve parameterised by arc length for which $k_\gamma(t) \neq 0$ for every $t \in [a, b]$.

1. The unit tangent vector to γ at t is $T(t) := \gamma'(t)$.
2. The principal normal vector to γ at t is $N(t) := \frac{T'(t)}{|T'(t)|}$.
3. The binormal vector to γ at t is $B(t) := T(t) \times N(t)$.

The triple $(T(t), N(t), B(t))$ for $t \in [a, b]$ is a positively oriented orthonormal basis for \mathbb{R}^3 referred to as the Frenet frame for γ at t .

Remark 2.4.2.

1. Note that the principal normal vector of γ is well-defined as $T' \neq 0$ by the assumption on γ . Moreover, as $T'(t) = \mathbf{k}(t)$ by Proposition 2.3.8 the principal normal vector is indeed orthogonal to the tangent vector.
2. In 3-dimensions there are infinitely many normal directions to the tangent vector. The principal normal vector is chosen canonically such that $N(t)$ lies in the oscillating plane of γ at t . The oscillating plane is well-defined when γ is not a straight line and so that is why we require that $k_\gamma(t) \neq 0$.

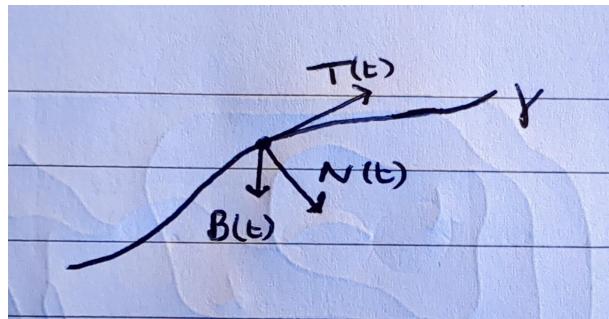


Figure 2.4.1: The Frenet frame for a curve in \mathbb{R}^3 .

Proposition 2.4.3. Let $\gamma : (a, b) \rightarrow \mathbb{R}^3$ be a regular curve parameterised by arc length, with $|\gamma''(t)| \neq 0$ for all $t \in (a, b)$. Then the following statements hold.

1. $T'(t) = k(t)N(t)$.
2. There exists a function $\tau : (a, b) \rightarrow \mathbb{R}$ such that

$$B'(t) = -\tau(t)N(t)$$

and

$$N'(t) = \tau(t)B(t) - k(t)T(t).$$

Proof.

1. $T'(t) = \gamma''(t) = \mathbf{k}_\gamma(t) = k(t)N(t)$ by Definition 2.4.1.
2. As $\langle B(t), B(t) \rangle = 1$ it follows that

$$0 = \frac{d}{dt} \langle B(t), B(t) \rangle = 2 \langle B'(t), B(t) \rangle.$$

Moreover,

$$\begin{aligned} B'(t) &= \frac{d}{dt}(T(t) \times N(t)) \\ &= T'(t) \times N(t) + T(t) \times N'(t) \\ &= T(t) \times N'(t). \end{aligned}$$

Hence, $B'(t)$ is orthogonal to $B(t)$ and $T(t)$. This implies that $B(t)$ is proportional to $N(t)$ and so there exists a $\tau : (a, b) \rightarrow \mathbb{R}$ such that

$$B'(t) = -\tau(t)N(t).$$

In particular, note that $N(t) = B(t) \times T(t)$ and so

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

□

Remark 2.4.4.

1. The equations of Proposition 2.4.3, also referred to as the Frenet equations, can be written in matrix form as

$$\frac{d}{dt} \begin{pmatrix} T \\ N \\ B \end{pmatrix} = \begin{pmatrix} 0 & k & 0 \\ -k & 0 & \tau \\ 0 & -\tau & 0 \end{pmatrix} \begin{pmatrix} T \\ N \\ B \end{pmatrix}.$$

2. The function $\tau = \tau_\gamma$ is referred to as the torsion on γ . Just as curvature can be interpreted as a measure of the failure of a curve to be a straight line, torsion can be interpreted as a measure of the failure of a curve to be planar.
3. From the Frenet equations it follows that torsion and curvature completely govern the Frenet frame.

Proposition 2.4.5. Let $\gamma : (a, b) \rightarrow \mathbb{R}^3$ be a regular curve parameterised by arc length, with $|\gamma''(t)| \neq 0$ for all $t \in (a, b)$. Then γ is contained in a plane if and only if $\tau \equiv 0$.

Proof. (\Leftarrow). It follows that $B' = -\tau N \equiv 0$ and hence $B(t) = \mathbf{C}$ for some $\mathbf{C} \in \mathbb{R}^n$. Observe that

$$\frac{d}{dt} \langle \gamma(t), \mathbf{C} \rangle = \langle \gamma'(t), \mathbf{C} \rangle = \langle T(t), B(t) \rangle \stackrel{(1)}{=} 0,$$

where in (1) we have used the fact that $B(t) = T(t) \times N(t)$. Therefore, $\langle \gamma(t), \mathbf{C} \rangle = d$ for some $d \in \mathbb{R}$, and so

$$\gamma(t) \in \{(x, y, z) \in \mathbb{R}^3 : \langle (x, y, z), \mathbf{C} \rangle = d\}$$

which is the plane perpendicular to the vector $\mathbf{C} = B(t)$. Thus, γ is contained in the plane spanned by T and N . (\Rightarrow). There exists a unit vector $\mathbf{v} \in \mathbb{R}^3$ and $d \in \mathbb{R}$ such that $\langle \gamma(t), \mathbf{v} \rangle = d$ for all $t \in [a, b]$. Which implies that $\langle \gamma'(t), \mathbf{v} \rangle = 0$ for all $t \in [a, b]$ and so

$$\langle T(t), \mathbf{v} \rangle = 0$$

for all $t \in [a, b]$. Again this means that $\langle T'(t), \mathbf{v} \rangle = 0$ for all $t \in [a, b]$ and so

$$\langle k(t)N(t), \mathbf{v} \rangle = 0$$

for all $t \in [a, b]$. Since $k(t) = |\gamma''(t)| \neq 0$ it follows that

$$\langle N(t), \mathbf{v} \rangle = 0$$

for all $t \in [a, b]$. In conclusion \mathbf{v} is orthogonal to both $T(t)$ and $N(t)$. Thus, as \mathbf{v} is a unit vector we have that $B(t) = \pm \mathbf{v}$ which implies that $0 = B'(t) = -\tau(t)N(t)$ and so $\tau \equiv 0$. □

Example 2.4.6.

1. Let $\gamma_1 : [0, 2\pi) \rightarrow \mathbb{R}^3$ be given by

$$\gamma_1(t) = (\cos(t), \sin(t), 0).$$

Then

$$T(t) = (-\sin(t), \cos(t), 0)$$

and so

$$N(t) = (-\cos(t), -\sin(t), 0).$$

Thus,

$$B(t) = T(t) \times N(t) = (0, 0, 1).$$

In this case,

$$k(t) = |T'(t)| = 1,$$

and $\tau \equiv 0$ as expected by Proposition 2.4.5.

2. Let $\gamma_2 : \mathbb{R} \rightarrow \mathbb{R}^3$ be given by

$$\gamma_2(t) = \left(\cos\left(\frac{t}{\sqrt{2}}\right), \sin\left(\frac{t}{\sqrt{2}}\right), \frac{t}{\sqrt{2}} \right).$$

Note that

$$|\gamma'_2(t)| = \frac{1}{\sqrt{2}} \left| \left(-\sin\left(\frac{t}{\sqrt{2}}\right), \cos\left(\frac{t}{\sqrt{2}}\right), 1 \right) \right| = 1,$$

and so γ is indeed parameterised by arc length. Then

$$T(t) = \frac{1}{\sqrt{2}} \left(-\sin\left(\frac{t}{\sqrt{2}}\right), \cos\left(\frac{t}{\sqrt{2}}\right), 1 \right)$$

and so

$$N(t) = \left(-\cos\left(\frac{t}{\sqrt{2}}\right), -\sin\left(\frac{t}{\sqrt{2}}\right), 0 \right).$$

Thus

$$B(t) = T(t) \times N(t) = \frac{1}{\sqrt{2}} \left(\sin\left(\frac{t}{\sqrt{2}}\right), -\cos\left(\frac{t}{\sqrt{2}}\right), 1 \right)$$

from which it follows that $B'(t) = -\frac{1}{2}N(t)$. In this case $k(t) \equiv \frac{1}{2}$ and $\tau \equiv \frac{1}{2}$.

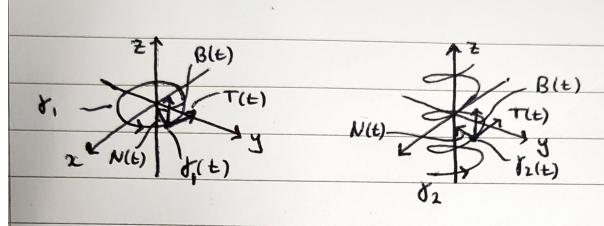


Figure 2.4.2: The curves of Example 2.4.6. Note how the basis vectors of the Frenet frame are drawn with the origin being the corresponding point on the curve at time t .

Definition 2.4.7. Let $\phi : [a, b] \rightarrow \mathbb{R}^3$ be a regular curve parameterised by arc length. Then a rigid motion of

ϕ in \mathbb{R}^3 is a regular curve $\psi : [a, b] \rightarrow \mathbb{R}^3$ such that there are $A \in \text{SO}(3)$ and $\mathbf{c} \in \mathbb{R}^3$ with

$$\psi = A\phi + \mathbf{c}.$$

Lemma 2.4.8. *For a regular curve parameterised by arc length, its arc length, curvature and torsion are preserved under rigid motion.*

Proof. Let $\gamma : [a, b] \rightarrow \mathbb{R}^3$ be a regular curve parameterised by arc length. Let $A \in \text{SO}(3)$ and $\mathbf{c} \in \mathbb{R}$. Let $\psi : [a, b] \rightarrow \mathbb{R}^3$ be given by $\psi = A\gamma + \mathbf{c}$. It follows that

$$|\psi'| = |A\gamma'| = |\gamma'| = 1$$

and so ψ is parameterised by arc length. Moreover,

$$k_\psi = |\psi''| = |(A\gamma)''| = |A\gamma''| = |\gamma''| = k_\gamma$$

and so ψ has the same curvature as γ . Assume that $\gamma''(t) \neq 0$ for all $t \in [a, b]$ such that τ_γ is well-defined. Note that $T_\psi = AT_\gamma$ and $N_\psi = AN_\gamma$ so that

$$B_\psi = T_\psi \times N_\psi = AT_\gamma \times AN_\gamma = AT_\gamma \times N_\gamma = AB_\gamma.$$

As $B'_\psi = -\tau_\psi N_\psi$ we have that

$$AB'_\gamma = (AB_\gamma)' = (B_\psi)' = -\tau_\psi N_\psi = -\tau_\psi (AN_\gamma) = A(-\tau_\psi N_\gamma)$$

which implies that $AB'_\gamma = A(-\tau_\psi N_\gamma)$. As A is invertible we deduce that $B'_\gamma = -\tau_\psi N_\gamma$ which implies that $\tau_\gamma N_\gamma = \tau_\psi N_\gamma$ and so $\tau_\psi = \tau_\gamma$ as $|N_\gamma| = 1$. \square

Proposition 2.4.9. *Let $I \subseteq \mathbb{R}$ be an interval with $t_0 \in I$ and let $A : I \rightarrow \mathbb{R}^{n \times n}$ be smooth. Then for any $X_0 \in \mathbb{R}^{n \times n}$ there exists a unique function $X : I \rightarrow \mathbb{R}^{n \times n}$ such that*

$$\dot{x}(t) = A(t)X(t)$$

for all $t \in [a, b]$ and $X(t_0) = X_0$.

Theorem 2.4.10 (Fundamental Theorem of the Local Theory of Curves). *For any smooth functions $k : [a, b] \rightarrow (0, \infty)$ and $\tau : [a, b] \rightarrow \mathbb{R}$, there exists a regular curve $\gamma : [a, b] \rightarrow \mathbb{R}^3$ parameterised by arc length such that $k_\gamma = k$ and $\tau_\gamma = \tau$. Moreover, γ is unique up to rigid motions of \mathbb{R}^3 .*

Proof. Suppose that regular curves $\gamma, \phi : [a, b] \rightarrow \mathbb{R}^3$ are parameterised by arc length and have curvature k and torsion τ . Now there exists a rigid motion such that

$$\begin{pmatrix} T_\gamma(a) \\ N_\gamma(a) \\ B_\gamma(a) \end{pmatrix} = A \begin{pmatrix} T_\phi(a) \\ N_\phi(a) \\ B_\phi(a) \end{pmatrix}.$$

Using Lemma 2.4.8 we can apply this rigid motion onto the curve ϕ whilst maintaining the curvature and torsion values. Henceforth, γ and ϕ will refer to the curves such that $T_\gamma(a) = T_\phi(a)$, $N_\gamma(a) = N_\phi(a)$ and $B_\gamma(a) = B_\phi(a)$. Observe that,

$$\begin{aligned} & \frac{1}{2} \frac{d}{dt} (\langle T_\phi - T_\gamma, T_\phi - T_\gamma \rangle + \langle N_\phi - N_\gamma, N_\phi - N_\gamma \rangle + \langle B_\phi - B_\gamma, B_\phi - B_\gamma \rangle) \\ &= \langle T_\phi - T_\gamma, T'_\phi - T'_\gamma \rangle + \langle N_\phi - N_\gamma, N_\phi - N'_\gamma \rangle + \langle B_\phi - B_\gamma, B'_\phi - B'_\gamma \rangle \\ &= k \langle T_\phi - T_\gamma, N_\phi - N_\gamma \rangle + (\tau \langle N_\phi - N_\gamma, B_\phi - B_\gamma \rangle - k \langle N_\phi - N_\gamma, T_\phi - T_\gamma \rangle) - \tau \langle B_\phi - B_\gamma, N_\phi - N_\gamma \rangle \\ &= 0. \end{aligned}$$

Therefore, the expression $\langle T_\phi - T_\gamma, T_\phi - T_\gamma \rangle + \langle N_\phi - N_\gamma, N_\phi - N_\gamma \rangle + \langle B_\phi - B_\gamma, B_\phi - B_\gamma \rangle$ is constant. At $t = a$ this expression is equal to zero, and so we deduce that

$$\langle T_\phi - T_\gamma, T_\phi - T_\gamma \rangle + \langle N_\phi - N_\gamma, N_\phi - N_\gamma \rangle + \langle B_\phi - B_\gamma, B_\phi - B_\gamma \rangle \equiv 0.$$

Consequently, we must have $T_\phi = T_\gamma \equiv 0$, $N_\phi = N_\gamma \equiv 0$ and $B_\phi - B_\gamma \equiv 0$, thus

$$\begin{aligned}\phi(t) &= \phi(a) + \int_a^t T_\phi(s) \, ds \\ &= \phi(a) + \int_a^t T_\gamma(s) \, ds \\ &= \phi(a) - \gamma(a) + \gamma(t).\end{aligned}$$

Therefore, $\phi \equiv \gamma + \mathbf{c}$ for $\mathbf{c} = \phi(a) - \gamma(a) \in \mathbb{R}^3$ a constant. Hence, γ is unique up to rigid motions. Now for $k : [a, b] \rightarrow (0, \infty)$ and $\tau : [a, b] \rightarrow \mathbb{R}$, fix (T_a, N_a, B_a) an positively oriented orthonormal basis of \mathbb{R}^3 , and consider the unique functions $T, N, B : [a, b] \rightarrow \mathbb{R}^3$, given by Proposition 2.4.9, such that

$$\begin{pmatrix} T'(t) \\ N'(t) \\ B'(t) \end{pmatrix} = \begin{pmatrix} 0 & k(t) & 0 \\ -k(t) & 0 & \tau(t) \\ 0 & -\tau(t) & 0 \end{pmatrix} \begin{pmatrix} T(t) \\ N(t) \\ B(t) \end{pmatrix} \quad (2.4.1)$$

with

$$\begin{pmatrix} T(a) \\ N(a) \\ B(a) \end{pmatrix} = \begin{pmatrix} T_a \\ N_a \\ B_a \end{pmatrix}.$$

Let

$$M(t) := \begin{pmatrix} | & | & | \\ T(t) & N(t) & B(t) \\ | & | & | \end{pmatrix}.$$

Then

$$\begin{aligned}\frac{d}{dt} (M^\top(t) M(t)) &= (M'(t))^\top M(t) + M(t)^\top M(t)' \\ &= \begin{pmatrix} 0 & k(t) & 0 \\ -k(t) & 0 & \tau(t) \\ 0 & -\tau(t) & 0 \end{pmatrix} M(t)^\top M(t) + M(t)^\top M(t) \begin{pmatrix} 0 & -k(t) & 0 \\ k(t) & 0 & -\tau(t) \\ 0 & \tau(t) & 0 \end{pmatrix}.\end{aligned}$$

Using the orthonormality of (T_a, N_a, B_a) it follows that $M^\top(a) M(a) = I$. Therefore, $M^\top(t) M(t)$ solves the linear system

$$\frac{d}{dt} A = \begin{pmatrix} 0 & k(t) & 0 \\ -k(t) & 0 & \tau(t) \\ 0 & -\tau(t) & 0 \end{pmatrix} A(t) + A(t) \begin{pmatrix} 0 & -k(t) & 0 \\ k(t) & 0 & -\tau(t) \\ 0 & \tau(t) & 0 \end{pmatrix}$$

with $A(a) = I$. Another solution to which is $A \equiv I$, therefore, by Proposition 2.4.9 it follows that $M(t)^\top M(t) = I$ for all $t \in [a, b]$. In other words, $(T(t), N(t), B(t))$ is an orthonormal basis. Let $\gamma : [a, b] \rightarrow \mathbb{R}$ be given by

$$\gamma(t) = \int_a^t T(s) \, ds$$

for $t \in [a, b]$. Let T_γ , N_γ and B_γ be the tangent, unit normal, and binormal vector of γ . Clearly, $T_\gamma = T$ which means that $k_\gamma \equiv k$. Then as $(T(t), N(t), B(t))$ solves (2.4.1) it follows that

$$N_\gamma(t) = \frac{T'_\gamma(t)}{|T'_\gamma(t)|} = \frac{T'(t)}{|T'(t)|} = \frac{k(t)N(t)}{|k(t)N(t)|} = \frac{k(t)N(t)}{k(t)} = N(t),$$

where we have used the fact that $|k(t)| = k(t)$ and $|N(t)| = 1$. Thus

$$B_\gamma(t) = T_\gamma(t) \times N_\gamma(t) = T(t) \times N(t) = B(t)$$

and so

$$-\tau_\gamma(t)N(t) = -\tau_\gamma(t)N_\gamma(t)(t) = B'_\gamma(t) = B'(t) \stackrel{(2.4.1)}{=} -\tau(t)N(t)$$

which implies that $\tau_\gamma \equiv \tau$. □

Remark 2.4.11. Note how the range of k in Theorem 2.4.10 is $(0, \infty)$ such that torsion for the corresponding curve is well-defined.

Corollary 2.4.12. If $\phi([a, b])$ is a regular curve in \mathbb{R}^3 that has torsion $\tau \equiv 0$, and curvature $k(t) \equiv c \in \mathbb{R}_{>0}$, then $\phi([a, b])$ is a segment of a circle of radius $\frac{1}{c}$.

Proof. By generalising the argument of statement 1. from Example 2.4.6, it follows that for $r > 0$ the curve of a circle of radius r given by $\gamma_r : [0, 2\pi] \rightarrow \mathbb{R}^3$ where

$$\gamma_r(t) = \left(r \cos\left(\frac{t}{r}\right), r \sin\left(\frac{t}{r}\right), 0 \right)$$

has curvature $k_r \equiv \frac{1}{r}$ and torsion $\tau_r \equiv 0$. Therefore, if a curve $\phi : [a, b] \rightarrow \mathbb{R}^3$ is such that $k_\phi \equiv c \in \mathbb{R}$ and $\tau_\phi \equiv 0$, it follows by Theorem 2.4.10 that under rigid motions in \mathbb{R}^3 the curve ϕ is equivalent to $\gamma_{\frac{1}{c}}$. Thus ϕ is a segment of a circle of radius $\frac{1}{c}$. □

Exercise 2.4.13. Let $I \subseteq \mathbb{R}$ be an interval and let $\gamma : I \rightarrow \mathbb{R}^3$ be a regular curve parameterised by arc length such that $\gamma''(t) \neq 0$, $k'(t) \neq 0$ and $\tau(t) \neq 0$ for all $t \in I$, where k is the curvature and τ is the torsion of γ . Then $\gamma(I)$ lies on a sphere of radius $R > 0$ if and only if

$$\frac{1}{k(t)^2} + \frac{k'(t)^2}{k(t)^4 \tau(t)^2} = R^2$$

for all $t \in I$.

2.5 Curve in \mathbb{R}^2

Theorem 2.4.10 is thought of as a local theorem as its conclusions and derivation can be restricted to a neighbourhood of the curve, and it does not take into account the global structure of the curve. To obtain a global result for curves we restrict to planar curves.

2.5.1 Signed Curvature

Consider $\gamma : [a, b] \rightarrow \mathbb{R}^2$ a regular curve, not necessarily parameterised by arc-length, given by

$$\gamma(t) = (x(t), y(t))$$

such that

$$\gamma'(t) = (x'(t), y'(t)).$$

Then let $n : [a, b] \rightarrow \mathbb{R}$ be given by

$$n(t) = \frac{(-y'(t), x'(t))}{|\gamma'(t)|}. \quad (2.5.1)$$

One can interpret the construction of n as rotating the tangent vector to γ at t and then normalising. Thus, n is a normal tangent vector to γ at t . Consequently, one observes that $\left\{ \frac{\gamma'(t)}{|\gamma'(t)|}, n(t) \right\}$ is a positively oriented orthonormal basis for \mathbb{R}^2 .

Definition 2.5.1. Suppose $\gamma : [a, b] \rightarrow \mathbb{R}^2$ is a regular curve parameterised by arc length. The signed curvature of γ is $\kappa : [a, b] \rightarrow \mathbb{R}$ given by

$$\kappa(t) = \langle n(t), \gamma''(t) \rangle = x'(t)y''(t) - y'(t)x''(t). \quad (2.5.2)$$

Remark 2.5.2. Recall, that for $\gamma : [a, b] \rightarrow \mathbb{R}^2$ a regular curve parameterised by arc length, its curvature is given by

$$k(t) = |\gamma''(t)|.$$

Thus,

$$\begin{aligned} k(t) &= |\gamma''(t)| \\ &\stackrel{(1)}{=} \langle \gamma'(t), \gamma''(t) \rangle + \langle N(t), \gamma''(t) \rangle \\ &\stackrel{(2)}{=} \langle N(t), \gamma''(t) \rangle \end{aligned}$$

where in (1) we are expanding $|\gamma''(t)|$ in terms of the orthonormal basis $\{\gamma'(t), n(t)\}$, in (2) we use the fact that $\gamma'(t)$ and $\gamma''(t)$ are orthogonal, and $N(t) = \pm n(t)$. Consequently, we observe that $|\kappa(t)| = k(t)$ for all $t \in [a, b]$, which means that κ changes sign when the curve is traversed in the opposite direction.

Example 2.5.3. Consider $\gamma_+ : [0, 2\pi) \rightarrow \mathbb{R}^2$ given by

$$t \mapsto (\cos(t), \sin(t)),$$

and $\gamma_- : [0, 2\pi) \rightarrow \mathbb{R}^2$ given by

$$t \mapsto (\cos(t), -\sin(t)).$$

Then the normal vector to γ_+ is

$$n_+(t) = (-\cos(t), -\sin(t))$$

and so the signed curvature of γ_+ is

$$\kappa_+(t) = \left\langle \begin{pmatrix} -\cos(t) \\ -\sin(t) \end{pmatrix}, \begin{pmatrix} -\cos(t) \\ -\sin(t) \end{pmatrix} \right\rangle = \cos^2(t) + \sin^2(t) = 1.$$

Similarly, the signed curvature of γ_- is $\kappa_-(t) \equiv 1$. This verifies the notion of Remark 2.5.2 that says signed curvature changes sign when the curve is traversed in the opposite direction.

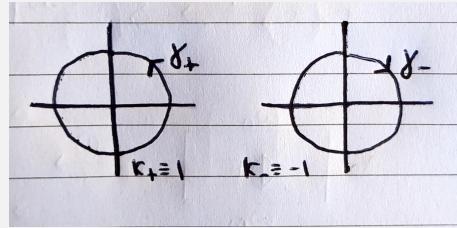


Figure 2.5.1: Curves traversed in different directions have opposite signs for their signed curvature.

Proposition 2.5.4. Let $\gamma : [a, b] \rightarrow \mathbb{R}^2$ be a regular curve. Then

$$\kappa(t) = \frac{\langle \gamma''(t), n(t) \rangle}{|\gamma'(t)|^2}.$$

Proof. Let $\psi(s) = (\gamma \circ f)(s)$ be a reparameterisation of γ with $f' > 0$ such that the orientation of γ is preserved and such that $|\psi'| \equiv 1$. Let

$$\psi(s) = (x(f(s)), y(f(s))).$$

From Proposition 2.2.6 we have $f = h^{-1}$ where

$$h(t) = \int_a^t |\gamma'(t)| dt.$$

Moreover, using (2.2.1) and (2.2.2) we note that

$$f'(s) = \frac{1}{|\gamma'(f(s))|}.$$

Since $\gamma(f(s)) = \psi(s)$ with γ and ψ parameterised in the same direction, it follows that $n_\gamma(f(s)) = n_\psi(s)$. Therefore,

$$\begin{aligned} n_\gamma(f(s)) &= n_\psi(s) \\ &= \frac{(-(y(f(s)))', (x(f(s)))')}{|\psi'(s)|} \\ &= (-(y(f(s)))', (x(f(s)))') \\ &= f'(s) (-y'(f(s)), x'(f(s))). \end{aligned}$$

On the other hand, $k_\gamma(f(s)) = k_\psi(s)$ and so

$$|\kappa_\psi(s)| = k_\psi(s) = k_\phi(f(s)) = |\kappa_\gamma(f(s))|.$$

Since γ and ψ are oriented in the same direction we have that $\kappa_\psi(s) = \kappa_\gamma(f(s))$. Therefore, using (2.5.2) it follows that

$$\begin{aligned} \kappa_\gamma(f(s)) &= \kappa_\psi(s) \\ &= (x(f(s)))' (y(f(s)))'' - (y(f(s)))' (x(f(s)))'' \\ &= (x'(f(s)) y''(f(s)) - y'(f(s)) x''(f(s))) (f'(s))^3 \\ &= \langle \gamma''(f(s)), (-y'(f(s)), x'(f(s))) \rangle (f'(s))^3 \\ &= \frac{\langle \gamma''(f(s)), n_\gamma(f(s)) \rangle}{(\gamma'(f(s)))^2} \\ &\stackrel{t=f(s)}{=} \frac{\langle \gamma''(t), n_\gamma(t) \rangle}{(\gamma'(t))^2}. \end{aligned}$$

□

Example 2.5.5. Let $\gamma : [a, b] \rightarrow \mathbb{R}^2$ be the graph of $f : [a, b] \rightarrow \mathbb{R}$. That is,

$$\gamma(t) = (t, f(t)).$$

Then

$$\gamma'(t) = (1, f'(t))$$

and

$$\gamma''(t) = (0, f''(t)).$$

Hence,

$$|\gamma'(t)| = \sqrt{1 + (f'(t))^2},$$

and

$$n_\gamma(t) = \frac{(-f'(t), 1)}{\sqrt{1 + (f'(t))^2}}.$$

Therefore,

$$\kappa_\gamma(t) = \frac{f''(t)}{\left(1 + (f'(t))^2\right)^{\frac{3}{2}}}.$$

2.5.2 Winding Number

Definition 2.5.6. $\gamma : [a, b] \rightarrow \mathbb{R}^2$ is a smooth closed curve if $\gamma^{(k)}(a) = \gamma^{(k)}(b)$ for $k \geq 0$.

Remark 2.5.7. If γ is a smooth closed curve, then the map $T(t) = \gamma'(t) : [a, b] \rightarrow \mathbb{R}^2$ is also a smooth closed curve.

Observe how a curve in \mathbb{R}^2 can be associated with a curve in \mathbb{C} . In particular, for $\gamma : [a, b] \rightarrow \mathbb{R}^2$ given by

$$\gamma(t) = (x(t), y(t)),$$

one can consider $\gamma : [a, b] \rightarrow \mathbb{C}$ where

$$\gamma(t) = x(t) + iy(t).$$

Definition 2.5.8. Let $\gamma : [a, b] \rightarrow \mathbb{C}$ be a closed curve. Then

$$\omega(\gamma) = \frac{1}{2\pi i} \int_{\gamma} \frac{1}{z} dz$$

is referred to as the winding number of γ .

Remark 2.5.9. The winding number $\omega(\gamma)$ measures the number of times γ winds around the origin. In particular, a positive wind corresponds to a counter-clockwise traversal around the origin, whereas a negative wind corresponds to a clockwise traversal around the origin.

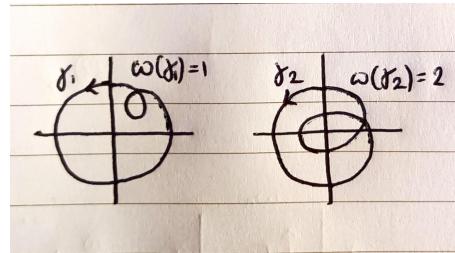


Figure 2.5.2: Winding number measures the number of times a curve winds around the origin.

Proposition 2.5.10. Let $\gamma : [a, b] \rightarrow \mathbb{C}$ be a smooth closed curve given by

$$\gamma(t) = x(t) + iy(t).$$

Then

$$\omega(\gamma) = \frac{1}{2\pi} \int_a^b \frac{\langle \gamma'(t), -y(t) + x(t) \rangle}{|\gamma(t)|^2} dt.$$

Proof. Observe that

$$\begin{aligned} \omega(\gamma) &= \frac{1}{2\pi i} \int_a^b \frac{x'(t) + iy'(t)}{x(t) + iy(t)} dt \\ &= \frac{1}{2\pi i} \int_a^b \frac{(x'(t) + iy'(t))(x(t) - iy(t))}{x(t)^2 + y(t)^2} dt \\ &= \frac{1}{2\pi i} \int_a^b \frac{x(t)x'(t) + y(t)y'(t)}{x(t)^2 + y(t)^2} + i \frac{x(t)y'(t) - y(t)x'(t)}{x(t)^2 + y(t)^2} dt \\ &= \frac{1}{2\pi i} \left([\log(x(t)^2 + y(t)^2)]_a^b + i \int_a^b \frac{x(t)y'(t) - y(t)x'(t)}{x(t)^2 + y(t)^2} dt \right) \\ &\stackrel{(1)}{=} \frac{1}{2\pi} \int_a^b \frac{\langle \gamma'(t), (-y(t), x(t)) \rangle}{|\gamma(t)|^2} dt \end{aligned}$$

where in (1) we have used the fact that γ is closed. \square

Theorem 2.5.11. If $\gamma : [a, b] \rightarrow \mathbb{R}^2$ is a regular closed curve parameterised by arc length, given by

$$\gamma(t) = (x(t), y(t)),$$

then

$$\omega(\gamma') = \frac{1}{2\pi} \int_a^b \kappa(t) dt,$$

where κ is the signed curvature of γ .

Proof. Using Remark 2.5.7, Proposition 2.5.10 can be applied to $\gamma' : [a, b] \rightarrow \mathbb{C}$ to give

$$\omega(\gamma') = \frac{1}{2\pi} \int_a^b \frac{\langle \gamma''(t), (-y'(t), x'(t)) \rangle}{|\gamma'(t)|^2} = \frac{1}{2\pi} \int_a^b \langle \gamma''(t), (-y'(t) + x'(t)) \rangle dt.$$

Thus it follows that

$$\omega(\gamma') = \frac{1}{2\pi} \int_a^b \kappa(t) dt.$$

\square

Remark 2.5.12.

1. The quantity $\omega(\gamma')$ for a $\gamma : [a, b] \rightarrow \mathbb{C}$ a regular closed curve is referred to as its index, or turning number and is denoted $\text{Ind}(\gamma)$. The index of a curve measures the number of times the unit tangent vector rotates around the origin as ϕ is traversed.
2. Theorem 2.5.11 concerns global properties of a curve. In particular, it relates a topological property, the turning number, to a geometrical property, the curvature.
3. One can observe that the turning number of a curve is robust to perturbations of γ . Geometrically, a small perturbation is unlikely to fully rotate the tangent vector of the curve. Concretely, the sign of the curvature means that small perturbations are likely to be cancelled out as they are integrated over.

Exercise 2.5.13. For each $n \in \mathbb{Z}$ find a regular closed curve $\gamma : I \rightarrow \mathbb{R}^2$, where $I \subset \mathbb{R}$ is an appropriate interval, such that $\text{Ind}(\gamma) = n$.

2.6 Solution to Exercise

Exercise 2.3.6

Solution.

1. The tangent vector to a point on a circle is perpendicular to the line from the point of the circle to the centre of the circle. Therefore, the circle C_v is tangent to γ at $\gamma(t_0)$ if and only if $\langle \gamma'(t_0)', \gamma(t_0) - v \rangle = 0$. As

$$f'_v(t) = \frac{d}{dt} \langle \gamma(t) - v, \gamma(t) - v \rangle = 2 \langle \gamma'(t), \gamma(t) - v \rangle,$$

it follows that C_v is tangent to γ at $\gamma(t_0)$ if and only if $f'_v(t_0) = 0$.

2. Let $v = \gamma(t_0) + \frac{\gamma''(t_0)}{|\gamma''(t_0)|^2}$. Then

$$f'_v(t_0) = -2 \left\langle \gamma'(t), \frac{\gamma''(t_0)}{|\gamma''(t_0)|^2} \right\rangle = 0,$$

as $\gamma'(t)$ and $\gamma''(t)$ are perpendicular to each other. Note that

$$f''_v(t) = \langle \gamma''(t), \gamma(t) - v \rangle + \langle \gamma'(t), \gamma'(t) \rangle = \langle \gamma''(t), \gamma(t) - v \rangle + 1$$

as γ is parameterised by arc length. Therefore,

$$f''_v(t_0) = - \left\langle \gamma''(t), \frac{\gamma''(t)}{|\gamma''(t)|^2} \right\rangle + 1 = -1 + 1 = 0.$$

Moreover, the radius of C_v is given by

$$|v - \gamma(t_0)| = \frac{|\gamma''(t_0)|}{|\gamma''(t_0)|^2} = \frac{1}{|\gamma''(t)|} = \frac{1}{k_\gamma(t_0)}.$$

□

Exercise 2.4.13

Solution. (\Rightarrow). Suppose that $\gamma(I)$ lies on the circle of radius R centred at p_0 . Namely, $\langle \gamma(t) - p_0, \gamma(t) - p_0 \rangle = R^2$ for all $t \in I$. Differentiating this it follows that

$$\langle \gamma'(t), \gamma(t) - p_0 \rangle = 0,$$

which when differentiated gives

$$\langle \gamma''(t), \gamma(t) - p_0 \rangle + \langle \gamma'(t), \gamma'(t) \rangle = 0$$

for all $t \in I$. In particular,

$$k(t) \langle N(t), \gamma(t) - p_0 \rangle = -1,$$

where we have used the fact that γ is parameterised by arc length. Differentiating this expression we deduce that

$$k'(t) \langle N(t), \gamma(t) - p_0 \rangle + k(t) \langle N'(t), \gamma(t) - p_0 \rangle + k(t) \langle N(t), \gamma'(t) \rangle = 0.$$

Thus, since $N'(t) = \tau(t)B(t) - k(t)T(t)$ it follows that

$$\frac{k'(t)}{k(t)} + k(t) \langle \tau(t)B(t) - k(t)T(t), \gamma(t) - p_0 \rangle = 0.$$

Or equivalently,

$$\langle B(t), \gamma(t) - p_0 \rangle = -\frac{k'(t)}{k(t)^2 \tau(t)}.$$

Therefore, since $\{T(t), N(t), B(t)\}$ is an orthonormal basis, we have

$$\begin{aligned} R^2 &= \langle \gamma(t) - p_0, \gamma(t) - p_0 \rangle \\ &= \langle T(t), \gamma(t) - p_0 \rangle^2 + \langle N(t), \gamma(t) - p_0 \rangle^2 + \langle B(t), \gamma(t) - p_0 \rangle^2 \\ &= 0 + \left(-\frac{1}{k(t)} \right)^2 + \left(-\frac{k'(t)}{k(t)^2 \tau(t)} \right)^2 \\ &= \frac{1}{k(t)^2} + \frac{k'(t)^2}{k(t)^4 \tau(t)^2}. \end{aligned}$$

(\Leftarrow). Let $\rho = \frac{1}{k}$ and $\sigma = \frac{1}{\tau}$ so that by assumption we have that

$$\rho^2 + (\rho' \sigma)^2 = R^2. \quad (2.6.1)$$

Differentiating this it follows that

$$\rho \rho' + (\rho' \sigma) (\rho' \sigma)' = 0,$$

thus

$$\frac{\rho}{\sigma} + (\rho' \sigma)' = 0. \quad (2.6.2)$$

Now let $\alpha : I \rightarrow \mathbb{R}^3$ be given by

$$\alpha(t) = \gamma(t) + \rho(t)N(t) + \rho'(t)\sigma(t)B(t),$$

where $\{T(t), N(t), B(t)\}$ is the orthonormal frame of γ at $\gamma(t)$. It follows that

$$\begin{aligned} \alpha'(t) &= T(t) + \rho'(t)N(t) + \rho(t)N'(t) + (\rho'(t)\sigma(t))' B(t) + (\rho'(t)\sigma(t)) B'(t) \\ &= T(t) + \rho'(t)N(t) + \rho(t) \left(\frac{B(t)}{\sigma(t)} - \frac{T(t)}{\rho(t)} \right) + (\rho'(t)\sigma(t))' B(t) + (\rho'(t)\sigma(t)) \left(-\frac{N(t)}{\sigma(t)} \right) \\ &= B(t) \left(\frac{\rho(t)}{\sigma(t)} + (\rho'(t)\sigma(t))' \right) \\ &\stackrel{(2.6.2)}{=} 0. \end{aligned}$$

Therefore, $\alpha(t) = p_0$ for some $p_0 \in \mathbb{R}$ and every $t \in I$. In particular, as $\{T(t), N(t), B(t)\}$ is an orthonormal basis it follows that

$$|\gamma(t) - p_0|^2 = |\rho(t)N(t) + \rho'(t)\sigma(t)B(t)|^2 = \rho(t)^2 + (\rho'(t)\sigma(t))^2 \stackrel{(2.6.1)}{=} R^2.$$

That is, $\gamma(t)$ lies on the sphere of radius R centred at p_0 . \square

Exercise 2.5.13

Solution. For $n > 0$ let $\gamma_n : [0, 2\pi n] \rightarrow \mathbb{C}$ be given by

$$\gamma_n(t) = \cos(t) + i \sin(t).$$

Then

$$\gamma'_n(t) = -\sin(t) + i \cos(t),$$

and so γ_n is indeed parameterised by arc length. Moreover,

$$\gamma''_n(t) = -\cos(t) - i \sin(t),$$

and so

$$\kappa_{\gamma_n}(t) = (-\sin(t))(-\sin(t)) - (-\cos(t))(\cos(t)) = 1.$$

Therefore,

$$\text{Ind}(\gamma_n) = \frac{1}{2\pi} \int_0^{2\pi n} \kappa_{\gamma_n}(t) dt = \frac{1}{2\pi} (2\pi n) = n.$$

For $n < 0$ let $\gamma_n : [0, 2\pi|n|] \rightarrow \mathbb{C}$ be given by

$$\gamma_n(t) = \cos(t) - i \sin(t).$$

Then

$$\gamma'_n(t) = -\sin(t) - i \cos(t)$$

and so γ_n is indeed parameterised by arc length. Moreover,

$$\gamma''_n(t) = -\cos(t) + i \sin(t)$$

and so

$$\kappa_{\gamma_n}(t) = (-\sin(t))(\sin(t)) - (-\cos(t))(-\cos(t)) = -1.$$

Therefore,

$$\text{Ind}(\gamma_n) = \frac{1}{2\pi} \int_0^{2\pi|n|} (-1) dt = \frac{1}{2\pi} (-2\pi|n|) = n.$$

For $n = 0$ consider $\gamma_0 : [0, 4\pi]$ given by

$$\gamma_0(t) = \begin{cases} -\cos(t) + 1 + i \sin(t) & t \in [0, 2\pi] \\ \cos(t) - 1 - i \sin(t) & t \in [2\pi, 4\pi] \end{cases}$$

Then

$$\gamma'_0(t) = \begin{cases} \sin(t) + i \cos(t) & t \in [0, 2\pi] \\ -\sin(t) - i \cos(t) & t \in [2\pi, 4\pi], \end{cases}$$

and so γ_0 is indeed parameterised by arc length. Moreover,

$$\gamma''_0(t) = \begin{cases} \cos(t) - i \sin(t) & t \in [0, 2\pi] \\ -\cos(t) - i \sin(t) & t \in [2\pi, 4\pi], \end{cases}$$

and so

$$\kappa_{\gamma_0}(t) = \begin{cases} (\sin(t))(-\sin(t)) - (\cos(t))(\cos(t)) & t \in [0, 2\pi] \\ (-\sin(t))(-\sin(t)) - (-\cos(t))(-\cos(t)) & t \in [2\pi, 4\pi] \end{cases} = \begin{cases} -1 & t \in [0, 2\pi] \\ 1 & t \in [2\pi, 4\pi]. \end{cases}$$

Therefore,

$$\text{Ind}(\gamma_0) = \int_0^{2\pi} -1 dt + \int_{2\pi}^{4\pi} 1 dt = 0.$$

□

3 Surfaces

Informally, a surface in \mathbb{R}^3 is a subset $S \subset \mathbb{R}^3$ that locally looks like \mathbb{R}^2 . As many notions for curves involve taking derivatives, it is essential that on surfaces we ought to be able to perform classical calculus. Recall that for curves a regularity condition ensured that one could perform calculus along the curve. Namely, a curve $\gamma : [a, b] \rightarrow \mathbb{R}^n$ is said to be regular if $|\gamma'(0)| \neq 0$ for all $t \in [a, b]$. Recall the curve $\gamma : \mathbb{R} \rightarrow \mathbb{R}^2$ given by $\gamma(t) = (t^3, t^2)$ from Example 2.1.3. Indeed this curve is not regular, in particular, it has a cusp at the origin which means that the derivative at the origin is not well-defined. Consequently, the tangent vector field to γ is not well-defined and the curve at the origin is not locally homeomorphic to a line. We would similarly like to define regular surfaces to avoid such issues. For a curve γ the regularity condition $|\gamma'(t)| \neq 0$ can be equivalently stated as $\gamma'(t)$ is injective for all $t \in [a, b]$. This rephrasing is used to generalise regular curves to regular surfaces.

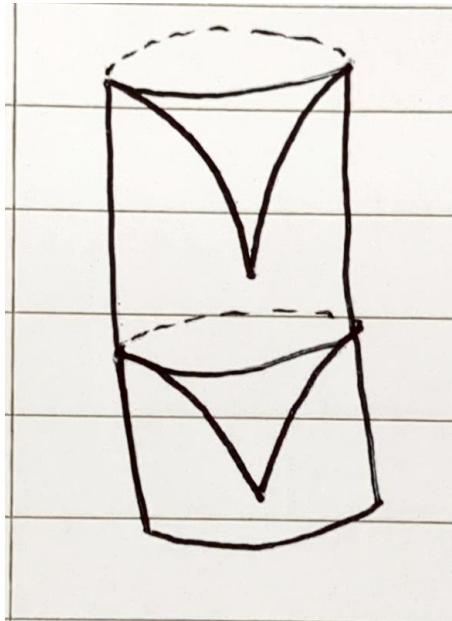


Figure 3.0.1: An example of a surface with a cusp that would not facilitate calculus to perform along the surface.

3.1 Charts

Definition 3.1.1. A regular surface is a set $S \subset \mathbb{R}^3$ such that for all $p \in S$ there exists

1. an open neighbourhood $V \subseteq \mathbb{R}^3$ of p ,
2. an open set $U \subseteq \mathbb{R}^2$, and
3. a smooth map $\phi : U \rightarrow \mathbb{R}^3$ such that
 - (a) $\phi(U) = V \cap S$,
 - (b) $\phi : U \rightarrow V \cap S$ is a homeomorphism, and
 - (c) for all $q \in U$ the derivative of ϕ at q , denoted $d\phi_q : \mathbb{R}^2 \rightarrow \mathbb{R}^3$, is injective.

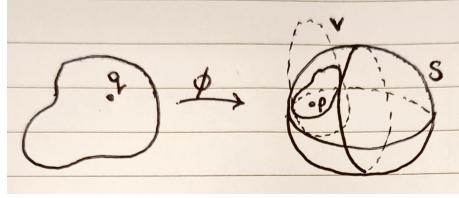


Figure 3.1.1: A regular surface locally resembles a plane in \mathbb{R}^2 , through the use of a chart ϕ .

Remark 3.1.2.

1. The pair (ϕ, U) from Definition 3.1.1 is referred to as a chart, or local parameterisation, of S at p .
2. Statements 3(a) and 3(b) of Definition 3.1.1 say that S locally resembles \mathbb{R}^2 . Statement 3(c) of Definition 3.1.1 ensures the S is sufficiently regular near p . Indeed it generalises the regularity condition for curves.

Let S be a regular surface with (ϕ, U) a chart for S at $p \in S$. Suppose that for $(u, v) \in U$ we have

$$\phi(u, v) = (x(u, v), y(u, v), z(u, v)).$$

Then by statement 3(c) of Definition 3.1.1 we have that

$$d\phi_q = \begin{pmatrix} \frac{\partial x}{\partial u}(q) & \frac{\partial x}{\partial v}(q) \\ \frac{\partial y}{\partial u}(q) & \frac{\partial y}{\partial v}(q) \\ \frac{\partial z}{\partial u}(q) & \frac{\partial z}{\partial v}(q) \end{pmatrix}$$

is injective. Observe that $d\phi_q$ is injective if and only if the columns $\frac{\partial \phi}{\partial u}(q)$ and $\frac{\partial \phi}{\partial v}(q)$ are linearly independent. Note that for $q = (u_0, v_0)$ the curves

$$u \mapsto \phi(u, v_0)$$

and

$$v \mapsto \phi(u_0, v)$$

are contained in S with the tangent vectors $\partial_u \phi(u_0, v_0)$ and $\partial_v \phi(u_0, v_0)$ respectively. Therefore, $d\phi_q$ is injective if and only if the tangent vectors to the curves span a plane.

Example 3.1.3.

1. The set $\{z = 0\} \subseteq \mathbb{R}^3$ is a regular surface. Indeed it is specified by the single chart $\phi : \mathbb{R}^2 \rightarrow \mathbb{R}^3$ given by $(u, v) \mapsto (u, v, 0)$. Observe that ϕ is homeomorphic to its image and

$$d\phi_q = \begin{pmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \end{pmatrix}$$

is injective for all $q \in \mathbb{R}^2$. Note that $\phi : \mathbb{R}^2 \rightarrow \mathbb{R}^3$ given by $\phi(u, v) = (u^3, v^3, 0)$ would not be a chart for $\{z = 0\}$ as its differential is 0 at the origin.

2. Let $f : \mathbb{R}^2 \rightarrow \mathbb{R}^3$ be smooth, then

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

is a regular surface. Indeed it is specified by the single chart

$$\phi(u, v) = (u, v, f(u, v)).$$

As ϕ is homeomorphic onto its image and

$$d\phi_q = \begin{pmatrix} 1 & 0 \\ 0 & 1 \\ \partial_u f & \partial_v f \end{pmatrix}$$

is injective for all $q \in \mathbb{R}^2$.

3. The unit sphere $S^2 = \{(x, y, z) \in \mathbb{R}^3 : \|x\| = 1\}$ is a regular surface. However, more than one chart is needed as S^2 is not homeomorphic to \mathbb{R}^2 . Let $\phi_N : \mathbb{R}^2 \rightarrow S^2 \setminus \{0, 0, 1\}$ and $\phi_S : \mathbb{R}^2 \rightarrow S^2 \setminus (0, 0, -1)$ be the stereographic projections from the north of S^2 , that is $(0, 0, 1)$, and the south of S^2 , that is $(0, 0, -1)$, respectively. More specifically,

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

and

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

Examples of surfaces that are not regular surfaces are the following.

1. The cone

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

is not a regular surface. There is no smooth chart at the origin.

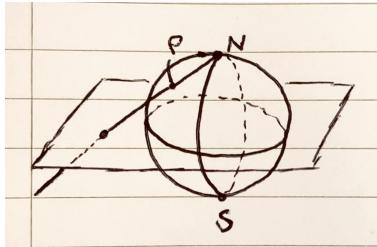
2. Let $\phi : (0, 2\pi) \times (-1, 1) \rightarrow \mathbb{R}^3$ be given by

$$\phi(u, v) = (\sin(u), \sin(2u), v).$$

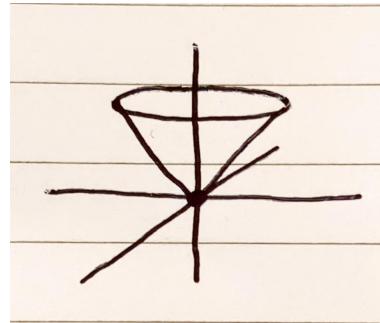
Note that ϕ is smooth, and it is also injective since it is defined on open intervals. Moreover,

$$d\phi_q = \begin{pmatrix} \cos(u) & 0 \\ 2\cos(2u) & 0 \\ 0 & 1 \end{pmatrix}$$

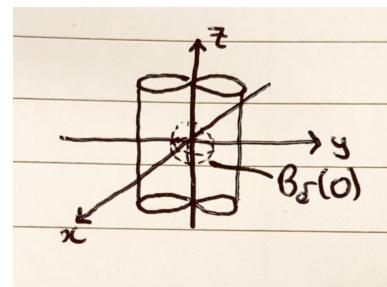
is injective for every $q = (u, v) \in U$. However, it is not homeomorphic to its image and thus is not a chart. More specifically, consider the point $(0, 0, 0) \in \text{im}(\phi)$. Then the pre-image of the neighbourhood $V = B_\delta(0, 0, 0) \subseteq \mathbb{R}^3$ for any $\delta > 0$ will be of the form $(0, \epsilon_1) \cup (2\pi - \epsilon_2, 2\pi) \times (-\delta, \delta)$ which is disconnected and thus cannot be homeomorphic to V which is connected.



(a) The stereographic projection map.



(b) The cone, which is not a regular surface due to the point at the origin.



(c) A self-intersection surface is not regular as charts are not homeomorphic to their images.

Figure 3.1.2: Illustrations supporting the examples and non-examples of surfaces given in Example 3.1.3.

3.2 Constructing Surfaces

Let $\gamma : I \rightarrow \mathbb{R}^2$ be a regular curve, with

$$\gamma(u) = (\lambda(u), \mu(u)).$$

Suppose that $\lambda(u) > 0$ for all $u \in I$. Then

$$S := \{(\lambda(u) \cos(v), \lambda(u) \sin(v), \mu(u)) : u \in I, v \in (0, 2\pi)\}$$

is a regular surface. More specifically, it is the surface of revolution γ around the y -axis.

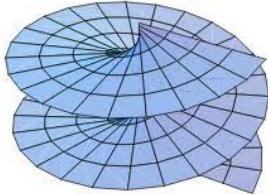
Example 3.2.1.

1. The helicoid is the set of points

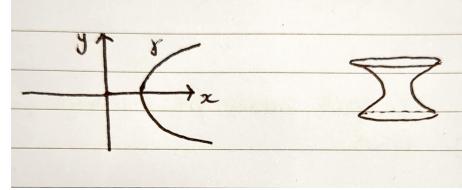
$$\{(u \cos(v), u \sin(v), v) : u, v \in \mathbb{R}\}.$$

A chart for the helicoid is given by $\phi(u, v) = (u \cos(v), u \sin(v), v)$.

2. The catenoid is the surface of revolution of the catenary curve, namely $\gamma : \mathbb{R} \rightarrow \mathbb{R}^2$ where $\gamma(u) = (\cosh(u), u)$.



(a) The helicoid.



(b) The cone, which is not a regular surface due to the point at the origin.

Figure 3.2.1: Surfaces of revolution.

Surfaces may also be constructed as the level sets of functions.

Definition 3.2.2. For $n \geq 1$, let $U, V \subset \mathbb{R}^n$ be open. Then a map $f : U \rightarrow V$ is a C^k -diffeomorphism, for $k \in \mathbb{N} \cup \{\infty\}$, if $f : U \rightarrow V$ is a homeomorphism, with $f : U \rightarrow V$ and $f^{-1} : V \rightarrow U$ in C^k .

Remark 3.2.3. Although Definition 3.2.2 distinguishes between diffeomorphisms of differing regularity, we will henceforth use diffeomorphism to refer to a C^∞ -diffeomorphism.

Example 3.2.4. The function $f(x) = x^3$ is not a diffeomorphism. Although it is a homeomorphism, its inverse is not smooth.

Theorem 3.2.5 (Inverse Function Theorem). Let $\Omega \subset \mathbb{R}^n$ be open, $f : \Omega \rightarrow \mathbb{R}^n$ a smooth map. Assume for some $p \in \Omega$ that $df_p : \mathbb{R}^n \rightarrow \mathbb{R}^n$ is invertible. Then, there is a neighbourhood $U \subset \Omega$ of p such that $f : U \rightarrow f(U)$ is a diffeomorphism.

Proposition 3.2.6. Let $\Omega \subset \mathbb{R}^3$ be open, $F : \Omega \rightarrow \mathbb{R}$ a smooth function, and $c \in \mathbb{R}^3$. Assume that $\nabla F(p) \neq 0$ for every $p \in \Omega$. Then

$$S := F^{-1}(c) = \{(x, y, z) \in \Omega : F(x, y, z) = c\}$$

is a regular surface.

Proof. As $\nabla F(p) \neq 0$, at least one of $\frac{\partial F}{\partial x}$, $\frac{\partial F}{\partial y}$ and $\frac{\partial F}{\partial z}$ is non-zero at p . Without loss of generality suppose $\frac{\partial F}{\partial z} \neq 0$ at p and consider $g : \Omega \rightarrow \mathbb{R}^3$ given by

$$g(x, y, z) = (x, y, F(x, y, z)).$$

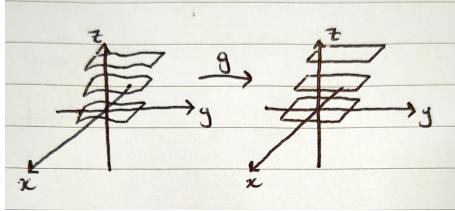


Figure 3.2.2

Then g is a smooth map on Ω with

$$dg_p = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ \frac{\partial F}{\partial x}(p) & \frac{\partial F}{\partial y}(p) & \frac{\partial F}{\partial z}(p) \end{pmatrix}.$$

Note that $\det(g_p) = \frac{\partial F}{\partial z}(p)$. Therefore, as by assumption we have $\frac{\partial F}{\partial z}(p) \neq 0$ it follows that dg_p is invertible and thus Theorem 3.2.5 can be applied. In particular, there exists a neighbourhood $U \subset \Omega$ of p such that $g : U \rightarrow g(U)$ is a diffeomorphism. Let

$$W := \{(u, v) \in \mathbb{R}^2 : (u, v, c) \in g^{-1}(U)\},$$

such that W is the projection of the intersection of the plane $z = c$ with $g^{-1}(U)$. Since $g^{-1}(U) \subset \mathbb{R}^3$ is open it follows that $W \subseteq \mathbb{R}^2$ is open. Let $\phi : W \rightarrow U$ be given by

$$\phi(u, v) = g^{-1}(u, v, c) = (u, v, h(u, v)),$$

where h is some smooth function. In particular, ϕ is a smooth homeomorphism onto its image, as Theorem 3.2.5 ensures g^{-1} is a smooth homeomorphism. Moreover,

$$d\phi_q = \begin{pmatrix} 1 & 0 \\ 0 & 1 \\ \partial_u h & \partial_v h \end{pmatrix}$$

is injective for all $q \in W$. Thus ϕ is a chart for $S = F^{-1}(c)$ at p . \square

Definition 3.2.7. A surface $S \subseteq \mathbb{R}^3$ is a regular level set if there is an open $\Omega \subset \mathbb{R}^3$ and a smooth function $F : \Omega \rightarrow \mathbb{R}$ such that $S = F^{-1}(c)$ for some $c \in \mathbb{R}$ and $\nabla F(p) \neq 0$ for all $p \in S$.

Example 3.2.8.

1. Consider $S^2 = \{x^2 + y^2 + z^2 = 1\}$. Let $\Omega = \mathbb{R}^3$, $F(x, y, z) = x^2 + y^2 + z^2$ and $c = 1$. Then $S^2 = F^{-1}(c)$ and

$$\nabla F(x, y, z) = (2x, 2y, 2z) \neq 0$$

for all $x, y, z \in S^2$. Hence, using Proposition 3.2.6, it follows that S^2 is a surface. Indeed, it is the surface of the unit sphere in \mathbb{R}^3 .

2. The torus

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

On the one hand, S can be viewed as the surface of revolution of the curve $\gamma : \dots$. On the other hand, S let

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

and $F(x, y, z) = (\sqrt{x^2 + y^2} - 2)^2 + z^2$. Observe that $S = F^{-1}(c)$. Moreover,

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

So that if $\nabla F = 0$ then $z = 0$ and either $\sqrt{x^2 + y^2} = 2$ or $x = y = 0$. Therefore, $\nabla F \neq 0$ on S and thus S is a regular surface by Proposition 3.2.6.

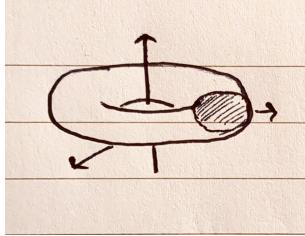
3. Let $\Omega = \mathbb{R}^3$, and let $F : \mathbb{R}^3 \rightarrow \mathbb{R}$ be given by

$$F(x, y, z) = yz.$$

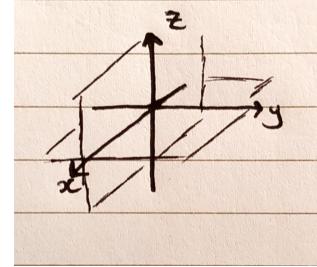
Then

$$\nabla F(x, y, z) = (0, z, y),$$

and so the Proposition 3.2.6 does not apply to $F^{-1}(0)$ which is $\{y = 0\} \cup \{z = 0\}$.



(a) The torus.



(b) The statement 2. of Example 3.2.8 is not a surfaces as it is self-intersecting.

Figure 3.2.3: Surfaces as level sets.

Proposition 3.2.9. Let $S \subseteq \mathbb{R}^3$ be a regular surface. Then for $p \in S$ there is a neighbourhood $V \subseteq S$ of p such that there is a smooth function f so that one of the following holds.

1. $V = \{z = f(x, y)\}$.
2. $V = \{y = f(x, z)\}$.
3. $V = \{x = f(y, z)\}$.

Proof. For $U \subset \mathbb{R}^2$ open, let $\phi : U \rightarrow S$ be a chart at p . In particular, let

$$\phi(u, v) = (x(u, v), y(u, v), z(u, v))$$

and $q = \phi^{-1}(p) \in U$. Then,

$$d\phi_q = \begin{pmatrix} \frac{\partial x}{\partial u} & \frac{\partial x}{\partial v} \\ \frac{\partial y}{\partial u} & \frac{\partial y}{\partial v} \\ \frac{\partial z}{\partial u} & \frac{\partial z}{\partial v} \end{pmatrix}$$

is injective and thus has rank 2. Hence, a 2×2 minor of $d\phi_q$ is invertible. Without loss of generality suppose that

$$\begin{pmatrix} \frac{\partial x}{\partial u} & \frac{\partial x}{\partial v} \\ \frac{\partial y}{\partial u} & \frac{\partial y}{\partial v} \end{pmatrix}$$

is invertible. Let $g : U \rightarrow \mathbb{R}^2$ be given by

$$g(u, v) = (x(u, v), y(u, v)).$$

By construction we can apply Theorem 3.2.5 to g to q to deduce there exists an open neighbourhood $V \subset U$ of q such that $g : V \rightarrow g(V)$ is a smooth diffeomorphism. Let $W = \phi(V)$, which is an open neighbourhood of $p = \phi(q)$ in S , then W is the graph of $f : g(V) \rightarrow \mathbb{R}$ given by

$$(x, y) \xrightarrow{g^{-1}} (u, v) \mapsto z(u, v).$$

That is, $f = z \circ g^{-1}$, which is smooth by the chain rule. \square

Remark 3.2.10. From Proposition 3.2.6 we have that regular level sets are regular surfaces. With Proposition 3.2.9 we have that a regular surface is locally a regular level set.

3.3 Tangent Vectors and Tangent Planes

Let $S \subset \mathbb{R}^3$ be a regular surface. For $p \in S$ there exists a linear space that best approximates the surface S at p .

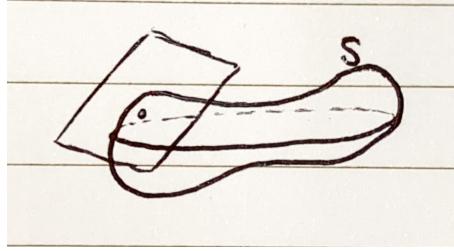


Figure 3.3.1: The best approximating plane to a surface at a point.

We can use these approximating surfaces to find the derivatives of functions of the form $f : S_1 \rightarrow S_2$ where S_1 and S_2 are regular surfaces.

Definition 3.3.1. Let $S \subseteq \mathbb{R}^3$ be a regular surface and let $p \in S$.

1. A vector $v \in \mathbb{R}^3$ is a tangent vector to S at p if there exists a smooth map $\gamma : (-\epsilon, \epsilon) \rightarrow S$ such that $\gamma(0) = p$ and $\gamma'(0) = v$.
2. The tangent plane of S at p is

$$T_p S = \{\gamma'(0) : \gamma(-\epsilon, \epsilon) \rightarrow S, \text{ smooth with } \gamma(0) = p\}.$$

That is, $T_p S$ is the set of all tangent vectors to S at p .

Remark 3.3.2.

1. Note that γ is not required to be a regular curve. This is so that the zero vector can be a tangent vector to the surface. Indeed, the zero vector is always in the tangent plane of a surface at a point as one can just take the curve $\gamma \equiv p$. The affine plane $T_p S + p$ is taken to be the plane that best approximates S at p .

2. Note this definition is independent of the chart used to describe S , however, it is a difficult characterisation to compute the tangent plane in practice.

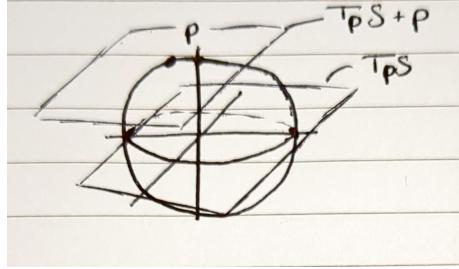


Figure 3.3.2: Using $T_p S + p$ to approximate a surface S at a point p .

Theorem 3.3.3. Let $S \subseteq \mathbb{R}^3$ be a regular surface. Let $p \in S$ and $\phi : U \rightarrow S$ be a chart with $\phi(q) = p$. Then

$$d\phi_q(\mathbb{R}^2) = \text{span} \left(\frac{\partial \phi}{\partial u}(q), \frac{\partial \phi}{\partial v}(q) \right) = T_p S.$$

In particular, $T_p S$ is a two-dimensional vector space.

Proof. Note that $d\phi_q(\mathbb{R}^2)$ is spanned by the columns of

$$d\phi_q = \begin{pmatrix} \frac{\partial \phi}{\partial u}(q) & \frac{\partial \phi}{\partial v}(q) \end{pmatrix}.$$

For any $v = a \frac{\partial \phi}{\partial u}(q) + b \frac{\partial \phi}{\partial v}(q) \in d\phi_q(\mathbb{R}^2)$, let $q = (u_0, v_0)$ and consider $\alpha : (-\epsilon, \epsilon) \rightarrow S$ given by

$$\alpha(t) = \phi(u_0 + at, v_0 + bt).$$

Then α is smooth with $\alpha(0) = p$. Moreover,

$$\begin{aligned} \alpha'(0) &= \frac{\partial \phi}{\partial u}(u_0, v_0) \frac{\partial u}{\partial t}(0) + \frac{\partial \phi}{\partial v}(u_0, v_0) \frac{\partial v}{\partial t}(0) \\ &= \frac{\partial \phi}{\partial y}(q)a + \frac{\partial \phi}{\partial v}(q)b \\ &= v. \end{aligned}$$

Therefore, $v \in T_p S$ and thus $d\phi_q(\mathbb{R}^2) \subseteq T_p S$. On the other hand, by Proposition 3.2.9, we can assume without loss of generality that S is given by $z = f(x, y)$ near p . Therefore, $\phi : U \rightarrow S$ is of the form

$$\phi(u, v) = (x(u, v), y(u, v), f(x(u, v), y(u, v))).$$

Let $q = \phi^{-1}(p) = (u_0, v_0)$. Moreover, consider $F : U \times (-\epsilon, \epsilon) \rightarrow \mathbb{R}^3$ given by

$$F(u, v, t) = (x(u, v), y(u, v), f(x(u, v), y(u, v)) + t).$$

Then $F(u_0, v_0, 0) = p$ and

$$dF_{(u_0, v_0, 0)} = \begin{pmatrix} x_u & x_v & 0 \\ y_u & y_v & 0 \\ f_x x_u + f_y y_u & f_x x_v + f_y y_v & 1 \end{pmatrix}.$$

Since $d\phi_q$ is invertible, the matrix

$$\begin{pmatrix} x_u & x_v \\ y_u & y_v \end{pmatrix}$$

is invertible, from the proof of Proposition 3.2.9. Thus $dF_{(u_0, v_0, 0)}$ is invertible and so Theorem 3.2.5 can be applied to F at $(u_0, v_0, 0)$ to obtain $G = F^{-1}$ a smooth homeomorphism near p . In particular, there are smooth functions $u(x, y)$ and $v(x, y)$ such that

$$G(x, y, f(x, y)) = (u(x, y), v(x, y), 0).$$

Assume that $\alpha'(0) \in T_p S$ for $\alpha : (-\epsilon, \epsilon) \rightarrow S$ a smooth map with $\alpha(0) = p$. Let $\alpha(t) = (x(t), y(t), v(x(t), y(t)))$ such that

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

Then by the chain rule it follows that

$$\alpha'(0) = \frac{\partial \phi}{\partial u}(q) \frac{\partial u}{\partial t}(0) + \frac{\partial \phi}{\partial v}(q) \frac{\partial v}{\partial t}(0).$$

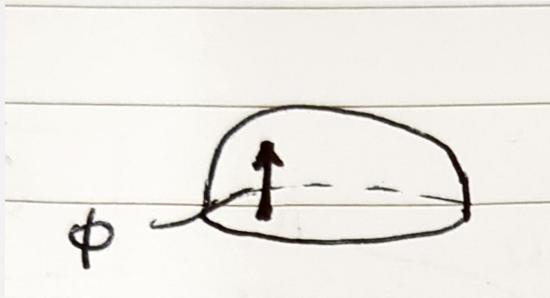
Thus $\alpha'(0) \in d\phi_q(\mathbb{R}^2)$ and so $T_p S \subseteq d\phi_q(\mathbb{R}^2)$. In conclusion it follows that $d\phi_q(\mathbb{R}^2) = T_p S$. \square

Example 3.3.4. Consider $S^2 = \{x^2 + y^2 + z^2 = 1\} \subseteq \mathbb{R}^3$ and $p = (0, 0, 1) \in S^2$. Let $\phi : \{u^2 + v^2 \leq 1\} \rightarrow S^2$ be given by

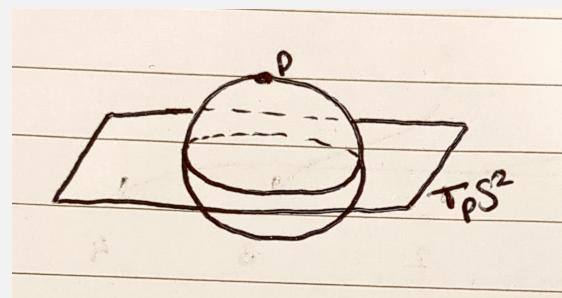
$$\phi(u, v) = \left(u, v, \sqrt{1 - u^2 - v^2} \right)$$

such that $\phi(0, 0) = (0, 0, 1)$. Then

$$\begin{aligned} T_p S^2 &= \text{span} \left(\frac{\partial \phi}{\partial u}(0), \frac{\partial \phi}{\partial v}(0) \right) \\ &= \text{span} \left(\left(1, 0, \frac{-u}{\sqrt{1-u^2-v^2}} \right) \Big|_{u=v=0}, \left(0, 1, \frac{-v}{\sqrt{1-v^2-u^2}} \right) \Big|_{u=v=0} \right) \\ &= \text{span}((1, 0, 0), (0, 1, 0)) \\ &= \{z = 0\}. \end{aligned}$$



(a) The chart ϕ used to calculate the tangent plane.



(b) The tangent plane for S at p .

Figure 3.3.3

Proposition 3.3.5. Let $F : \mathbb{R}^3 \rightarrow \mathbb{R}$ be smooth, with $\nabla F \neq 0$ on $S = F^{-1}(0)$. Then for any $p \in S$ we have

$$T_p S = \{v \in \mathbb{R}^3 : \langle v, \nabla F(0) \rangle = p\} = (\nabla F(p))^\perp.$$

Proof. Let $\gamma : (-\epsilon, \epsilon) \rightarrow S$ be a smooth map with $\gamma(0) = p$. Then $F(\gamma(t)) = 0$ for all $t \in (-\epsilon, \epsilon)$, which in particular means that $\frac{dF(\gamma(t))}{dt} = 0$. Hence,

$$\begin{aligned} 0 &= \frac{d}{dt} (F(\gamma(t)))|_{t=0} \\ &= \langle \nabla F(\gamma(0)), \gamma'(0) \rangle \\ &= \langle \nabla F(p), \gamma'(0) \rangle. \end{aligned}$$

Hence, $T_p S \subseteq (\nabla F(p))^\perp$. Therefore, as $T_p S$ and $(\nabla F(p))^\perp$ are two-dimensional vector spaces, it follows that $T_p S = (\nabla F(p))^\perp$. \square

Remark 3.3.6. The set $(\nabla F(p))^\perp$ is referred to as the orthogonal complement.

Example 3.3.7. Let

$$S = \{(x, y, z) \in \mathbb{R}^3 : z = x^2 + y^2\} = F^{-1}(0)$$

where $F(x, y, z) = x^2 + y^2 - z$. Let $p = (1, 3, 10)$. As

$$\nabla F = (2x, 2y, -1)$$

meaning

$$\nabla F(p) = (2, 6, -1),$$

it follows by Proposition 3.3.5 that

$$T_p S = (\nabla F(p))^\perp = \{(x, y, z) \in \mathbb{R}^3 : 2x + 6y - z = 0\}.$$

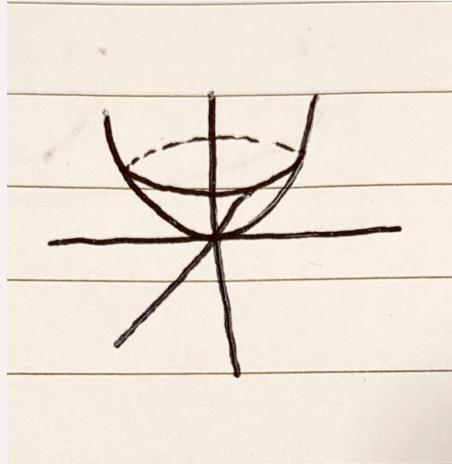


Figure 3.3.4: Paraboloid

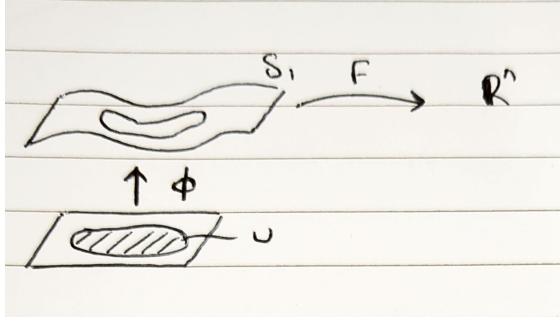
3.4 Smooth Maps on Surfaces

Definition 3.4.1. Let $S_1, S_2 \subseteq \mathbb{R}^3$ be regular surfaces.

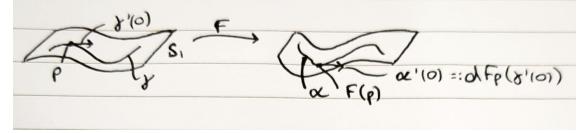
1. A map $F : S_1 \rightarrow \mathbb{R}^n$ is smooth if $F \circ \phi : U \rightarrow \mathbb{R}^n$ is smooth for every chart $\phi : U \rightarrow S_1$ for S_1 .
2. A map $F : S_1 \rightarrow S_2$ is smooth if it is smooth when considered as a map into \mathbb{R}^3 .

3. The differential of $F : S_1 \rightarrow S_2$ at $p \in S_1$ is the map $dF_p : T_p S_1 \rightarrow T_{F(p)} S_2$ is given as follows. For $\gamma'(0) \in T_p S_1$, where $\gamma : (-\epsilon, \epsilon) \rightarrow S_1$ is a smooth map with $\gamma(0) = p$ note that $\alpha(t) := F(\gamma(t)) : (-\epsilon, \epsilon) \rightarrow S_2$ is a smooth map with $\alpha(0) = F(\gamma(0)) = F(p)$. Then let

$$dF_p(\gamma'(0)) := \gamma'(0) = \frac{dF(\gamma(t))}{dt} \Big|_{t=0}.$$



(a) The composition of $F \circ \phi$ is a map from an open subset of \mathbb{R}^2 into \mathbb{R}^n for which we have a notion of smoothness.



(b) The differential map considers the tangent of curves.

Figure 3.4.1

Exercise 3.4.2. Let $S \subseteq \mathbb{R}^3$ be a regular surface. For $p \in S$ if $F \circ \phi : U \rightarrow \mathbb{R}^n$ is smooth for a chart $\phi : U \rightarrow S_1$ of p , show that $F : S \rightarrow \mathbb{R}^n$ is smooth as per statement 1. of Definition 3.4.1.

Proposition 3.4.3. Statement 3. of Definition 3.4.1 is independent of the choice of γ . That is, if $\gamma_1, \gamma_2 : (-\epsilon, \epsilon) \rightarrow S_1$ are such that $\gamma_1(0) = \gamma_2(0) = p$ and $\gamma'_1(0) = \gamma'_2(0)$ then

$$dF_p(\gamma'_1(0)) = dF_p(\gamma'_2(0)).$$

Proof. For a given chart $\phi : U \rightarrow S_1$ for S_1 at p consider the smooth maps $t \mapsto (u_1(t), v_1(t))$ and $t \mapsto (u_2, v_2(t))$ as constructed in the proof of Theorem 3.3.3 such that

$$\gamma_1(t) = \phi(u_1(t), v_1(t))$$

and

$$\gamma_2(t) = \phi(u_2(t), v_2(t)).$$

Let $\phi^{-1}(p) = (q_1, q_2)$, then

$$\gamma'_1(0) = \frac{\partial \phi}{\partial u}(q_1, q_2) \frac{\partial u_1}{\partial t}(0) + \frac{\partial \phi}{\partial v}(q_1, q_2) \frac{\partial v_1}{\partial t}(0)$$

and

$$\gamma'_2(0) = \frac{\partial \phi}{\partial u}(q_1, q_2) \frac{\partial u_2}{\partial t}(0) + \frac{\partial \phi}{\partial v}(q_1, q_2) \frac{\partial v_2}{\partial t}(0).$$

Since $\gamma'_1(0) = \gamma'_2(0)$ and $\left\{ \frac{\partial \phi}{\partial u}(q_1, q_2), \frac{\partial \phi}{\partial v}(q_1, q_2) \right\}$ are linearly independent, it follows that $u'_1(0) = u'_2(0)$ and $v'_1(0) = v'_2(0)$. That is, (u_1, v_1) and (u_2, v_2) have the same tangent vector at $t = 0$. On the other hand, as $F \circ \phi : \mathbb{R}^2 \rightarrow \mathbb{R}^3$ the chain rule can be applied to obtain

$$\begin{aligned} dF_p(\gamma'_i(0)) &= (F \circ \gamma_i)'(0) \\ &= \frac{d}{dt}(F \circ \phi(u_i(t), v_i(t)))|_{t=0} \\ &= \frac{\partial(F \circ \phi)}{\partial u}(q_1, q_2) \frac{\partial u_i}{\partial t}(0) + \frac{\partial(F \circ \phi)}{\partial v}(q_1, q_2) \frac{\partial v_i}{\partial t}(0). \end{aligned}$$

Thus, $dF_p(\gamma'_1(0)) = dF_p(\gamma'_2(0))$ meaning dF_p is independent of the choice of γ . \square

Proposition 3.4.4. *Let S_1, S_2 be regular surfaces. For $F : S_1 \rightarrow S_2$ and $p \in S_1$ the differential $dF_p : T_p S_1 \rightarrow T_{F(p)} S_2$ is a linear map.*

Proof. Let $v = \gamma'_1(0)$ and $w = \gamma'_2(0)$ be vectors in $T_p S_1$ with $\gamma_1, \gamma_2 : (-\epsilon, \epsilon) \rightarrow S_1$. Let $\phi : U \rightarrow S_1$ be a chart for S_1 at p . Then, as in the proof of Proposition 3.4.3, there are smooth maps $t \mapsto (u_1(t), v_1(t))$ and $t \mapsto (u_2, v_2(t))$ such that

$$\gamma_1(t) = \phi(u_1(t), v_1(t))$$

and

$$\gamma_2(t) = \phi(u_2(t), v_2(t)).$$

Without loss of generality let $\phi(0, 0) = p$. Let $\lambda \in \mathbb{R}$ be arbitrary and consider $\gamma_3 : (-\epsilon, \epsilon) \rightarrow S_1$ given by

$$\gamma_3(t) = \phi(u_1(t) + \lambda u_2(t), v_1(t) + \lambda v_2(t)).$$

Then $\gamma_3(0) = p$ and

$$\begin{aligned} \gamma'_3(0) &= \frac{\partial \phi}{\partial u}(0, 0)(u'_1(0) + \lambda u'_2(0)) + \frac{\partial \phi}{\partial v}(0, 0)(v'_1(0) + \lambda v'_2(0)) \\ &= \alpha'_1(0) + \lambda \alpha'_2(0) \\ &= v + \lambda w. \end{aligned}$$

Hence,

$$\begin{aligned} dF_p(v + \lambda w) &= dF_p(\gamma'_3(0)) \\ &= \frac{d}{dt}(F \circ \phi(u_1(t) + \lambda u_2(t), v_1(t) + \lambda v_2(t)))|_{t=0} \\ &= \frac{\partial(F \circ \phi)}{\partial u}(0, 0)(u'_1(0) + \lambda u'_2(0)) + \frac{\partial(F \circ \phi)}{\partial v}(0, 0)(v'_1(0) + \lambda v'_2(0)) \\ &= \left(\frac{\partial(F \circ \phi)}{\partial u}(0, 0)u'_1(0) + \frac{\partial(F \circ \phi)}{\partial v}(0, 0)v'_1(0) \right) \\ &\quad + \lambda \left(\frac{\partial(F \circ \phi)}{\partial u}(0, 0)u'_2(0) + \frac{\partial(F \circ \phi)}{\partial v}(0, 0)v'_2(0) \right). \end{aligned} \tag{3.4.1}$$

Using the chain rule observe that

$$\begin{aligned} \frac{\partial(F \circ \phi)}{\partial u}(0, 0)u'_1(0) + \frac{\partial(F \circ \phi)}{\partial v}(0, 0)v'_1(0) &= \frac{d}{dt}(F \circ \phi(u_1(t), v_1(t)))|_{t=0} \\ &= dF_p \left(\frac{d}{dt}\phi(u_1(t), v_1(t))|_{t=0} \right) \\ &= dF_p(\alpha'_1(0)) \\ &= dF_p(v). \end{aligned}$$

Similarly,

$$\frac{\partial(F \circ \phi)}{\partial u}(0, 0)u'_2(0) + \frac{\partial(F \circ \phi)}{\partial v}(0, 0)v'_2(0) = dF_p(w).$$

Therefore, (3.4.1) becomes

$$dF_p(v + \lambda w) = dF_p(v) + \lambda dF_p(w),$$

which shows that dF_p is linear. \square

If $S \subseteq \mathbb{R}^3$ is a regular surface, then the differential of $f : S \rightarrow \mathbb{R}$ at $p \in S$ is $df_p : T_p S \rightarrow \mathbb{R}$ given by

$$df_p(\gamma'(0)) = \frac{df(\gamma(t))}{dt} \Big|_{t=0}.$$

All results for the differential of smooth maps between surfaces hold for df_p , namely df_p is well-defined and linear.

Example 3.4.5. Recall that for $S^2 = \{x^2 + y^2 + z^2 = 1\} \subseteq \mathbb{R}^3$ and $p = (0, 0, 1)$, we have $T_p S^2 = \{z = 0\}$ and the chart $\phi : \{u^2 + v^2 \leq 1\} \rightarrow S^2$ given by

$$\phi(u, v) = (u, v, \sqrt{1 - u^2 - v^2})$$

such that $p = \phi(0, 0)$. Let $f : S^2 \rightarrow \mathbb{R}$ be given by $f(x, y, z) = y$. Then $f \circ \phi : \{u^2 + v^2 \leq 1\} \rightarrow \mathbb{R}$ is given by

$$f \circ \phi(u, v) = v,$$

which means that f is smooth. The vectors $\left\{ \frac{\partial \phi}{\partial u}(0, 0), \frac{\partial \phi}{\partial v}(0, 0) \right\}$ form a basis for $T_p S^2$. They are the tangent vectors to the curves $t \mapsto \phi(t, 0)$ and $t \mapsto \phi(0, t)$ respectively. Thus

$$df_p \left(\frac{\partial \phi}{\partial u}(0, 0) \right) = \frac{df \circ \phi(t, 0)}{dt} \Big|_{t=0} = 0$$

and

$$df_p \left(\frac{\partial \phi}{\partial v}(0, 0) \right) = \frac{df \circ \phi(0, t)}{dt} \Big|_{t=0} = 1.$$

In particular, if $w \in T_p S^2$ we can write

$$w = w_1 \frac{\partial \phi}{\partial u}(0, 0) + w_2 \frac{\partial \phi}{\partial v}(0, 0) = (w_1, w_2, 0).$$

Hence, $df_p(w) = w_2$.

3.5 Normal Vectors and the Gauss Map

Recall the importance of the normal in defining the curvature of a curve. Thus, to start discussing the curvature of a surface, it will be useful to investigate the normal vectors to surfaces.

Definition 3.5.1. Let $S \subseteq \mathbb{R}^3$ be a regular surface. Given $p \in S$, the normal $N \in \mathbb{R}^3$, to S at p is such that

$$\langle N, v \rangle = 0$$

for all $v \in T_p S$. In particular, N is a unit normal if $\langle N, N \rangle = 1$.

Definition 3.5.2. Let $S \subseteq \mathbb{R}^3$ be a regular surface. Then a smooth map $N : S \rightarrow S^2 \subseteq \mathbb{R}^3$ is a unit normal field if $N(p)$ is a unit normal to S at p for every $p \in S$.

Locally, unit normal fields always exist. If $\phi : U \rightarrow S$ is a chart, then $\left\{ \frac{\partial \phi}{\partial u}(q), \frac{\partial \phi}{\partial v}(q) \right\}$ spans $T_{\phi(q)} S$ for all $q \in U$. Thus,

$$N(p) := \frac{\frac{\partial \phi}{\partial u}(q) \times \frac{\partial \phi}{\partial v}(q)}{\left| \frac{\partial \phi}{\partial u}(q) \times \frac{\partial \phi}{\partial v}(q) \right|}.$$

Similarly, if $S = F^{-1}(c)$ for some smooth function $F : \mathbb{R}^3 \rightarrow \mathbb{R}$ with $\nabla F(p) \neq 0$ and $c \in \mathbb{R}$. Then, $T_p S = (\nabla F(p))^\perp$ and so

$$N(p) = \frac{\nabla F(p)}{|\nabla F(p)|}$$

is a unit normal field. Therefore, in this case, the unit normal field exists globally, however, this is not always the case.

Definition 3.5.3. A regular surface $S \subseteq \mathbb{R}^3$ is orientable if there exists a unit normal field $N : S \rightarrow S^2$.

Remark 3.5.4. The tangent plane at a point of a regular surface $S \subset \mathbb{R}^3$ is a two-dimensional subspace of \mathbb{R}^3 . Consequently, there exist two unit normal vectors to the tangent plane. The choice of normal vector fields is canonically for regular sets using $\nabla F(p)$. In other cases, we refer to the choice as an orientation of a surface. In particular, an oriented surface is an orientable surface for which the choice of normal has been made.

Definition 3.5.5. For an oriented surface, S , the map $N : S \rightarrow S^2$ is referred to as the Gauss map of S .

Example 3.5.6.

1. The Möbius strip is a non-orientable surface.
2. Recall that $S^2 = F^{-1}(1)$ where $F : \mathbb{R}^3 \rightarrow \mathbb{R}$ is given by $F(x, y, z) = x^2 + y^2 + z^2$. Therefore, S^2 is orientable. In particular,

$$N(x, y, z) = \frac{\nabla F(x, y, z)}{|\nabla F(x, y, z)|} = (x, y, z).$$

Hence, the Gauss map for S^2 , namely $N : S^2 \rightarrow S^2$ is the identity map.

3. Consider $S = \{ax + by + cz = d\} \subseteq \mathbb{R}^3$ for some $a, b, c, d \in \mathbb{R}$. Then $S = F^{-1}(d)$ for $F : \mathbb{R}^3 \rightarrow \mathbb{R}$ given by $F(x, y, z) = ax + by + cz$. Thus,

$$N(x, y, z) = \frac{(a, b, c)}{\sqrt{a^2 + b^2 + c^2}},$$

which is constant.

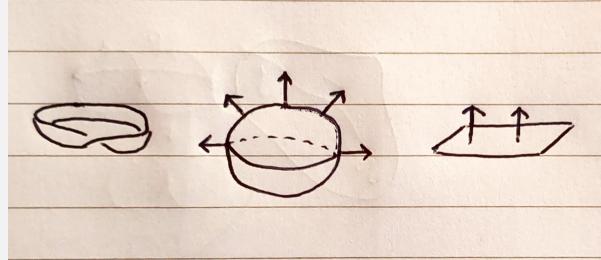


Figure 3.5.1: The Möbius strip is not orientable as a global normal unit field will not be continuous, it will flip along a boundary. The sphere and the plane are orientable surfaces.

Exercise 3.5.7. Show that the Gauss map for S^2 obtain in statement 2. of Example 3.5.6 can similarly be obtain through the chart $\phi : \{u^2 + v^2 \leq 1\} \rightarrow S^2$ given by

$$\phi(u, v) = \left(u, v, \sqrt{1 - u^2 - v^2} \right).$$

The differential of N at $p \in S$, namely $dN_p : T_p S \rightarrow T_{N(p)} S^2$ is a linear map.

Proposition 3.5.8. Let $S \subseteq \mathbb{R}^3$ be an orientable surface with Gauss map $N : S \rightarrow S^2$. Then for each $p \in S$ we have $T_p S = T_{N(p)} S^2$.

Proof. Recall that $q \in S^2$ is normal to $T_q S^2$. That is,

$$T_{N(p)} = \{v \in \mathbb{R}^3 : \langle N(p), v \rangle = 0\} = T_p S.$$

□

In particular, from Proposition 3.5.8 we see that dN_p is a linear map with

$$dN_p : T_p S \rightarrow T_p S.$$

Example 3.5.9.

1. Let

$$S_r^2 := \{x^2 + y^2 + z^2 = r^2\} = F^{-1}(r^2),$$

where $F(x, y, z) = x^2 + y^2 + z^2$. Hence,

$$N(x, y, z) = \frac{1}{r}(x, y, z).$$

Let $\gamma : (-\epsilon, \epsilon) \rightarrow S_r^2$ be a regular curve with $\gamma(0) = p$. Then

$$dN_p(\gamma'(0)) = \frac{dN(\gamma(t))}{dt} \Big|_{t=0} = \frac{1}{r} \frac{d(\gamma(t))}{dt} \Big|_{t=0} = \frac{1}{r} \gamma'(0).$$

Thus, $dN_p : T_p S_r^2 \rightarrow T_p S_r^2$ is $dN_p = \frac{1}{r} \text{Id}$.

2. For the plane $S = \{ax + by + cz = d\} \subseteq \mathbb{R}^3$ we have $N = \frac{(a, b, c)}{\sqrt{a^2 + b^2 + c^2}}$ and so $dN_p = 0$.

These suggest a connection between dN_p and the curvature of a surface, as the map dN_p conforms with our intuition of the curvature of a surface.

The derivative of the Gauss map, $dN_p : T_p S \rightarrow T_{N(p)} S^2$, can be viewed from different perspectives.

1. As Proposition 3.5.8 notes, the tangent plane $T_{N(p)} S^2$ consists of the vectors orthogonal to $N(p)$, thus it is the same as $T_p S$. Therefore, we can view the derivative as a map $dN_p : T_p S \rightarrow T_p S$.
2. For $\gamma'(0) \in T_p S$, since N is the unit normal we must have $\langle N(\gamma(t)), N(\gamma(t)) \rangle = 1$. Consequently,

$$\begin{aligned} \langle dN_p(\gamma'(0)), N_p(\gamma(0)) \rangle &= \left\langle \frac{d}{dt} N_p(\gamma(t)) \Big|_{t=0}, N_p(\gamma(0)) \right\rangle \\ &= \frac{1}{2} \frac{d}{dt} \langle N_p(\gamma(t)), N_p(\gamma(t)) \rangle \Big|_{t=0} \\ &= 0. \end{aligned}$$

Thus, $dN_p(\gamma'(0))$ is orthogonal to $N(\gamma(0))$, meaning $dN_p(\gamma'(0)) \in T_p S$.

Proposition 3.5.10. Let $S \subseteq \mathbb{R}^3$ be a non-empty, compact, connected and oriented regular surface. Then the Gauss map $N : S \rightarrow S^2$ is surjective.

Proof. Step 1: Characterise the normal vectors of S .

For $v \in S^2$, let $f_v(x) = \langle x, v \rangle$. Suppose that f_v has a maximum at $p \in S$. For $w \in T_p S$ there exists a smooth map $\gamma : (-\epsilon, \epsilon) \rightarrow S$ with $\gamma(0) = p$ and $\gamma'(0) = w$. Let $f := f_v \circ \gamma$. Then f has a maximum at $t = 0$ as $\gamma(0) = p$. It follows that

$$0 = \frac{df}{dt} \Big|_{t=0} = \frac{d}{dt} \langle \gamma(t), v \rangle \Big|_{t=0} = \langle \gamma'(0), v \rangle = \langle w, v \rangle.$$

Which implies that $v \in (T_p S)^\perp$, and so v is normal to S at p .

Step 2: Show that v as characterised in step 1 is an outward normal vector to S .

For $v \in S^2$ suppose that f_v is maximized at $p \in S$, that is

$$\langle x, v \rangle \leq \langle p, v \rangle =: c$$

for all $x \in S$. Note that $\{x \in \mathbb{R}^3 : \langle x, v \rangle = c\}$ is a plane containing p and divides \mathbb{R}^3 . In particular,

$$S \subseteq \{x \in \mathbb{R}^3 : \langle x, v \rangle \leq c\}.$$

Thus, v is an outward normal to S .

Step 3: Deduce that N is surjective.

Observe that for any $v \in S^2$ we have

$$\begin{aligned} |f_v(s_1) - f_v(s_2)| &= |\langle s_1, v \rangle - \langle s_2, v \rangle| \\ &= |\langle s_1 - s_2, v \rangle| \\ &\stackrel{(1)}{\leq} |s_1 - s_2| |v| \\ &= |s_1 - s_2|, \end{aligned}$$

where (1) is an application of the Cauchy-Schwartz inequality. Hence, we see that f_v is continuous. In particular, as S is compact this means that the function $f_v : S \rightarrow \mathbb{R}$ achieves its maximum at some point $p \in S$. From part step 2 we know that v is normal to S at p . Therefore, $N(p) = v$ which implies that N is surjective. \square

3.6 Second Fundamental Form

Throughout let S be an oriented surface with $p \in S$.

Definition 3.6.1. *The second fundamental form of S at p is the map $A_p : T_p S \times T_p S \rightarrow \mathbb{R}$ given by*

$$A_p(x, y) = -\langle x, dN_p(y) \rangle,$$

where $N : S \rightarrow S^2$ is the Gauss map of S .

Example 3.6.2.

1. For S_r^2 , the sphere of radius r , as $N = \frac{1}{r} \text{id}$ we have that

$$A_p(x, y) = -\frac{1}{r} \langle x, y \rangle$$

for all $p \in S_r^2$.

2. For S a plane, as N is constant we have that $A_p(x, y) \equiv 0$ for all $p \in S$.

Proposition 3.6.3. *The second fundamental form $A_p : T_p S \times T_p S \rightarrow \mathbb{R}$ is a symmetric bilinear map.*

Proof. Observe that

$$\begin{aligned} A_p(x, \lambda_1 y + \lambda_2 z) &= -\langle z, dN_p(\lambda_1 y + \lambda_2 z) \rangle \\ &= -\langle x, \lambda_1 dN_p(y) + \lambda_2 dN_p(z) \rangle \\ &= \lambda_1 \langle -x, dN_p(y) \rangle - \lambda_2 \langle x, dN_p(z) \rangle \\ &= \lambda_1 A_p(x, y) + \lambda_2 A_p(x, z), \end{aligned}$$

and

$$\begin{aligned} A_p(\lambda_1 x + \lambda_2 y, z) &= -\langle \lambda_1 x + \lambda_2 y, dN_p(z) \rangle \\ &= -\lambda_1 \langle x, dN_p(z) \rangle - \lambda_2 \langle y, dN_p(z) \rangle \\ &= \lambda_1 A_p(x, z) + \lambda_2 A_p(y, z), \end{aligned}$$

meaning A_p is bilinear. Let $\phi : U \rightarrow S$ be a chart for S at p , and let $q = \phi^{-1}(p)$. Then

$$\begin{aligned} A_p\left(\frac{\partial\phi}{\partial u}(q), \frac{\partial\phi}{\partial v}(q)\right) &= -\left\langle \frac{\partial\phi}{\partial u}(q), dN_p\left(\frac{\partial\phi}{\partial v}(q)\right) \right\rangle \\ &= -\left\langle \frac{\partial\phi}{\partial u}(q), \frac{\partial(N \circ \phi)}{\partial v}(q) \right\rangle. \end{aligned} \quad (3.6.1)$$

Since $N \circ \phi$ maps into vectors normal to S , and $\frac{\partial\phi}{\partial u}$ is in the tangent space of S it follows that

$$\left\langle \frac{\partial\phi}{\partial u}, N \circ \phi \right\rangle = 0.$$

Differentiating with respect to v it follows that

$$0 = \frac{\partial}{\partial v} \left\langle \frac{\partial\phi}{\partial u}, N \circ \phi \right\rangle = \left\langle \frac{\partial^2\phi}{\partial v \partial u}, N \circ \phi \right\rangle + \left\langle \frac{\partial\phi}{\partial u}, \frac{\partial(N \circ \phi)}{\partial v} \right\rangle.$$

Similarly,

$$0 = \left\langle \frac{\partial^2\phi}{\partial u \partial v}, N \circ \phi \right\rangle + \left\langle \frac{\partial\phi}{\partial v}, \frac{\partial(N \circ \phi)}{\partial u} \right\rangle,$$

where we have exchanged the order of differentiation in the first inner product as ϕ is smooth. Combined with (3.6.1) it follows that

$$\begin{aligned} A_p\left(\frac{\partial\phi}{\partial u}(q), \frac{\partial\phi}{\partial v}(q)\right) &= -\left\langle \frac{\partial\phi}{\partial u}(q), \frac{\partial(N \circ \phi)}{\partial v}(q) \right\rangle \\ &= \left\langle \frac{\partial^2\phi}{\partial v \partial u}(q), (N \circ \phi)(q) \right\rangle \\ &= -\left\langle \frac{\partial\phi}{\partial v}(q), \frac{\partial(N \circ \phi)}{\partial u}(q) \right\rangle \\ &= A_p\left(\frac{\partial\phi}{\partial v}(q), \frac{\partial\phi}{\partial u}(q)\right). \end{aligned}$$

Therefore, as $\left\{ \frac{\partial\phi}{\partial u}(q), \frac{\partial\phi}{\partial v}(q) \right\}$ forms a basis for $T_p(S)$ we deduce that A_p is symmetric. □

Remark 3.6.4. If ϕ is a chart for S at p , then as $\left\{ \frac{\partial\phi}{\partial u}(q), \frac{\partial\phi}{\partial v}(q) \right\}$ is an orthogonal basis for $T_p S$. Thus we can recover $dN_p(x)$ through

$$dN_p(x) = -A_p\left(\frac{\partial\phi}{\partial u}(q), x\right) \frac{\partial\phi}{\partial u}(q) - A_p\left(\frac{\partial\phi}{\partial v}(q), x\right) \frac{\partial\phi}{\partial v}(q),$$

for $x \in T_p S$.

Proposition 3.6.5. The differential of the Gauss map, $dN_p : T_p S \rightarrow T_p S$ is diagonalisable with real eigenvalues. That is, there exists $\lambda_1, \lambda_2 \in \mathbb{R}$ and an orthonormal basis $\{X_1, X_2\}$ for $T_p S$ such that $dN_p(X_1) = -\lambda_1 X_1$ and $dN_p(X_2) = -\lambda_2 X_2$.

Proof. Let $\{v, w\}$ be an orthonormal basis for $T_p S$ with

$$M = \begin{pmatrix} a_1 & a_2 \\ b_1 & b_2 \end{pmatrix}$$

being the associated matrix for dN_p . That is,

$$\begin{cases} dN_p(v) = a_1 v + a_2 w \\ dN_p(w) = b_1 v + b_2 w. \end{cases}$$

However, using Proposition 3.6.3 we have

$$a_2 = \langle w, dN_p(v) \rangle = -A_p(w, v) = -A_p(v, w) = \langle v, dN_p(w) \rangle = b_1.$$

Thus, M is a real symmetric matrix and thus diagonalisable with real eigenvalues. \square

Definition 3.6.6.

1. The real numbers $\lambda_1 \leq \lambda_2$ from Proposition 3.6.5 are referred to as the principal curvatures of the surface S at p .
2. The orthonormal tangent vectors $\{X_1, X_2\}$ from Proposition 3.6.5 are referred to as the principal directions of S at p .

Remark 3.6.7.

1. One should understand λ_1, λ_2 as functions of $p \in S$.

2. Note that

$$A_p(X_1, X_1) = -\langle X_1, dN_p(X_1) \rangle = \langle X_1, \lambda_1 X_1 \rangle = \lambda_1 |X_1|^2 = \lambda_1(p).$$

Similarly, $A_p(X_2, X_2) = \lambda_2(p)$ and $A_p(X_1, X_2) = A_p(X_2, X_1) = 0$.

Proposition 3.6.8.

If $\lambda_1(p) \leq \lambda_2(p)$ are the principal curvatures at $p \in S$, then

$$\lambda_1 = \min \{A_p(x, x) : x \in T_p S, |x| = 1\}$$

and

$$\lambda_2 = \max \{A_p(x, x) : x \in T_p S, |x| = 1\}.$$

Proof. For $x \in T_p S$ with $|x| = 1$, one can write $x = c_1 X_1 + c_2 X_2$ where $c_1^2 + c_2^2 = 1$. Then as A_p is bilinear it follows that

$$\begin{aligned} A_p(x, x) &= A_p(c_1 X_1 + c_2 X_2, c_1 X_1 + c_2 X_2) \\ &= c_1^2 A_p(X_1, X_1) + 2c_1 c_2 A_p(X_1, X_2) + c_2^2 A_p(X_2, X_2). \end{aligned}$$

Therefore,

$$A_p(x, x) = c_1^2 \lambda_1 + c_2^2 \lambda_2 \geq c_1^2 \lambda_1 + c_2^2 \lambda_1 = \lambda_1,$$

and

$$A_p(x, x) = c_1^2 \lambda_1 + c_2^2 \lambda_2 \leq c_1^2 \lambda_2 + c_2^2 \lambda_2 = \lambda_2.$$

With λ_1 and λ_2 being realised for $x = X_1$ and $x = X_2$ respectively. \square

Example 3.6.9.

1. For S_r^2 , the sphere of radius r , we have that $A_p(x, y) = -\frac{1}{r}\langle x, y \rangle$ for all $x, y \in T_p S$. Thus,

$$\lambda_1(p) = \lambda_2(p) = -\frac{1}{r}$$

for all $p \in S_r^2$. If one were to re-orientate the surface such that N points inward, the signs of the principal curvatures would switch.

2. If S is a plane then $A_p(x, y) = 0$ for all $x, y \in T_p S$, and so

$$\lambda_1(p) = \lambda_2(p) = 0$$

for all $p \in S$.

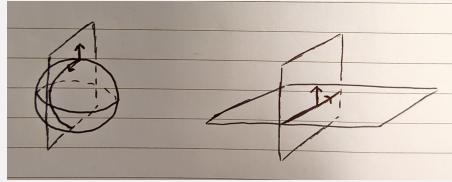


Figure 3.6.1: The intersecting planar curves for the sphere and plane.

Exercise 3.6.10. Suppose S is a connected surface with $\lambda_1(p) = \lambda_2(p) = 0$ for all $p \in S$. Show then that S must lie in a plane.

3.7 Normal Curvature

Let $\gamma : (-\epsilon, \epsilon) \rightarrow S$ be a regular curve in S with $\gamma(0) = p$. The curvature of γ at p is given by $\mathbf{k}(0) := \gamma''(0) \in \mathbb{R}^3$. We can write

$$\mathbf{k}(0) = \langle \mathbf{k}(0), N(p) \rangle N(p) + \mathbf{k}_{\text{tang}}(0),$$

where $\langle \mathbf{k}(0), N(p) \rangle N(p) \in (T_p S)^\perp$ and $\mathbf{k}_{\text{tang}}(0) \in T_p S$. The curvature component perpendicular to S , namely $\langle \mathbf{k}(0), N(p) \rangle N(p)$, measure the curving of S at p in the direction of $\gamma'(0)$. In particular,

$$k_n(0) := \langle \mathbf{k}(0), N(p) \rangle$$

is referred to as the normal curvature of S at p in the direction $\gamma'(0)$.

Theorem 3.7.1. Let $S \subset \mathbb{R}^3$ be an orientable regular surface. Let $p \in S$ and $v \in T_p S$ with $|v| = 1$. Then, the normal curvature of S at p in the direction of v satisfies

$$k_n(p) = A_p(v, v).$$

Proof. Let $\gamma : (-\epsilon, \epsilon) \rightarrow S$ be a regular curve parameterised by arc length, with $\gamma(0) = p$ and $\gamma'(0) = v$. Then for $t \in (-\epsilon, \epsilon)$ we have

$$\langle \gamma'(t), N(\gamma(t)) \rangle = 0.$$

Differentiating this with respect to t , and evaluating at $t = 0$ yields

$$\begin{aligned} 0 &= \langle \gamma''(0), N(\gamma(0)) \rangle + \langle \gamma'(0), dN_{\gamma(0)}(c'(0)) \rangle \\ &= \langle \mathbf{k}(0), N(p) \rangle + \langle v, dN_p(v) \rangle \\ &= k_n(p) - A_p(v, v). \end{aligned}$$

□

Remark 3.7.2.

1. A regular curve $\gamma : I \rightarrow S$ is an asymptotic line if the normal curvature at every point $\gamma(t)$ is zero. That is, $\langle \mathbf{k}(t), N(\gamma(t)) \rangle = 0$ for all $t \in I$.
2. Theorem 3.7.1 says that for any $x \in T_p S$ with $|x| = 1$, the planar curve

$$S \cap \text{span} \{x, N(p)\} \subseteq \text{span} \{x, N(p)\}$$

has curvature at p is $A_p(x, x)$.

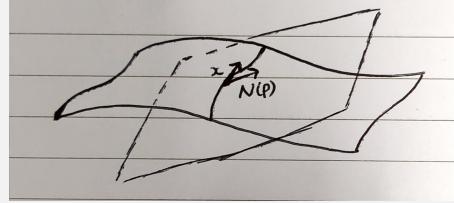


Figure 3.7.1

Thus, in conjunction with Proposition 3.6.8, we note then that the principal curvatures of an orientable surface are the minimum and maximum values of the normal curvature at p along all directions in $T_p S$ respectively.

3.8 Gauss and Mean Curvature

Definition 3.8.1. Let S be an oriented surface with Gauss map $N : S \rightarrow \mathbb{S}^2$.

1. The Gauss curvature of S is the map $K : S \rightarrow \mathbb{R}$ given by

$$K(p) = \det(dN_p) = \lambda_1(p)\lambda_2(p).$$

2. The mean curvature of S is the map $H : S \rightarrow \mathbb{R}$ given by

$$H(p) := -\frac{1}{2}\text{tr}(dN_p) = \frac{\lambda_1(p) + \lambda_2(p)}{2}.$$

Remark 3.8.2.

1. The map K can be thought of as the geometric average of principal curvatures, whereas H is the arithmetic average.
2. The constructions of λ_1, λ_2, K and H are very much extrinsic. However, as an object K is an intrinsic object, which is made precise in Theorem 3.14.1.

Example 3.8.3.

1. The sphere of radius r , \mathbb{S}_r^2 , has $\lambda_1(p) = \lambda_2(p) = \frac{1}{r}$ for all $p \in \mathbb{S}_r^2$. Thus,

$$K(p) = \frac{1}{r^2}$$

and

$$H(p) = \frac{1}{r}$$

for all $p \in S_r^2$.

2. The plane, Π , has $\lambda_1(p) = \lambda_2(p) = 0$ for all $p \in \Pi$. So $K \equiv H \equiv 0$.

3. Consider the cylinder

$$C_r := \{(x, y, z) \in \mathbb{R}^3 : x^2 + y^2 = r^2\} = F^{-1}(r^2)$$

where $F(x, y, z) = x^2 + y^2$. Note that

$$\nabla F(x, y, z) = 2(x, y, 0),$$

and so $\nabla F(x, y, z) \neq 0$ on C_r . Hence, C_r is a regular level set. In particular,

$$N(x, y, z) = \frac{2(x, y, 0)}{\sqrt{4(x^2 + y^2)}} = \frac{1}{r}(x, y, 0).$$

Given $v = (v_1, v_2, v_3) = \gamma'(0) \in T_{(x,y,z)} C_r$, where $\gamma : (-\epsilon, \epsilon) \rightarrow C_r$ is some smooth map, we have

$$\begin{aligned} dN_{(x,y,z)}(v) &= \frac{d(N(\gamma(t)))}{dt} \Big|_{t=0} \\ &= \frac{1}{r} (\gamma'_1(0), \gamma'_2(0), 0) \\ &= \frac{1}{r} (v_1, v_2, 0), \end{aligned}$$

hence,

$$A_{(x,y,z)}(v, w) = -\frac{1}{r} (v_1 w_1 + v_2 w_2).$$

Observe that $X_1 = (0, 0, 1)$ and $X_2 = \frac{1}{r}(-y, x, 0)$ are unit tangent vectors with

$$dN_{(x,y,z)}(X_1) = 0$$

and

$$dN_{(x,y,z)}(X_2) = \frac{1}{r^2} (-y, x, 0) = \frac{1}{r} X_2.$$

Therefore, X_1 and X_2 are the principal directions and the corresponding principal curvatures are $\lambda_1(p) = 0$ and $\lambda_2(p) = -\frac{1}{r}$. In particular, $K(p) = 0$ and $H(p) = -\frac{1}{2r}$ for all $p \in C_r$.

These surfaces are examples of constant mean curvature surfaces. Moreover, the plane is an example of a minimal surface, that is $H \equiv 0$.

4. Consider the surface

$$S = \{x^2 - y^2 = z\} = F^{-1}(0)$$

where $F(x, y, z) = x^2 - y^2 - z$.

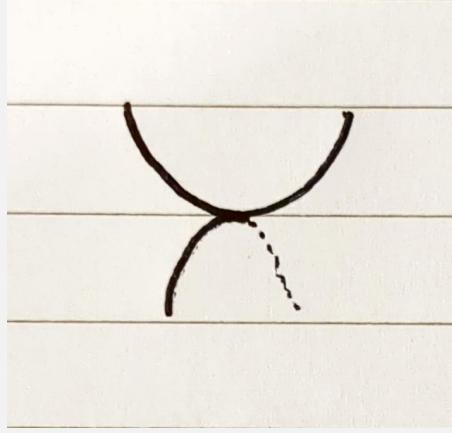


Figure 3.8.1: A surface with negative Gauss curvature.

Observe that

$$\nabla F(x, y, z) = (2x, -2y, -1) \neq 0$$

on S . Thus,

$$N(x, y, z) = \frac{\nabla F}{|\nabla F|} = \frac{(2x, -2y, -1)}{\sqrt{4(x^2 + y^2) + 1}}.$$

In particular,

$$N(0) = (0, 0, -1).$$

For $(v_1, v_2, v_3) \in T_0 S$ let $\gamma : (-\epsilon, \epsilon) \rightarrow S$ be a smooth map such that $\gamma(0) = 0$ and $\gamma'(0) = (v_1, v_2, v_3)$. Then

$$(N \circ \gamma)(t) = \frac{1}{\sqrt{4(\gamma_1(t)^2 + \gamma_2(t)^2) + 1}} (2\gamma_1(t), -2\gamma_2(t), -1).$$

Note that

$$\frac{d}{dt} \left(\frac{2\gamma_1(t)}{\sqrt{4(\gamma_1(t)^2 + \gamma_2(t)^2) + 1}} \right) = \frac{2\gamma'_1(t)\sqrt{4(\gamma_1(t)^2 + \gamma_2(t)^2) + 1} - \frac{4(\gamma_1(t)\gamma'_1(t) + \gamma_2(t)\gamma'_2(t))2\gamma_1(t)}{4(\gamma_1(t)^2 + \gamma_2(t)^2) + 1}}{4(\gamma_1(t)^2 + \gamma_2(t)^2) + 1}$$

so that

$$\frac{d}{dt} \left(\frac{2\gamma_1(t)}{\sqrt{4(\gamma_1(t)^2 + \gamma_2(t)^2) + 1}} \right) \Big|_{t=0} = 2v_1.$$

Similarly, one shows that

$$\frac{d}{dt} \left(-\frac{2\gamma_2(t)}{\sqrt{4(\gamma_1(t)^2 + \gamma_2(t)^2) + 1}} \right) \Big|_{t=0} = -2v_2$$

and

$$\frac{d}{dt} \left(-\frac{1}{\sqrt{4(\gamma_1(t)^2 + \gamma_2(t)^2) + 1}} \right) \Big|_{t=0} = 0,$$

so that

$$dN_0(v_1, v_2, v_3) = (2v_1, -2v_2, 0).$$

Then note that $X_1 = (1, 0, 0), X_2 = (0, 1, 0) \in T_0 S$ are unit vectors with

$$dN_0(X_1) = 2X_1$$

and

$$dN_0(X_2) = -2X_2.$$

Thus $\lambda_1(0) = -2$ and $\lambda_2(0) = 2$. This implies that $K(0) = -4$ and $H(0) = 0$.

Exercise 3.8.4. Compute the Gauss curvature and mean curvature for the

1. helicoid, and
2. catenoid

from Example 3.2.1.

Remark 3.8.5. If the orientation of S is reversed, that is N is replaced with $-N$, then the sign of H changes whereas the sign of K does not.

Proposition 3.8.6. For a compact regular surface S , there exists a $p \in S$ such that $K(p) > 0$.

Proof. For S , there exists a point $p \in S$ that attains the maximum of the continuous map $x \mapsto |x|$. Thus, for any curve $\gamma : (\epsilon, \epsilon) \rightarrow S$ with $\gamma(0) = p$ by Proposition 2.3.10 we have that

$$|k_\gamma(0)| \geq \frac{1}{|\gamma'(0)|} = \frac{1}{|p|}. \quad (3.8.1)$$

Recall that $k_\gamma(0)$ is equal to the normal curvature of the surface S at p in the direction $\gamma'(0)$. Thus, from Theorem 3.7.1 as $|\gamma'(0)| = 1$, we have that

$$|k_\gamma(0)| = |A_p(\gamma'(0), \gamma'(0))|.$$

Thus, using (3.8.1) it follows that for any $v \in T_p S$ with $|v| = 1$ we have

$$|A_p(v, v)| \geq \frac{1}{|p|}. \quad (3.8.2)$$

Now suppose $K(p) < 0$, then assuming $\lambda_1(p) \leq \lambda_2(p)$ it must be the case that $\lambda_1(p) > 0$ and $\lambda_2(p) > 0$. In particular, by continuity and using Proposition 3.6.8 it follows that there exists a $v \in T_p S$ such that $A_p(v, v) = 0$. However, this contradicts (3.8.2) as $\frac{1}{|p|} > 0$. Therefore, $\lambda_1(p)$ and $\lambda_2(p)$ have the same sign and thus $K(p) > 0$. \square

Exercise 3.8.7. Let $\gamma : I \rightarrow S$ be an asymptotic line as given by statement 1 of Remark 3.7.2.

1. Show that $K(p) \leq 0$ for all points $p \in \gamma(I)$.
2. Moreover, show that if $\mathbf{k}(t) \neq 0$ for all $t \in I$, then $|\tau(p)| = \sqrt{-K(p)}$, where τ is the torsion of γ .

3.9 Umbilical Points

Definition 3.9.1. Let S be an oriented surface.

1. A point $p \in S$ is referred to as an umbilical if $\lambda_1(p) = \lambda_2(p)$.
2. The surface S is said to be totally umbilic if every point $p \in S$ is umbilical.

Remark 3.9.2. At umbilical points, $dN_p = -\lambda(p)\text{Id}$ and $A_p(x, y) = \lambda(p)\langle x, y \rangle$.

Henceforth, we assume that all surfaces are connected.

Theorem 3.9.3 (Classification of Totally Umbilic Surfaces). *Let S be an orientable surface that is totally umbilic. Then S is an open subset of either a plane or a sphere.*

Proof. Let $\phi : U \rightarrow S$ be a chart. There exists $\lambda : S \rightarrow \mathbb{R}$ such that $\lambda_1(p) = \lambda_2(p) = \lambda(p)$ for all $p \in S$.

Step 1: Show that λ is a constant function.

Observe that

$$\frac{\partial(N \circ \phi)}{\partial u}(q) = dN_{\phi(q)} \left(\frac{\partial \phi}{\partial u}(q) \right) = -\lambda(\phi(q)) \frac{\partial \phi}{\partial u}(q) \quad (3.9.1)$$

and

$$\frac{\partial(N \circ \phi)}{\partial v}(q) = dN_{\phi(q)} \left(\frac{\partial \phi}{\partial v}(q) \right) = -\lambda(\phi(q)) \frac{\partial \phi}{\partial v}(q) \quad (3.9.2)$$

for all $q \in U$. Hence,

$$\frac{\partial^2(N \circ \phi)}{\partial u \partial v} = -\partial_v(\lambda \circ \phi) \frac{\partial \phi}{\partial u} - (\lambda \circ \phi) \frac{\partial^2 \phi}{\partial u \partial v}$$

and

$$\frac{\partial^2(N \circ \phi)}{\partial u \partial v} = -\partial_u(\lambda \circ \phi) \frac{\partial \phi}{\partial v} - (\lambda \circ \phi) \frac{\partial^2 \phi}{\partial u \partial v}$$

where we have used the fact $N \circ \phi$ and ϕ are smooth and so the derivatives commutes. Thus,

$$\partial_u(\lambda \circ \phi) \frac{\partial \phi}{\partial v} = \partial_v(\lambda \circ \phi) \frac{\partial \phi}{\partial u}$$

in U . However, since $\left\{ \frac{\partial \phi}{\partial u}, \frac{\partial \phi}{\partial v} \right\}$ are linearly independent it follows that

$$\partial_u(\lambda \circ \phi) = \partial_v(\lambda \circ \phi) = 0,$$

that is $\lambda \circ \phi : U \rightarrow \mathbb{R}$ is constant. As ϕ is an arbitrary chart it follows that λ is constant.

Step 2: Show that $\lambda \equiv 0$ implies S is an open subset of a plane.

In this case, $dN \equiv 0$ which implies that $N(p) = v$ for some $v \in S^2$ and all $p \in S$. Let $p, p' \in \phi(U)$. Consider $\gamma : [0, 1] \rightarrow U$ a smooth curve with $\gamma(0) = \phi^{-1}(p)$ and $\gamma(1) = \phi^{-1}(p')$. Then $\frac{d(\phi \circ \gamma)}{dt}(t) \in T_{\gamma(t)}S$ for all $t \in [0, 1]$ and hence orthogonal to v . Therefore,

$$\frac{d}{dt} \langle \phi(\gamma(t)), v \rangle = \left\langle \frac{d(\phi \circ \gamma)}{dt}(t), v \right\rangle = 0.$$

In particular,

$$\langle p, v \rangle = \langle \phi(\gamma(0)), v \rangle = \langle \phi(\gamma(1)), v \rangle = \langle p', v \rangle.$$

As ϕ is arbitrary and S is connected it follows that

$$\langle p, v \rangle = \langle p', v \rangle$$

for all $p, p' \in S$, that is S is contained in a plane.

Step 3: Show that $\lambda \neq 0$ implies S is an open subset of a sphere.

Let us assume without loss of generality that $\lambda_0 > 0$. From (3.9.1) and (3.9.2) we obtain

$$\frac{\partial}{\partial u} \left(\phi + \frac{1}{\lambda_0} (N \circ \phi) \right) = 0$$

and

$$\frac{\partial}{\partial v} \left(\phi + \frac{1}{\lambda_0} (N \circ \phi) \right) = 0.$$

Thus, $\phi + \frac{1}{\lambda_0}(N \circ \phi)$ is constant on U and thus constant on S . Let $\phi + \frac{1}{\lambda_0}(N \circ \phi) \equiv v \in \mathbb{R}^3$, then

$$|\phi - v| = \left| \frac{1}{\lambda_0}(N \circ \phi) \right| = \frac{1}{\lambda_0},$$

which means that $\phi(U)$ is contained in the sphere of radius $\frac{1}{\lambda_0}$ with centre at v . As S is connected we deduce that all of S is contained in the sphere of radius $\frac{1}{\lambda_0}$ about v . \square

3.10 Elliptic, Parabolic and Hyperbolic Points

Exercise 3.10.1. For an oriented surface S consider a smooth map $\gamma : (-\epsilon, \epsilon) \rightarrow S$. Then,

$$A_{\gamma(t)}(\gamma'(t), \gamma'(t)) = \langle \gamma''(t), N(\gamma(t)) \rangle.$$

Principal curvatures are indicative of the local shape of the surface, and thus provide a method to categorise the points of a surface. In particular, for a surface S let $\phi : U \rightarrow S$ be a chart with $0 \in U$ and $\phi(0) = p \in S$. Given $c, d \in \mathbb{R}$ let $\gamma : (-\epsilon, \epsilon) \rightarrow S$ be given by $\gamma(t) = \phi(ct, dt)$. Note that

$$\gamma'(t) = c \frac{\partial \phi}{\partial u}(ct, dt) + d \frac{\partial \phi}{\partial v}(ct, dt)$$

and

$$\gamma''(t) = c^2 \frac{\partial^2 \phi}{\partial u^2}(0) + 2cd \frac{\partial^2 \phi}{\partial u \partial v}(0) + d^2 \frac{\partial^2 \phi}{\partial v^2}(0).$$

Hence, using Exercise 3.10.1 it follows that

$$A_p \left(c \frac{\partial \phi}{\partial u}(0) + d \frac{\partial \phi}{\partial v}(0), c \frac{\partial \phi}{\partial u}(0) + d \frac{\partial \phi}{\partial v}(0) \right) = \left\langle c^2 \frac{\partial^2 \phi}{\partial u^2}(0) + 2cd \frac{\partial^2 \phi}{\partial u \partial v}(0) + d^2 \frac{\partial^2 \phi}{\partial v^2}(0), N_0(p) \right\rangle. \quad (3.10.1)$$

Suppose without loss of generality that $\phi(0) = 0 \in \mathbb{R}^3$ and

$$\frac{\partial \phi}{\partial u}(0) = (1, 0, 0)$$

and

$$\frac{\partial \phi}{\partial v}(0) = (0, 1, 0)$$

are the principal directions at 0.

Proposition 3.10.2. Let $\phi : U \rightarrow S$ be a chart for S , as above. Then as $u, v \rightarrow 0$ we have

$$\phi(u, v) = \left(u, v, \frac{1}{2} (\lambda_1 u^2 + \lambda_2 v^2) \right) + R(u, v),$$

where λ_1, λ_2 are the principal curvatures at 0. Moreover, $R(u, v)$ is a function such that

$$\lim_{u, v \rightarrow 0} \frac{R_3(u, v)}{u^2 + v^2} = 0$$

and

$$\lim_{u, v \rightarrow 0} \frac{R_i(u, v)}{|u| + |v|} = 0$$

for $i = 1, 2$.

Proof. Using a Taylor expansion we have

$$\phi(u, v) = (u, v, 0) + \frac{1}{2} \left(\frac{\partial^2 \phi}{\partial u^2}(0)u^2 + 2 \frac{\partial^2 \phi}{\partial u \partial v}(0)uv + \frac{\partial^2 \phi}{\partial v^2}(0)v^2 \right) + \tilde{R}(u, v), \quad (3.10.2)$$

where

$$\lim_{u,v \rightarrow 0} \frac{\tilde{R}(u,v)}{u^2 + v^2}.$$

Note that

$$N(0,0,0) = \frac{\frac{\partial \phi}{\partial u}(0) \times \frac{\partial \phi}{\partial v}(0)}{\left| \frac{\partial \phi}{\partial u}(0) \times \frac{\partial \phi}{\partial v}(0) \right|} = (0,0,1)$$

Hence,

$$\begin{aligned} \left\langle \frac{1}{2} \left(\frac{\partial^2 \phi}{\partial u^2}(0)u^2 + 2 \frac{\partial^2 \phi}{\partial u \partial v}(0)uv + \frac{\partial^2 \phi}{\partial v^2}(0)v^2 \right), (0,0,1) \right\rangle &\stackrel{(3.10.1)}{=} \frac{1}{2} A_0((u,v,0), (u,v,0)) \\ &= \frac{1}{2} A_0(uX_1 + vX_2, uX_1 + vX_2) \\ &= \frac{1}{2} A_0(X_1, X_1)u^2 + A_0(X_2, X_2)v^2 \\ &= \frac{1}{2} \lambda_1^2 u^2 + \lambda_2^2 v^2. \end{aligned}$$

Thus, (3.10.2) can be written as

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

where

$$\lim_{u,v \rightarrow 0} \frac{R_3(u,v)}{u^2 + v^2} = 0$$

and

$$\lim_{u,v \rightarrow 0} \frac{R_i(u,v)}{|u| + |v|} = 0$$

for $i = 1, 2$.

□

Remark 3.10.3. Proposition 3.10.2 says that locally around zero, S is approximated by the graph of the function $f(x,y) = \frac{1}{2} (\lambda_1 x^2 + \lambda_2 y^2)$.

Definition 3.10.4. Let S be an oriented surface.

1. A point $p \in S$ is elliptic if $K(p) > 0$. That is, $\lambda_1(p)$ and $\lambda_2(p)$ have the same sign.
2. A point $p \in S$ is hyperbolic if $K(p) < 0$. That is, $\lambda_1(p)$ and $\lambda_2(p)$ have the opposite sign.
3. A point $p \in S$ is parabolic if $K(p) = 0$ and $H(p) \neq 0$. That is, exactly one of $\lambda_1(p)$ and $\lambda_2(p)$ is non-zero.
4. A point $p \in S$ is planar if $K(p) = H(p) = 0$. That is, $\lambda_1(p) = \lambda_2(p) = 0$.

Example 3.10.5.

1. Every point on S_r^2 is elliptic.
2. Every point on C_r is parabolic.
3. Every point on $\{x^2 - y^2 = z\}$ is hyperbolic.
4. Every point on the plane is planar.

5. Every point on the paraboloid $\{z = x^2 + y^2\}$ is elliptic.

Proposition 3.10.6. Let $S \subset \mathbb{R}^3$ be a regular surface. For $p \in S$ the following statements hold.

1. If p is an elliptic point, then there is a neighbourhood $V \subset \mathbb{R}^3$ of p such that $S \cap V$ lies on one side of $p + T_p S$ and $(S \cap V) \cap (p + T_p S) = \{p\}$.
2. If p is a hyperbolic point, then on any neighbourhood $V \subset \mathbb{R}^3$ of p , $S \cap V$ meets both sides of $p + T_p S$.

Proof. Let $\phi : U \rightarrow S$ be a chart for S at p , with $\phi(0,0) = p$. Then by Taylor's theorem

$$\begin{aligned}\phi(u,v) &= \phi(0,0) + \left(\frac{\partial \phi}{\partial u}(0,0)u + \frac{\partial \phi}{\partial v}(0,0)v \right) \\ &\quad + \frac{1}{2} \left(\frac{\partial^2 \phi}{\partial u^2}(0,0)u^2 + 2 \frac{\partial^2 \phi}{\partial u \partial v}(0,0)uv + \frac{\partial^2 \phi}{\partial v^2}(0,0)v^2 \right) + R(u,v)\end{aligned}$$

in a neighbourhood of 0 and where

$$\lim_{(u,v) \rightarrow (0,0)} \frac{R(u,v)}{u^2 + v^2} = 0.$$

Since, $\frac{\partial \phi}{\partial u}(0,0)u + \frac{\partial \phi}{\partial v}(0,0)v \in T_p S$ it follows that

$$\begin{aligned}\langle \phi(u,v) - p, N(p) \rangle &= \frac{1}{2} \left\langle \frac{\partial^2 \phi}{\partial u^2}(0,0)u^2 + 2 \frac{\partial^2 \phi}{\partial u \partial v}(0,0)uv + \frac{\partial^2 \phi}{\partial v^2}(0,0)v^2, N(p) \right\rangle \\ &\quad \langle R(u,v), N(p) \rangle \\ &\stackrel{(3.10.1)}{=} \frac{1}{2} A_p \left(\frac{\partial \phi}{\partial u}(0,0)u + \frac{\partial \phi}{\partial v}(0,0)v, \frac{\partial \phi}{\partial u}(0,0)u + \frac{\partial \phi}{\partial v}(0,0)v \right) \\ &\quad + \langle R(u,v), N(p) \rangle.\end{aligned}\tag{3.10.3}$$

- If $K(p) > 0$, then without loss of generality suppose that $\lambda_2(p) \geq \lambda_1(p) > 0$. Then by Proposition 3.6.8, it follows that for every $w \in T_p S \setminus \{0\}$ we have

$$A_p(w, w) \geq \lambda_1(p)|w|^2 > 0.$$

Thus, with (3.10.3) it follows that

$$\langle \phi(u,v) - p, N(p) \rangle > 0$$

for small values of u and v with $(u,v) \neq (0,0)$.

- If $K(p) < 0$ then $\lambda_1(p)$ and $\lambda_2(p)$ have different signs. Thus when w points in a principal direction we have that $A_p(w, w) = \lambda_1(p)|w|^2$ or $A_p(w, w) = \lambda_2(p)|w|^2$. Thus, A_p takes on both positive and negative values. Therefore, from (3.10.3) it follows that $\langle \phi(u,v) - p, N(p) \rangle$ takes positive and negative values in any neighbourhood of $(0,0)$.

□

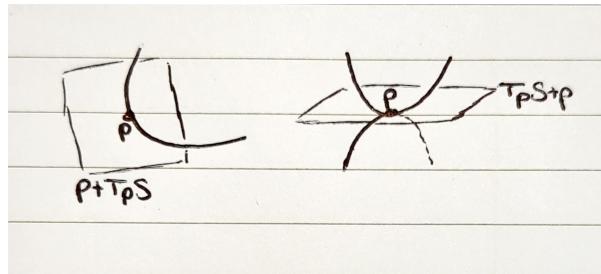


Figure 3.10.1: Illustration of the conclusions of Proposition 3.10.6.

3.11 Gauss and Mean Curvature in Charts

Definition 3.11.1. Let S be an oriented surface with a chart $\phi: U \rightarrow S$.

1. Let $M := \begin{pmatrix} E & F \\ F & G \end{pmatrix}$ where $E = \left| \frac{\partial \phi}{\partial u} \right|^2$, $F = \left\langle \frac{\partial \phi}{\partial u}, \frac{\partial \phi}{\partial v} \right\rangle$ and $G = \left| \frac{\partial \phi}{\partial v} \right|^2$.
2. Let $\Sigma := \begin{pmatrix} e & f \\ f & g \end{pmatrix}$ where $e = A_p \left(\frac{\partial \phi}{\partial u}, \frac{\partial \phi}{\partial u} \right) = \left\langle \frac{\partial^2 \phi}{\partial u^2}, N(p) \right\rangle$, $f = A_p \left(\frac{\partial \phi}{\partial u}, \frac{\partial \phi}{\partial v} \right) = \left\langle \frac{\partial^2 \phi}{\partial u \partial v}, N(p) \right\rangle$ and $g = A_p \left(\frac{\partial \phi}{\partial v}, \frac{\partial \phi}{\partial v} \right) = \left\langle \frac{\partial^2 \phi}{\partial v^2}, N(p) \right\rangle$.

Remark 3.11.2. Note that functions E, F, G, e, f and g of Definition 3.11.1 are functions from $U \rightarrow \mathbb{R}$.

Proposition 3.11.3. With the notation of Definition 3.11.1 we have

$$K(\phi(u, v)) = \det(M^{-1}\Sigma) = \frac{\det(\Sigma)}{\det(M)} = \frac{eg - f^2}{EG - F^2},$$

and

$$H(\phi(u, v)) = \frac{1}{2} \operatorname{tr}(M^{-1}\Sigma) = \frac{1}{2} \frac{eG + gE - 2fF}{EG - F^2}.$$

Proof. Fix an orthonormal basis for $T_p S$ and represent $dN\phi(u, v)$, ϕ_u and ϕ_v in the basis such that

$$\begin{aligned} \Sigma &= \begin{pmatrix} \phi_u & \phi_v \end{pmatrix} \begin{pmatrix} | & | \\ -dN_{\phi(u,v)}(\phi_u) & -dN_{\phi(u,v)}(\phi_v) \end{pmatrix} \\ &= \begin{pmatrix} \phi_u & \phi_v \end{pmatrix} (-dN_{\phi(u,v)}) \begin{pmatrix} | & | \\ \phi_u & \phi_v \end{pmatrix}. \end{aligned}$$

It follows that,

$$\begin{aligned} \det(\Sigma) &= \det \left(\begin{pmatrix} \phi_u & \phi_v \end{pmatrix} \right) \det(-dN_{\phi(u,v)}) \det \left(\begin{pmatrix} | & | \\ \phi_u & \phi_v \end{pmatrix} \right) \\ &= \lambda_1(p)\lambda_2(p) \det \left(\begin{pmatrix} \phi_u & \phi_v \end{pmatrix} \right) \\ &= K \det(M). \end{aligned}$$

Similarly,

$$\begin{aligned} \Sigma &= \begin{pmatrix} \phi_u & \phi_v \end{pmatrix} \begin{pmatrix} | & | \\ \phi_u & \phi_v \end{pmatrix} \begin{pmatrix} | & | \\ \phi_u & \phi_v \end{pmatrix}^{-1} (-dN_{\phi(u,v)}) \begin{pmatrix} | & | \\ \phi_u & \phi_v \end{pmatrix} \\ &= M \left(\begin{pmatrix} | & | \\ \phi_u & \phi_v \end{pmatrix}^{-1} (-dN_{\phi(u,v)}) \begin{pmatrix} | & | \\ \phi_u & \phi_v \end{pmatrix} \right). \end{aligned}$$

Therefore,

$$\frac{1}{2} \operatorname{tr}(M^{-1}\Sigma) = \frac{1}{2} \operatorname{tr}(-dN_{\phi(u,v)}) = \frac{\lambda_1(p) + \lambda_2(p)}{2} = H(p).$$

□

Remark 3.11.4. Note the simplifications when $\frac{\partial \phi}{\partial u}$ and $\frac{\partial \phi}{\partial v}$ are the principal directions we have $M = I$ and $\Sigma = \begin{pmatrix} \lambda_1(p) & 0 \\ 0 & \lambda_2(p) \end{pmatrix}$. Therefore,

$$K(p) = \det(\Sigma) = \lambda_1(p)\lambda_2(p)$$

and

$$H(p) = \frac{1}{2}\text{tr}(\Sigma) = \frac{\lambda_1(p) + \lambda_2(p)}{2}$$

as expected.

Example 3.11.5. Let $S = \{z = x^2 + y^2\}$. Then a chart for S is $\phi : \mathbb{R}^2 \rightarrow S$ given by

$$\phi(u, v) = (u, v, u^2 - v^2).$$

Note that

$$\frac{\partial \phi}{\partial u} = (1, 0, 2u)$$

and

$$\frac{\partial \phi}{\partial v} = (0, 1, -2v)$$

so that

$$N = \frac{\frac{\partial \phi}{\partial u} \times \frac{\partial \phi}{\partial v}}{\left| \frac{\partial \phi}{\partial u} \times \frac{\partial \phi}{\partial v} \right|} = \frac{(-2u, 2v, 1)}{\sqrt{1 + 4u^2 + 4v^2}}.$$

Moreover,

$$\begin{cases} \frac{\partial^2 \phi}{\partial u^2} = (0, 0, 2) \\ \frac{\partial^2 \phi}{\partial u \partial v} = (0, 0, 0) \\ \frac{\partial^2 \phi}{\partial v^2} = (0, 0, -2) \end{cases}$$

so that

$$M = \begin{pmatrix} 1 + 4u^2 & -4uv \\ -4uv & 1 + 4v^2 \end{pmatrix}$$

and

$$\Sigma = \begin{pmatrix} \frac{2}{\sqrt{1+4u^2+4v^2}} & 0 \\ 0 & -\frac{2}{\sqrt{1+4u^2+4v^2}} \end{pmatrix}.$$

Therefore,

$$\begin{aligned} K(\phi(u, v)) &= \det(M^{-1}\Sigma) \\ &= \frac{-\frac{4}{1+4u^2+4v^2}}{(1+4u^2)(1+4v^2)-16u^2v^2} \\ &= -\frac{4}{(1+4u^2+4v^2)^2} \end{aligned}$$

and

$$\begin{aligned}
H(\phi(u, v)) &= \frac{1}{2} \text{tr} \left(\frac{1}{1+4u^2+v^2} \begin{pmatrix} 1+4v^2 & 4uv \\ 4uv & 1+4u^2 \end{pmatrix} \begin{pmatrix} \frac{2}{\sqrt{1+4u^2+4v^2}} & 0 \\ 0 & -\frac{2}{\sqrt{1+4u^2+4v^2}} \end{pmatrix} \right) \\
&= \frac{1}{2(1+4u^2+4v^2)} \text{tr} \begin{pmatrix} \frac{2(1+4v^2)}{\sqrt{1+4u^2+4v^2}} & -\frac{8uv}{\sqrt{1+4u^2+4v^2}} \\ \frac{8uv}{\sqrt{1+4u^2+4v^2}} & -\frac{2(1+4u^2)}{\sqrt{1+4u^2+4v^2}} \end{pmatrix} \\
&= \frac{4v^2 - 4u^2}{(1+4u^2+4v^2)^{\frac{3}{2}}}.
\end{aligned}$$

Exercise 3.11.6. Repeat Exercise 3.8.4 by using Proposition 3.11.3.

Example 3.11.7. Using the computations of Exercise 3.11.6 one can identify the asymptotic lines of the helicoid and catenoid.

1. For the helicoid S , consider the chart $\phi : U \rightarrow S$ given by

$$\phi(u, v) = (u \cos(v), u \sin(v), v).$$

Then a regular curve $\gamma : I \rightarrow S$ can be written as $\gamma(t) = (\phi \circ \sigma)(t)$ where $\sigma : I \rightarrow U$ is given by $\sigma(t) = (u(t), v(t))$ for smooth curves u, v . In particular,

$$\gamma'(t) = \frac{\partial \phi}{\partial u} u'(t) + \frac{\partial \phi}{\partial v} v'(t).$$

Therefore,

$$A_{\gamma(t)}(\gamma'(t), \gamma'(t)) = (u'(t) \quad v'(t)) \Sigma \begin{pmatrix} u'(t) \\ v'(t) \end{pmatrix}$$

where

$$\Sigma = \frac{1}{\sqrt{u^2+t}} \begin{pmatrix} 0 & -1 \\ -1 & 0 \end{pmatrix}$$

is the matrix of $A_{\gamma(t)}$ with respect to the basis $\left\{ \frac{\partial \phi}{\partial u}, \frac{\partial \phi}{\partial v} \right\}$ as determined in Exercise 3.11.6. Therefore, γ is an asymptotic line if and only if

$$-\frac{2u'(t)v'(t)}{\sqrt{u(t)^2+1}} = 0$$

for all $t \in I$. That is, either $u'(t) = 0$ or $v'(t) = 0$. Therefore, the asymptotic lines of the helicoid are

$$\gamma(t) = (c \cos(v(t)), c \sin(v(t)), v(t))$$

and

$$\gamma(t) = (u(t) \cos(c), u(t) \sin(c), c)$$

for $c \in \mathbb{R}$.

2. For the catenoid S , consider the chart $\phi : U \rightarrow S$ given by

$$\phi(u, v) = (\cosh(u) \cos(v), \cosh(u) \sin(v), u).$$

Then a regular curve $\gamma : I \rightarrow S$ can be written as $\gamma(t) = (\phi \circ \sigma)(t)$ where $\sigma : I \rightarrow U$ is given by $\sigma(t) = (u(t), v(t))$ for smooth curves u, v . In particular,

$$\gamma'(t) = \frac{\partial \phi}{\partial u} u'(t) + \frac{\partial \phi}{\partial v} v'(t).$$

Therefore,

$$A_{\gamma(t)}(\gamma'(t), \gamma'(t)) = (u'(t) \quad v'(t)) \Sigma \begin{pmatrix} u'(t) \\ v'(t) \end{pmatrix}$$

where

$$\Sigma = \begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix}$$

is the matrix of $A_{\gamma(t)}$ with respect to the basis $\left\{ \frac{\partial \phi}{\partial u}, \frac{\partial \phi}{\partial v} \right\}$ as determined in Exercise 3.11.6. Therefore, γ is an asymptotic line if and only if

$$-(u'(t))^2 + (v'(t))^2 = 0$$

for all $t \in I$. That is, either $u'(t) - v'(t) = 0$ or $u'(t) + v'(t) = 0$. Therefore, the asymptotic lines of the catenoid are

$$\gamma(t) = (\cosh(u(t)) \cos(u(t) + c), \cosh(u(t)) \sin(u(t) + c), u(t))$$

and

$$\gamma(t) = (\cosh(u(t)) \cos(c - u(t)), \cosh(u(t)) \sin(c - u(t)), u(t))$$

for $c \in \mathbb{R}$.

3.12 First Fundamental Form

The intrinsic geometry of a surface is captured by the first fundamental form.

Definition 3.12.1. The first fundamental form of a surface S at $p \in S$ is the bilinear map $g : T_p S \times T_p S \rightarrow \mathbb{R}$ given by $g(x, y) = \langle x, y \rangle$.

Remark 3.12.2. The first fundamental form at a point p is the restriction of the Euclidean dot product onto the tangent space of S at p .

If $\phi : U \rightarrow S$ is a chart for S , then $T_p S = \text{span} \left(\frac{\partial \phi}{\partial u}, \frac{\partial \phi}{\partial v} \right)$. In particular,

$$\begin{aligned} g(x, y) &= g \left(a \frac{\partial \phi}{\partial u} + b \frac{\partial \phi}{\partial v}, c \frac{\partial \phi}{\partial u} + d \frac{\partial \phi}{\partial v} \right) \\ &= ac \left\langle \frac{\partial \phi}{\partial u}, \frac{\partial \phi}{\partial u} \right\rangle + (ad + bc) \left\langle \frac{\partial \phi}{\partial u}, \frac{\partial \phi}{\partial v} \right\rangle + bd \left\langle \frac{\partial \phi}{\partial v}, \frac{\partial \phi}{\partial v} \right\rangle \\ &= (a \quad b) M \begin{pmatrix} c \\ d \end{pmatrix}. \end{aligned}$$

That is, M is the matrix of g with respect to the basis $\left\{ \frac{\partial \phi}{\partial u}, \frac{\partial \phi}{\partial v} \right\}$. In particular, this allows us to write intrinsic notions of curves such as length using the fundamental form. More specifically, let $\gamma : (a, b) \rightarrow S$ be a regular curve and suppose that $\gamma((a, b)) \subseteq \phi(U)$. Recall that

$$L(\gamma) = \int_a^b \left| \frac{d\gamma}{dt}(t) \right| dt.$$

Then supposing that $\gamma(t) = \phi(u(t), v(t))$ it follows that

$$\begin{aligned} L(\gamma) &= \int_a^b \left| \frac{du}{dt}(t) \frac{\partial \phi}{\partial u}(u(t), v(t)) + \frac{dv}{dt}(t) \frac{\partial \phi}{\partial v}(u(t), v(t)) \right| dt \\ &= \int_a^b \sqrt{\left(\frac{du}{dt} - \frac{dv}{dt} \right) M \left(\frac{du}{dt} \right)} dt \\ &= \int_a^b \sqrt{\left(\frac{du}{dt} \right)^2 E + 2 \frac{du}{dt} \frac{dv}{dt} F + \left(\frac{dv}{dt} \right)^2 G}. \end{aligned}$$

Similarly, one can express angels using the first fundamental form.

Definition 3.12.3. Let $S_1, S_2 \subseteq \mathbb{R}^3$ be regular surface. A smooth map $F : S_1 \rightarrow S_2$ is a local isometry if it preserves the first fundamental form. That is, for any $p \in S_1$ we have

$$\langle dF_p(x), dF_p(y) \rangle = \langle x, y \rangle$$

for all $x, y \in T_p S_1$. Moreover, F is an isometry if it is a local isometry and a bijection between S_1 and S_2 .

Remark 3.12.4. Let $F : S_1 \rightarrow S_2$ be a local isometry.

1. Then $dF_p : T_p S_1 \rightarrow T_{F(p)} S_2$ is a bijection for all $p \in S_1$. Indeed if $dF_p(v) = 0$ then

$$|v|^2 = \langle v, v \rangle = \langle dF_p(v), dF_p(v) \rangle = |dF_p(v)|^2 = 0$$

and so $v = 0$. Hence dF_p is injective. Therefore, since $T_p S_1$ and $T_{F(p)} S_2$ are finite-dimensional linear spaces it follows that dF_p is also surjective.

2. From Theorem 3.2.5 there are neighbourhoods $U_1 \subseteq S_1$ p and $U_2 \subseteq S_2$ of $F(p)$ such that

$$F|_{U_1} : U_1 \rightarrow U_2$$

is a diffeomorphism.

Example 3.12.5.

1. Rigid motions of \mathbb{R}^3 induce isometries. Let $S \subset \mathbb{R}^3$, then for $A \in \text{SO}(3)$ we can consider

$$S' = A(S) = \{Ap : p \in S\}.$$

Then let $F : S \rightarrow S'$ be given by $p \mapsto Ap$. Observe that F is smooth. Moreover, for any $p \in S$ let $v \in T_p S$ then for $\gamma : (-\epsilon, \epsilon) \rightarrow \mathbb{R}^3$ with $\gamma'(0) = v$ we have

$$dF_p(v) = \frac{dA\gamma(t)}{dt} \Big|_{t=0} = A\gamma'(t)|_{t=0} = Av.$$

Therefore,

$$\begin{aligned} \langle dF_p(v), dF_p(w) \rangle &= \langle Av, Aw \rangle \\ &= (Av)^\top (Aw) \\ &= v^\top A^\top Aw \\ &= v^\top w \\ &= \langle v, w \rangle \end{aligned}$$

which means that F is a local isometry. What's more, as A is invertible it follows that F is an isometry.

2. Let $S_1 = \{(x, y, z) \in \mathbb{R}^3 : z = 0\}$ and $S_2 = \{(x, y, z) \in \mathbb{R}^3 : x^2 + y^2 = 1\}$. Furthermore, let $F : S_1 \rightarrow S_2$ be given by

$$F(x, y, 0) = (\cos(x), \sin(x), y).$$

Then for any $(x, y, 0) \in S_1$, the tangent plane is S_1 , namely $T_p S_1 = S_1$. In particular, for any $v = (v_1, v_2, 0) \in T_p S_1$ write $\gamma(t) = (x + tv_1, y + tv_2, 0)$ so that $\gamma(0) = (x, y, 0)$ and $\gamma'(0) = v$. Then,

$$\begin{aligned} dF_{(x,y,0)}(v) &= \frac{dF(\gamma(t))}{dt} \Big|_{t=0} \\ &= \frac{d}{dt} (\cos(x + tv_1), \sin(x + tv_1), y + tv_2) \Big|_{t=0} \\ &= (-v_1 \sin(x), v_1 \cos(x), v_2). \end{aligned}$$

Hence,

$$\begin{aligned} \langle dF_{(x,y,0)}(v), dF_{(x,y,0)}(v) \rangle &= (v_1)^2 (\sin^2(x) + \cos^2(x)) + (v_2)^2 \\ &= (v_1)^2 + (v_2)^2 \\ &= \langle v, v \rangle. \end{aligned}$$

It follows that

$$\langle dF_{(x,y,0)}(x), dF_{(x,y,0)}(y) \rangle = \langle x, y \rangle$$

for all $x, y \in T_p S_1$. Indeed,

$$\begin{aligned} \langle dF_{(x,y,0)}(x), dF_{(x,y,0)}(y) \rangle &= \frac{1}{2} \left(|dF_{(x,y,0)}(x+y)|^2 - |dF_{(x,y,0)}(x)|^2 - |dF_{(x,y,0)}(y)|^2 \right) \\ &= \frac{1}{2} (|x+y|^2 - |x|^2 - |y|^2) \\ &= \langle x, y \rangle. \end{aligned}$$

Thus, F is a local isometry, however, it is not an isometry as F is not injective.

Lemma 3.12.6. Let $\varphi : U \rightarrow S$ and $\tilde{\varphi} : U \rightarrow \tilde{S}$ be charts. Suppose that

$$M = \begin{pmatrix} |\varphi_u|^2 & \langle \varphi_u, \varphi_v \rangle \\ \langle \varphi_v, \varphi_u \rangle & |\varphi_v|^2 \end{pmatrix} = \begin{pmatrix} |\tilde{\varphi}_u|^2 & \langle \tilde{\varphi}_u, \tilde{\varphi}_v \rangle \\ \langle \tilde{\varphi}_v, \tilde{\varphi}_u \rangle & |\tilde{\varphi}_v|^2 \end{pmatrix} = \tilde{M}.$$

Then $f : \varphi(U) \rightarrow \tilde{S}$ given by $f = \tilde{\varphi} \circ \varphi^{-1}$ is a local isometry.

Proof. Let $p = \varphi(q)$ where $q = (q_1, q_2)$. Then

$$\begin{aligned} df_p(\varphi_u(q)) &= \frac{d}{dt} f(\varphi(q_1 + t, q_2)) \\ &= \frac{d}{dt} \tilde{\varphi}(q_1 + t, q_2) \\ &= \tilde{\varphi}_u(q). \end{aligned}$$

Similarly, $d f_p(\varphi_v(q)) = \tilde{\varphi}_v(q)$. Therefore, for $v \in T_p S$ we have

$$\begin{aligned} \langle d f_p(v), d f_p(v) \rangle &= \langle d f_p(a\varphi_u(q) + b\varphi_v(q)), d f_p(a\varphi_u(q) + b\varphi_v(q)) \rangle \\ &= \langle a\tilde{\varphi}_u(q) + b\tilde{\varphi}_v(q), a\tilde{\varphi}_u(q) + b\tilde{\varphi}_v(q) \rangle \\ &= (a \quad b) \tilde{M} \begin{pmatrix} a \\ b \end{pmatrix} \\ &= (a \quad b) M \begin{pmatrix} a \\ b \end{pmatrix} \\ &= \langle a\varphi_u(q) + b\varphi_v(q), a\varphi_u(q) + b\varphi_v(q) \rangle \\ &= \langle v, v \rangle. \end{aligned}$$

Therefore, f is a local isometry. \square

Exercise 3.12.7. Let

$$S_1 = \{(\cosh(u) \cos(v), \cosh(u) \sin(v), u) : (u, v) \in \mathbb{R}^2\}$$

be the catenoid and

$$S_2 = \{(u \cos(v), u \sin(v), v) : (u, v) \in \mathbb{R}^2\}$$

be the helicoid. Show that S_1 and S_2 are locally isometric.

Proposition 3.12.8. Let $F : S_1 \rightarrow S_2$ be a smooth map between regular surfaces. Then F is a local isometry if and only if F preserves the length of all curves. That is, for any smooth curve $\gamma : (a, b) \rightarrow S_1$ we have

$$L_{S_1}(\gamma) = L_{S_2}(F \circ \gamma).$$

Proof. (\Rightarrow). Using $(F \circ \gamma)'(t) = dF_{\gamma(t)}(\gamma'(t))$ it follows that

$$\begin{aligned} L_{S_2}(F \circ \gamma) &= \int_a^b |(F \circ \gamma)'(t)| dt \\ &= \int_a^b |dF_{\gamma(t)}(\gamma'(t))| dt \\ &\stackrel{(1)}{=} \int_a^b \sqrt{\langle dF_{\gamma(t)}(\gamma'(t)), dF_{\gamma(t)}(\gamma'(t)) \rangle} dt \\ &= \int_a^b \sqrt{\langle \gamma'(t), \gamma'(t) \rangle} dt \\ &= \int_a^b |\gamma'(t)| dt \\ &= L_{S_1}(\gamma), \end{aligned}$$

where in (1) the local isometry property of F is used.

(\Leftarrow). Let $p \in S_1$ and consider $v \in T_p S_1$. Choose $\gamma : (-\epsilon, \epsilon) \rightarrow S_1$ a smooth curve such that $\gamma(0) = p$ and $\gamma'(0) = v$. Then for all $0 < t < \epsilon$ we have

$$L_{S_1}(\gamma|_{(-\epsilon, t)}) = L_{S_2}(F \circ \gamma|_{(-\epsilon, t)}).$$

Consequently,

$$\frac{d}{dt} \int_{-\epsilon}^t |\gamma'(s)| ds \Big|_{t=0} = \frac{d}{dt} \int_{-\epsilon}^t |(F \circ \gamma)'(s)| ds \Big|_{t=0}.$$

Therefore, $|\gamma'(0)| = |(F \circ \alpha)'(0)|$, or in other words, $|v| = |dF_p(v)|$. As p and v were arbitrary it follows that

$$|v| = |dF_p(v)|$$

for all $p \in S_1$ and $v \in T_p S_1$ which means that F is a local isometry using the same reasoning as that used in statement 2 of Example 3.12.5. \square

3.13 Christoffel Symbols

Let $\phi : U \rightarrow S$ be a chart of a regular surface S with $N : S \rightarrow S^2$ a Gauss map. Then $\left\{ \frac{\partial \phi}{\partial u}, \frac{\partial \phi}{\partial v}, N \right\}$ forms an orthonormal basis for \mathbb{R}^3 . With $x^1 := u$ and $x^2 := v$ and let

$$g_{ij} = g \left(\frac{\partial \phi}{\partial x^i}, \frac{\partial \phi}{\partial x^j} \right) = \left\langle \frac{\partial \phi}{\partial x^i}, \frac{\partial \phi}{\partial x^j} \right\rangle$$

for $i, j = 1, 2$. Moreover, let (g^{ij}) be the inverse of matrix $M = (g_{ij})$. That is,

$$\sum_{k=1}^2 g_{ik} g^{kj} = \delta_i^j = \begin{cases} 1 & i = j \\ 0 & i \neq j. \end{cases}$$

Note that $\frac{\partial^2 \phi}{\partial x^i \partial x^j}$ can be written as

$$\frac{\partial^2 \phi}{\partial x^i \partial x^j} = \Gamma_{ij}^1 \frac{\partial \phi}{\partial x^1} + \Gamma_{ij}^2 \frac{\partial \phi}{\partial x^2} + A_{ij} N \quad (3.13.1)$$

for some functions $\Gamma_{ij}^k : U \rightarrow \mathbb{R}$ with $i, j, k = 1, 2$, and where

$$\begin{aligned} A_{ij} &= \langle A_{ij} N, N \rangle \\ &= \left\langle \frac{\partial^2 \phi}{\partial x^i \partial x^j}, N \right\rangle \\ &= A \left(\frac{\partial \phi}{\partial x^i}, \frac{\partial \phi}{\partial x^j} \right). \end{aligned}$$

Definition 3.13.1. The functions $\Gamma_{ij}^k : U \rightarrow \mathbb{R}$ for $i, j, k = 1, 2$ as determined by (3.13.1) are referred to as Christoffel symbols of the chart ϕ .

Remark 3.13.2.

1. Note that Christoffel symbols are only present when dealing with surfaces. Indeed for a curve $\gamma : (a, b) \rightarrow \mathbb{R}^3$ a chart $\phi : U \rightarrow \gamma((a, b))$ is

$$\phi(u, v) = \gamma(u)$$

and thus

$$\frac{\partial^2 \phi}{\partial x^i \partial x^j} = 0$$

meaning the Christoffel symbols vanish.

2. As $\frac{\partial^2 \phi}{\partial x^i \partial x^j} = \frac{\partial^2 \phi}{\partial x^j \partial x^i}$ for $i, j = 1, 2$ it follows that $\Gamma_{ij}^k = \Gamma_{ji}^k$ for $i, j = 1, 2$.

Proposition 3.13.3. Let $\phi : U \rightarrow S$ be a chart for a regular surface S . Then

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

Proof. Using (3.13.1) we have

$$\begin{aligned} \left\langle \frac{\partial^2 \phi}{\partial x_i \partial x_j}, \frac{\partial \phi}{\partial x_l} \right\rangle &= \Gamma_{ij}^1 \left\langle \frac{\partial \phi}{\partial x_1}, \frac{\partial \phi}{\partial x_l} \right\rangle + \Gamma_{ij}^2 \left\langle \frac{\partial \phi}{\partial x_2}, \frac{\partial \phi}{\partial x_l} \right\rangle + A_{ij} \left\langle N, \frac{\partial \phi}{\partial x_l} \right\rangle \\ &= \Gamma_{ij}^1 g_{1l} + \Gamma_{ij}^2 g_{2l}, \end{aligned} \quad (3.13.2)$$

for $l = 1, 2$. Hence,

$$\begin{aligned} \partial_{x^i} g_{jl} &= \frac{\partial}{\partial x_i} \left\langle \frac{\partial \phi}{\partial x_j}, \frac{\partial \phi}{\partial x_l} \right\rangle \\ &= \left\langle \frac{\partial^2 \phi}{\partial x_i \partial x_j}, \frac{\partial \phi}{\partial x_l} \right\rangle + \left\langle \frac{\partial \phi}{\partial x_j}, \frac{\partial^2 \phi}{\partial x_i \partial x_l} \right\rangle \\ &= \sum_{m=1}^2 (\Gamma_{ij}^m g_{ml} + \Gamma_{il}^m g_{jm}). \end{aligned} \quad (3.13.3)$$

Similarly,

$$\partial_{x^j} g_{il} = \sum_{m=1}^2 (\Gamma_{ij}^m g_{ml} + \Gamma_{jl}^m g_{im}). \quad (3.13.4)$$

and

$$\partial_{x^l} g_{ij} = \sum_{m=1}^2 (\Gamma_{il}^m g_{mj} + \Gamma_{jl}^m g_{im}). \quad (3.13.5)$$

Considering (3.13.3)+(3.13.4)-(3.13.5) it follows that

$$\partial_{x^i} g_{il} + \partial_{x^j} g_{il} - \partial_{x^l} g_{ij} = \sum_{m=1}^2 2\Gamma_{ij}^m g_{ml}.$$

Multiplying by $\frac{1}{2}g^{lk}$ we conclude that

$$\begin{aligned} \sum_{l=1}^2 \frac{1}{2}g^{kl} (\partial_{x^i} g_{jl} + \partial_{x^j} g_{il} - \partial_{x^l} g_{ij}) &= \sum_{m,l=1}^2 \Gamma_{ij}^m g_{ml} g^{lk} \\ &= \Gamma_{ij}^m. \end{aligned}$$

□

Remark 3.13.4. If $F : S \rightarrow \tilde{S}$ is a local isometry then by shrinking U if necessary we have that $F \circ \phi : U \rightarrow \tilde{S}$ is a chart for \tilde{S} . Then,

$$\begin{aligned} \tilde{g}_{ij} &= \left\langle \frac{\partial F \circ \phi}{\partial x^i}, \frac{\partial F \circ \phi}{\partial x^j} \right\rangle \\ &= \left\langle dF \left(\frac{\partial \phi}{\partial x^i} \right), dF \left(\frac{\partial \phi}{\partial x^j} \right) \right\rangle \\ &= \left\langle \frac{\partial \phi}{\partial x^i}, \frac{\partial \phi}{\partial x^j} \right\rangle \\ &= g_{ij}. \end{aligned}$$

Thus, Proposition 3.13.3 we have that

$$\tilde{\Gamma}_{ij}^k(u, v) = \Gamma_{ij}^k(u, v)$$

for $i, j, k = 1, 2$ for all $(u, v) \in U$. Thus, Christoffel symbols are an intrinsic property of a surface. Indeed any object that can be expressed in terms of the first fundamental form is said to be an intrinsic property.

Example 3.13.5.

1. Let $S_1 = \{z = 0\}$. Then $\Phi : \mathbb{R}^2 \rightarrow S_1$ given by $\phi(u, v) = (u, v, 0)$ is a chart. In particular,

$$\frac{\partial^2 \phi}{\partial u^2} = \frac{\partial^2 \phi}{\partial v^2} = \frac{\partial^2 \phi}{\partial u \partial v} = 0,$$

so

$$\Gamma_{ij}^k = 0$$

for $i, j, k = 1, 2$.

2. Let $S_2 = \{x^2 + y^2 = 1\}$. Then $F : S_1 \rightarrow S_2$ given by $F(x, y, 0) = (\cos(x), \sin(x), y)$ was shown to be a local isometry in statement 2 of Example 3.12.5. Indeed, for the chart $\psi(u, v) := F \circ \phi(u, v)$ of S_2 the Christoffel symbols of S_2 vanish as expected by Proposition 3.13.3

Exercise 3.13.6. Let S be the graph of a smooth function $f : \mathbb{R}^2 \rightarrow \mathbb{R}$ with chart $\phi : \mathbb{R}^2 \rightarrow S$ given by

$$\phi(u, v) = (u, v, f(u, v)).$$

Compute the Christoffel symbols Γ_{ij}^k .

3.14 Theorem Egregium

Theorem 3.14.1 (Egregium). Gauss curvature K is intrinsic. In particular, with S, \tilde{S} and F as above, it follows that

$$K(\phi(u, v)) = \tilde{K}(\tilde{\phi}(u, v)),$$

where \tilde{K} is the Gauss curvature of \tilde{S} . Indeed,

$$K(\phi(u, v)) = \frac{Y(u, v)G(u, v) - X(u, v)F(u, v)}{\det(M(u, v))} \quad (3.14.1)$$

where

$$X = \Gamma_{12}^2 \Gamma_{12}^1 - \Gamma_{11}^2 \Gamma_{22}^1 + \partial_u(\Gamma_{12}^1) - \partial_v(\Gamma_{11}^1)$$

and

$$Y = \Gamma_{11}^1 \Gamma_{21}^2 + \Gamma_{11}^2 \Gamma_{22}^2 - \Gamma_{12}^1 \Gamma_{11}^2 - (\Gamma_{12}^2)^2 + \partial_v(\Gamma_{11}^2) - \partial_u(\Gamma_{12}^2).$$

Proof. It suffices to show (3.14.1) as M and the Christoffel symbols, Proposition 3.13.3, are invariant under local isometries. Let $\phi : U \rightarrow S$ be a chart for S . Since ϕ is smooth its partial derivatives commute, in particular,

$$\frac{\partial}{\partial v} \left(\frac{\partial^2 \phi}{\partial u \partial v} \right) = \frac{\partial}{\partial u} \left(\frac{\partial^2 \phi}{\partial u \partial v} \right),$$

which can equivalently be written as

$$\frac{\partial}{\partial v} \left(\Gamma_{11}^1 \frac{\partial \phi}{\partial u} + \Gamma_{11}^2 \frac{\partial \phi}{\partial v} + A_{11}N \right) = \frac{\partial}{\partial u} \left(\Gamma_{12}^1 \frac{\partial \phi}{\partial u} + \Gamma_{12}^2 \frac{\partial \phi}{\partial v} + A_{12}N \right).$$

Thus

$$\begin{aligned} (\Gamma_{11}^1 \phi_{uv} + (\Gamma_{11}^1)_v \phi_u) + (\Gamma_{11}^2 \phi_{vv} + (\Gamma_{11}^2)_v \phi_v) + ((A_{11})_v N + A_{11}N_v) &= (\Gamma_{12}^1 \phi_{uu} + (\Gamma_{12}^1)_u \phi_u) \\ &\quad + (\Gamma_{12}^2 \phi_{vu} + (\Gamma_{12}^2)_u \phi_v) + ((A_{12})_u N + A_{12}N_u). \end{aligned} \quad (3.14.2)$$

As $\{\phi_u, \phi_v, N\}$, where N is the Gauss map, is linearly independent we can write the vectors $\phi_{uv}, \phi_{vv}, \phi_{uu}, N_u$ and N_v in terms of these vectors. Indeed, we know that

$$\begin{cases} \phi_{uv} = \frac{\partial^2 \phi}{\partial v \partial u} = \Gamma_{11}^1 \phi_u + \Gamma_{21}^2 \phi_v + A_{12} N \\ \phi_{vv} = \frac{\partial^2 \phi}{\partial v^2} = \Gamma_{22}^1 \phi_u + \Gamma_{22}^2 \phi_v + A_{22} N \\ \phi_{uu} = \frac{\partial^2 \phi}{\partial u^2} = \Gamma_{11}^1 \phi_u + \Gamma_{11}^2 \phi_v + A_{11} N. \end{cases} \quad (3.14.3)$$

On the other hand, we know that

$$\begin{cases} N_u = a\phi_u + b\phi_v \\ N_v = c\phi_u + d\phi_v \end{cases}$$

for some $a, b, c, d \in \mathbb{R}$ as each is orthogonal to N . Then

$$\begin{aligned} -A_{11} &= -A(\phi_u, \phi_u) \\ &= \langle \phi_u, dN(\phi_u) \rangle \\ &= \left\langle \phi_u, \frac{\partial N \circ \phi}{\partial u} \right\rangle \\ &= \langle \phi_u, N_u \rangle \\ &= aE + bF. \end{aligned}$$

Recalling that $\Sigma = (A_{ij})$, through similar computations we arrive at the matrix equation

$$-\Sigma = M \begin{pmatrix} a & c \\ b & d \end{pmatrix}.$$

Therefore,

$$\begin{pmatrix} a & c \\ b & d \end{pmatrix} = -\frac{1}{\det(M)} \begin{pmatrix} G & -F \\ -F & E \end{pmatrix} \begin{pmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{pmatrix} = -\frac{1}{\det(M)} M^{-1} \Sigma.$$

In particular, substituting the values of a and c into (3.14.2) along with (3.14.3) and comparing the coefficients of ϕ_u it follows that

$$\begin{aligned} \Gamma_{11}^1 \Gamma_{21}^1 (\Gamma_{11}^1)_v + \Gamma_{11}^2 \Gamma_{22}^1 + A_{11} \left(\frac{FA_{22} - GA_{12}}{\det(M)} \right) &= \Gamma_{12}^1 \Gamma_{11}^1 + (\Gamma_{12}^1)_u \\ &\quad + \Gamma_{12}^2 \Gamma_{12}^1 + A_{12} \left(\frac{FA_{21} - GA_{11}}{\det(M)} \right). \end{aligned}$$

Using the fact that $\Gamma_{ij}^k = \Gamma_{ji}^k$ for all $i, j, k = 1, 2$, we obtain

$$(\Gamma_{11}^1)_v - (\Gamma_{12}^1)_v = \Gamma_{12}^2 \Gamma_{12}^1 - \Gamma_{11}^2 \Gamma_{22}^1 + \frac{(A_{12}A_{21} - A_{11}A_{22})F}{\det(M)}.$$

With $K = \frac{\det(\Sigma)}{\det(M)}$ we can write

$$KF = \Gamma_{12}^2 \Gamma_{12}^1 - \Gamma_{11}^2 \Gamma_{22}^1 + (\Gamma_{12}^1)_u - (\Gamma_{11}^1)_v = X.$$

Similarly, comparing the coefficients of ϕ_v yields

$$KE = \Gamma_{11}^1 \Gamma_{21}^2 + \Gamma_{11}^2 \Gamma_{22}^2 - \Gamma_{12}^1 \Gamma_{11}^2 - \Gamma_{12}^2 \Gamma_{12}^2 + (\Gamma_{11}^2)_v - (\Gamma_{12}^2)_u = Y.$$

Therefore,

$$\begin{aligned} K &= \frac{K \det(M)}{\det(M)} \\ &= \frac{K(EG - F^2)}{\det(M)} \\ &= \frac{YG - XF}{EG - F^2} \\ &= \frac{YG - XF}{\det(M)}, \end{aligned}$$

as required. \square

Remark 3.14.2.

1. It follows that $\det(\Sigma)$ is an intrinsic quantity, despite Σ itself being extrinsic.
2. As a plane has $K \equiv 0$ and a sphere of radius r has $K \equiv \frac{1}{r^2}$, it follows from Theorem 3.14.1 that the plane and sphere are not locally isometric. More specifically, consider regular surfaces $S_1, S_2 \subseteq \mathbb{R}^3$ with Gauss curvatures K_1 and K_2 respectively. Then if $F : S_1 \rightarrow S_2$ is a local isometry then $K_2 \circ F = K_1$.

3.15 Surfaces of Constant Curvature

Theorem 3.15.1. Let S be a compact connected regular oriented surface. If S has constant positive Gauss curvature, $K > 0$, then S is a sphere.

Proof. Let $\lambda_1(x) \leq \lambda_2(x)$ be the principal curvatures for $x \in S$. By the compactness of S there exists a $p \in S$ such that

$$\lambda_2(p) = \max_{x \in S} \lambda_2(x).$$

Since $\lambda_1(x)\lambda_2(x) = K > 0$ it follows that

$$\lambda_1(p) = \min_{x \in S} \lambda_1(x).$$

By a rigid motion in \mathbb{R}^3 and a translation we can assume without loss of generality that $p = (0, 0, 0)$ and the principal curvatures at p are $X_1 = (1, 0, 0)$ and $X_2 = (0, 1, 0)$. In particular, near p , from Proposition 3.10.2 we know that S is the graph of a function of the form

$$F(u, v) = \frac{\lambda_1(p)u^2 + \lambda_2(p)v^2}{2} + R(u, v).$$

Consider the chart $\phi : U \rightarrow S$ given by

$$\phi(u, v) = (u, v, F(u, v)).$$

Note that

$$\begin{cases} \phi_u = (1, 0, F_u) \\ \phi_v = (0, 1, F_v) \\ \phi_{uu} = (0, 0, F_{uu}) \\ \phi_{uv} = (0, 0, F_{uv}) \\ \phi_{vv} = (0, 0, F_{vv}) \end{cases}$$

Thus, the unit normal to S near p is

$$N = \frac{\phi_u \times \phi_v}{|\phi_u \times \phi_v|} = \frac{(-F_u, -F_v, 1)}{\sqrt{1 + |\nabla F|^2}}$$

and the second fundamental form is

$$\Sigma = \begin{pmatrix} \langle N, \phi_{uu} \rangle & \langle N, \phi_{uv} \rangle \\ \langle N, \phi_{vu} \rangle & \langle N, \phi_{vv} \rangle \end{pmatrix} = \frac{1}{\sqrt{1 + |\nabla F|^2}} \begin{pmatrix} F_{uu} & F_{uv} \\ F_{vu} & F_{vv} \end{pmatrix}.$$

At each $(u, v) \in U$ consider

$$e_1(u, v) = \frac{\phi_u}{|\phi_u|} = \frac{(1, 0, F_u(u, v))}{\sqrt{1 + F_u^2(u, v)}} \in T_{\phi(u, v)} S$$

and

$$e_2(u, v) = \frac{\phi_v}{|\phi_v|} = \frac{(0, 1, F_v(u, v))}{\sqrt{1 + F_v^2(u, v)}} \in T_{\phi(u, v)} S.$$

Then consider,

$$\begin{aligned}
h_1(t) &:= A_{\phi(0,t)}(e_1(0,t), e_1(0,1)) \\
&= \frac{1}{1 + F_u^2(0,t)} A_{\phi(0,t)}(\phi_u(0,t), \phi_u(0,t)) \\
&= \frac{1}{1 + F_u^2(0,t)} \langle N(0,t), \phi_{uu}(0,t) \rangle \\
&= \frac{1}{1 + F_u^2(0,t)} \frac{F_{uu}(0,t)}{\sqrt{1 + |\nabla F(0,t)|^2}}
\end{aligned}$$

and similarly,

$$\begin{aligned}
h_2(t) &:= A_{\phi(t,0)}(e_2(t,0), e_2(t,0)) \frac{1}{1 + F_v^2(0,t)} \\
&= \frac{F_{vv}(0,t)}{\sqrt{1 + |\nabla F(0,t)|^2}}.
\end{aligned}$$

Note that

$$h_1(0) = A_p((1,0,0), (1,0,0)) = \lambda_1(p)$$

and

$$h_2(0) = A_p((0,1,0), (0,1,0)) = \lambda_2(p).$$

Since λ_1 is minimised at p , and λ_2 is maximized at p it follows by Proposition 3.6.8 that

$$\begin{aligned}
h_1(0) &= \lambda_1(p) \\
&\leq \lambda_1(\phi(0,t)) \\
&= \min_{x \in T_{\phi(0,t)}, |x|=1} A_{\phi(0,t)}(x, x) \\
&\leq A_{\phi(0,t)}(e_1(0,t), e_1(0,t)) \\
&= h_1(t).
\end{aligned}$$

Similarly,

$$h_2(0) = \lambda_2(p) \geq h_2(t).$$

Thus $h_1(t)$ has a local minimum and $h_2(t)$ has a local maximum at $t = 0$. Thus, $h_1''(0) \geq 0$ and $h_2''(0) \leq 0$ meaning

$$h_1''(0) - h_2''(0) \geq 0. \quad (3.15.1)$$

Recall that

$$\nabla F(u, v) = (\lambda_1(p)u, \lambda_2(p)v) + O(|u|^2 + |v|^2)$$

so that

$$|\nabla F(u, v)|^2 = \lambda_1^2(p)u^2 + \lambda_2^2(p)v^2 + O(|u|^3 + |v|^3).$$

Therefore,

$$\begin{aligned}
h_1(t) &= \frac{1}{1 + O(t^4)} \frac{F_{uu}(0,t)}{\sqrt{1 + \lambda_2^2(p)t^2 + O(t^3)}} \\
&= (1 - O(t^4)) \left(1 - \frac{1}{2}\lambda_2^2(p)t^2 + O(t^3) \right) F_{uu}(0,t) \\
&= \left(1 - \frac{1}{2}\lambda_2^2(p)t^2 \right) F_{uu}(0,t) + O(t^3).
\end{aligned}$$

Similarly,

$$h_2(t) = \left(1 - \frac{1}{2}\lambda_1^2(p)t^2 \right) F_{vv}(t,0) + O(t^3).$$

Therefore,

$$\begin{aligned} h'_1(t) - h'_2(t) &= \left(\left(1 - \frac{\lambda_2^2(p)t^2}{2} \right) F_{uuv}(0, t) - \lambda_2^2(p)tF_{uu}(0, t) + O(t^2) \right) \\ &\quad - \left(\left(1 - \frac{\lambda_1^2(p)t^2}{2} \right) F_{vvu}(t, 0) - \lambda_1^2(p)tF_{vv}(t, 0) + O(t^2) \right) \end{aligned}$$

and thus

$$\begin{aligned} h''_1(t) - h''_2(t) &= \left(\left(1 - \frac{\lambda_2^2(p)t^2}{2} \right) F_{uuvv}(0, t) - 2\lambda_2^2(p)tF_{uuv}(0, t) - \lambda_2^2(p)F_{uu}(0, t) + O(t) \right) \\ &\quad - \left(\left(1 - \frac{\lambda_1^2(p)t^2}{2} \right) F_{vvuu}(t, 0) - 2\lambda_1^2(p)tF_{vvu}(t, 0) - \lambda_1^2(p)F_{vv}(t, 0) + O(t) \right). \end{aligned}$$

Hence,

$$\begin{aligned} h''_1(0) - h''_2(0) &= \lambda_1^2(p)F_{vv}(0, 0) - \lambda_2^2(p)F_{uu}(0, 0) \\ &= \lambda_1^2(p)\lambda_2(p) - \lambda_2^2(p)\lambda_1(p) \\ &= \lambda_1(p)\lambda_2(p)(\lambda_1(p) - \lambda_2(p)) \\ &= K(p)(\lambda_1(p) - \lambda_2(p)). \end{aligned}$$

With (3.15.1) it follows that

$$K(p)(\lambda_1(p) - \lambda_2(p)) \geq 0.$$

This implies that $\lambda_1(p) - \lambda_2(p) \geq 0$ as $K(p) > 0$ and so $\lambda_1(p) \geq \lambda_2(p)$. However, as we assumed $\lambda_1(p) \leq \lambda_2(p)$ it follows that $\lambda_1(p) = \lambda_2(p)$. Thus, we deduce that $\lambda_1(x) = \lambda_2(x)$ for all $x \in S$. Therefore, S is totally umbilic with non-zero curvature and so from Theorem 3.9.3 it must be contained within a sphere. Since S is compact it must be the case that S is a sphere. \square

3.16 Integration of Surfaces

Let $S \subseteq \mathbb{R}^3$ be a regular surface, and let $\phi : U \rightarrow S$ be a chart. For simplicity let $0 \in U$ and assume that $0 < \delta_u, \delta_v \ll 1$ are such that $R := [0, \delta_u] \times [0, \delta_v] \subset U$. In particular, note that R has area $\delta_u \delta_v$. Under the transformation ϕ the rectangle R is approximately mapped to the parallelogram P spanned by $\phi_u(0, 0)$ and $\phi_v(0, 0)$ scaled by δ_u and δ_v respectively. More specifically, P is the parallelogram with corners

$$\{p, p + \delta_u \phi_u(0, 0), p + \delta_v \phi_v(0, 0), p + \delta_u \phi_u(0, 0) + \delta_v \phi_v(0, 0)\}$$

where $p := \phi(0, 0)$. In particular, P has area given by

$$\text{area}(P) = |\delta_u \phi_u(0, 0) \times \delta_v \phi_v(0, 0)| = \delta_u \delta_v |\phi_u(0, 0) \times \phi_v(0, 0)|.$$

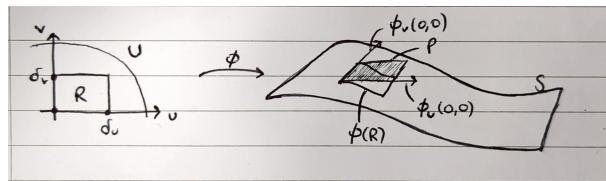


Figure 3.16.1: Area element on a surface.

Definition 3.16.1. Given $D \subseteq U$ compact, let

$$\text{area}(\phi(D)) = \int_D |\phi_u(u, v) \times \phi_v(u, v)| \, du \, dv.$$

Proposition 3.16.2. Let S be a regular surface with charts $\phi : U \rightarrow S$ and $\psi : U' \rightarrow S$. Suppose that for compact sets $D \subseteq U$ and $D' \subseteq U'$ we have $\phi(D) = \psi(D')$. Then,

$$\text{area}(\phi(D)) = \text{area}(\psi(D')).$$

Proof. Consider $f : U' \rightarrow U$ given by $f = \phi^{-1} \circ \psi$, and in particular assume that

$$f(u, v) = (x(u, v), y(u, v)).$$

Then

$$\psi(u, v) = (\phi \circ f)(u, v) = \phi(x(u, v), y(u, v))$$

and so

$$\begin{aligned} \frac{\partial \psi}{\partial u} \times \frac{\partial \psi}{\partial v} &= \left(\frac{\partial \phi}{\partial x} \frac{\partial x}{\partial u} + \frac{\partial \phi}{\partial y} \frac{\partial y}{\partial u} \right) \times \left(\frac{\partial \phi}{\partial x} \frac{\partial x}{\partial v} + \frac{\partial \phi}{\partial y} \frac{\partial y}{\partial v} \right) \\ &= \left(\frac{\partial \phi}{\partial x} \times \frac{\partial \phi}{\partial y} \right) \left(\frac{\partial x}{\partial u} \frac{\partial y}{\partial u} - \frac{\partial y}{\partial u} \frac{\partial x}{\partial v} \right) \end{aligned}$$

where we have used the bilinearity and anti-symmetry properties of the cross-product. Therefore, recalling the change of coordinates formula, it follows that

$$\begin{aligned} \text{area}(\psi(D')) &= \int_{D'} \left| \frac{\partial \psi}{\partial u} \times \frac{\partial \psi}{\partial v} \right| du dv \\ &= \int_{D'} \left| \frac{\partial \phi}{\partial x} \times \frac{\partial \phi}{\partial y} \right| \left| \det \begin{pmatrix} x_u & y_u \\ x_v & y_v \end{pmatrix} \right| du dv \\ &= \int_D \left| \frac{\partial \phi}{\partial x} \times \frac{\partial \phi}{\partial y} \right| dx, dy \\ &= \text{area}(\phi(D)). \end{aligned}$$

□

The area of a surface can also be expressed in terms of the first fundamental form.

Proposition 3.16.3. Let $\phi : U \rightarrow S$ be a chart for a regular surface S . Then for a compact set $D \subseteq U$ we have

$$\begin{aligned} \text{area}(\phi(D)) &= \int_D \sqrt{\det(M(u, v))} du dv \\ &= \int_D \sqrt{EG - F^2} du dv \end{aligned}$$

where

$$M = \begin{pmatrix} E & F \\ F & G \end{pmatrix} = \begin{pmatrix} |\phi_u|^2 & \langle \phi_u, \phi_v \rangle \\ \langle \phi_u, \phi_v \rangle & |\phi_v|^2 \end{pmatrix}.$$

Proof. Let $v, w \in \mathbb{R}^3$ with v non-zero. Then, v is orthogonal to $w - \frac{\langle v, w \rangle}{|v|^2} v$ and so

$$\begin{aligned} |v \times w|^2 &= \left| v \times \left(w - \frac{\langle v, w \rangle v}{|v|^2} \right) \right|^2 \\ &= |v|^2 \left| w - \frac{\langle v, w \rangle v}{|v|^2} \right|^2 \\ &= |v|^2 \left(|w|^2 - 2 \frac{\langle v, w \rangle \langle v, w \rangle}{|v|^2} + \left(\frac{\langle v, w \rangle}{|v|^2} \right)^2 |v|^2 \right) \\ &= |v|^2 |w|^2 - \langle v, w \rangle^2. \end{aligned}$$

In particular, with $v = \phi_u$ and $w = \phi_v$ it follows that

$$|\phi_u \times \phi_v|^2 = |\phi_u|^2 |\phi_v|^2 - \langle \phi_u, \phi_v \rangle^2 = EG - F^2.$$

Therefore,

$$\begin{aligned} \text{area}(\phi(D)) &= \int_D |\phi_u \times \phi_v| \, dudv \\ &= \int_D \sqrt{EG - F^2} \, du \, dv \\ &= \int_D \sqrt{\det(M(u, v))} \, dudv. \end{aligned}$$

□

Definition 3.16.4. If $f : S \rightarrow \mathbb{R}$ is smooth, $\phi : U \rightarrow S$ is a chart and $D \subseteq U$ is compact. Then the integral of f on $\phi(D)$ is given by

$$\int_{\phi(D)} f \, dA := \int_D (f \circ \phi)(u, v) \sqrt{EG - F^2} \, du \, dv.$$

If S is a compact surface, then we can write $S = \bigcup_{i=1}^k S_i$ such that the following hold.

- For $i \neq j$ we have $S_i \cap S_j \subseteq \partial S_i \cap \partial S_j$.
- For $i = 1, \dots, k$ there is a chart $\phi_i : U_i \rightarrow S$ and $D_i \subseteq U_i$ such that $\phi_i(D_i) = S_i$.

Hence, we let

$$\begin{aligned} \int_S f \, dA &:= \sum_{i=1}^k \int_{\phi(D_i)} f \, dA \\ &= \sum_{i=1}^k \int_{D_i} (f \circ \phi_i)(u, v) \sqrt{E_i G_i - F_i^2} \, du \, dv. \end{aligned}$$

This is independent of the chosen decomposition of S .

Example 3.16.5. Let $\psi : (\epsilon, 2\pi - \epsilon) \times (\epsilon, \pi - \epsilon) \rightarrow S^2$ be given by

$$\psi(\theta, \phi) = (\cos(\theta) \sin(\phi), \sin(\theta) \sin(\phi), \cos(\phi)).$$

Note that ψ defines a chart for the surface

$$\tilde{S}^2 := \psi((\epsilon, 2\pi - \epsilon) \times (\epsilon, \pi - \epsilon)).$$

We cannot define a chart for S^2 directly since the poles and meridian lines cause problems. Indeed \tilde{S}^2 is a subset of S^2 which avoids these points. Observe that

$$\begin{cases} \frac{\partial \psi}{\partial \theta} = (-\sin(\theta) \sin(\phi), \cos(\theta) \sin(\phi), 0) \\ \frac{\partial \psi}{\partial \phi} = (\cos(\theta) \cos(\phi), \sin(\theta) \cos(\phi), -\sin(\phi)) \end{cases}$$

such that

$$\frac{\partial \psi}{\partial \theta} \times \frac{\partial \psi}{\partial \phi} = (-\cos(\theta) \sin^2(\phi), -\sin(\theta) \sin^2(\phi), -\cos(\phi) \sin(\phi)).$$

In particular,

$$\begin{aligned} \left| \frac{\partial \psi}{\partial \theta} \times \frac{\partial \psi}{\partial \phi} \right| &= \sqrt{\cos^2(\theta) \sin^4(\phi) + \sin^2(\theta) \sin^4(\phi) + \cos^2(\phi) \sin^2(\phi)} \\ &= \sqrt{\sin^2(\phi) (\sin^2(\phi) + \cos^2(\phi))} \\ &= \sin(\phi). \end{aligned}$$

Therefore,

$$\begin{aligned} \text{area } (\tilde{S}^2) &= \int_{\epsilon}^{2\pi-\epsilon} \int_{\epsilon}^{\pi-\epsilon} \sin(\phi) d\phi d\theta \\ &= (2\pi - 2\epsilon)(2\cos(\epsilon)). \end{aligned}$$

Strictly speaking, we should only compute the area of compact sets, which \tilde{S}^2 . However, this detail turns out to be insignificant, so in any case sending $\epsilon \rightarrow 0$ it follows that

$$\text{area } (S^2) = 4\pi$$

as expected.

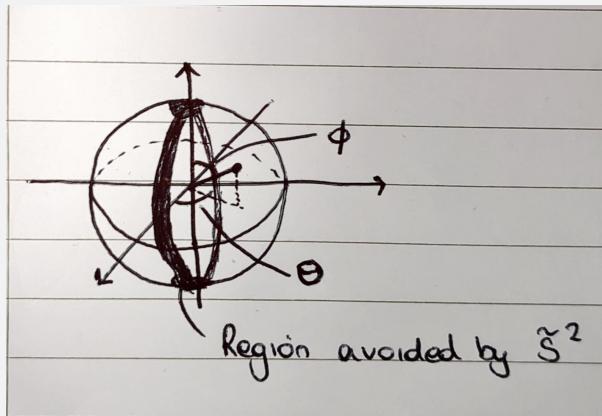


Figure 3.16.2

3.17 Solution to Exercises

Exercise 3.4.2

Solution. Suppose that $\psi : U' \rightarrow S$ is another chart for $p \in S$. More specifically, $\psi(U') = V \cap S$, where $V \subseteq \mathbb{R}^3$ is an open neighbourhood of p with $\phi(U) = V \cap S$. Then as $\phi : U \rightarrow V \cap S$ is a homeomorphism we can write

$$F \circ \psi = F \circ (\phi \circ \phi^{-1}) \circ \psi : U' \rightarrow S^1.$$

As $d\phi_q$ is invertible it follows that $\phi^{-1} \circ \psi$ is smooth. Therefore, as $F \circ \phi$ is smooth it follows that $F \circ \psi$ is smooth. In particular, this means that $F \circ \psi$ is smooth for any chart ψ , and so $F : S \rightarrow \mathbb{R}^n$ is smooth as per statement 1. of Definition 3.4.1. \square

Exercise 3.5.7

Proof. Observe that

$$\frac{\partial \phi}{\partial u} = \left(1, 0, -\frac{u}{\sqrt{1-u^2-v^2}} \right)$$

and

$$\frac{\partial \phi}{\partial v} = \left(0, 1, -\frac{v}{\sqrt{1-u^2-v^2}} \right).$$

So that,

$$\frac{\partial \phi}{\partial u} \times \frac{\partial \phi}{\partial v} = \left(\frac{u}{\sqrt{1-u^2-v^2}}, \frac{v}{\sqrt{1-u^2-v^2}}, 1 \right).$$

Noting that

$$\left| \frac{\partial \phi}{\partial u} \times \frac{\partial \phi}{\partial v} \right| = \frac{1}{\sqrt{1-u^2-v^2}}$$

it follows that

$$\begin{aligned} N(p) &= \frac{\frac{\partial \phi}{\partial u} \times \frac{\partial \phi}{\partial v}}{\left| \frac{\partial \phi}{\partial u} \times \frac{\partial \phi}{\partial v} \right|} \\ &= \sqrt{1-u^2-v^2} \left(\frac{u}{\sqrt{1-u^2-v^2}}, \frac{v}{\sqrt{1-u^2-v^2}}, 1 \right) \\ &= (u, v, \sqrt{1-u^2-v^2}). \end{aligned}$$

Therefore, we similarly, obtain that the Gauss map S^2 is the identity map. \square

Exercise 3.6.10

Solution. Let $\phi : U \rightarrow S$ be a chart for S at p such that $U \subseteq \mathbb{R}^2$ is connected. Then for any $p' \in \phi(U)$ there exists a smooth path $\gamma : [0, 1] \rightarrow U$ with $\gamma(0) = \phi^{-1}(p)$ and $\gamma(1) = \phi^{-1}(p')$. In particular, $\phi \circ \gamma : [0, 1] \rightarrow S$ is a smooth path from p to p' . As $\lambda_1 = \lambda_2 \equiv 0$ we have that $dN_p \equiv 0$, thus $N \equiv v$ for some $v \in S^2$. Therefore, as $\frac{d}{dt}(\phi \circ \gamma)(t) \in T_{\phi(\gamma(t))}S$ it must be perpendicular to v . Hence,

$$0 = \left\langle \frac{d}{dt}(\phi(\gamma(t))), v \right\rangle = \frac{d}{dt} \langle \phi(\gamma(t)), v \rangle.$$

Hence, $\langle \phi(\gamma(t)), v \rangle$ is constant and so $\langle p', v \rangle = \langle p, v \rangle$. As S is connected it follows that $\langle p', v \rangle = \langle p, v \rangle$ for all $p' \in S$, which means that S lies in a plane. \square

Exercise 3.8.4

Solution.

1. A chart for the helicoid S is

$$\phi(u, v) = (u \cos(v), u \sin(v), v).$$

In particular,

$$\begin{cases} x = u \cos(v) \\ y = u \sin(v) \\ z = v. \end{cases}$$

Observe that

$$\frac{\partial \phi}{\partial u} = (\cos(v), \sin(v), 0)$$

and

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

Hence,

$$\begin{aligned} N(u, v) &= \frac{\frac{\partial \phi}{\partial u}(u, v) \times \frac{\partial \phi}{\partial v}(u, v)}{\left| \frac{\partial \phi}{\partial u}(u, v) \times \frac{\partial \phi}{\partial v}(u, v) \right|} \\ &= \frac{1}{\sqrt{u^2+1}} (\sin(v), -\cos(v), u). \end{aligned}$$

In particular,

$$N(x, y, z) = \frac{1}{\sqrt{x^2 + y^2 + 1}} (\sin(z), -\cos(z), \sqrt{x^2 + y^2}).$$

For $(v_1, v_2, v_3) \in T_{(x,y,z)}S$, let $\gamma : (-\epsilon, \epsilon) \rightarrow S$ be a smooth map such that $\gamma(0) = (x, y, z)$ and $\gamma'(0) = (v_1, v_2, v_3)$. Note that

$$\left. \frac{d}{dt} \left(\frac{\sin(\gamma_3(t))}{\sqrt{\gamma_1(t)^2 + \gamma_2(t)^2 + 1}} \right) \right|_{t=0} = \frac{(x^2 + y^2 + 1) \cos(z)v_3 - \sin(z)(xv_1 + yv_2)}{(x^2 + y^2 + 1)^{\frac{3}{2}}}$$

and similarly,

$$\left. \frac{d}{dt} \left(-\frac{\cos(\gamma_3(t))}{\sqrt{\gamma_1(t)^2 + \gamma_2(t)^2 + 1}} \right) \right|_{t=0} = \frac{(x^2 + y^2 + 1) \sin(z)v_3 + \cos(z)(xv_1 + yv_2)}{(x^2 + y^2 + 1)^{\frac{3}{2}}}.$$

Moreover,

$$\left. \frac{d}{dt} \left(\frac{\sqrt{\gamma_1(t)^2 + \gamma_2(t)^2}}{\sqrt{\gamma_1(t)^2 + \gamma_2(t)^2 + 1}} \right) \right|_{t=0} = \frac{xv_1 + yv_2}{(x^2 + y^2 + 1)^{\frac{3}{2}} \sqrt{x^2 + y^2}},$$

therefore,

$$\begin{aligned} dN_{(x,y,z)}(v_1, v_2, v_3) = & \left(\frac{(x^2 + y^2 + 1) \cos(z)v_3 - \sin(z)(xv_1 + yv_2)}{(x^2 + y^2 + 1)^{\frac{3}{2}}}, \right. \\ & \frac{(x^2 + y^2 + 1) \sin(z)v_3 + \cos(z)(xv_1 + yv_2)}{(x^2 + y^2 + 1)^{\frac{3}{2}}}, \\ & \left. \frac{xv_1 + yv_2}{(x^2 + y^2 + 1)^{\frac{3}{2}} \sqrt{x^2 + y^2}} \right). \end{aligned}$$

Let $Y_1 = \left(\frac{x}{\sqrt{x^2 + y^2}}, \frac{y}{\sqrt{x^2 + y^2}}, 0 \right)$ and $Y_2 = (-y, x, 1)$. Then

$$\langle Y_1, N(x, y, z) \rangle = \langle Y_2, N(x, y, z) \rangle = 0.$$

Moreover,

$$dN_{(x,y,z)}(Y_1) = \frac{1}{(x^2 + y^2 + 1)^{\frac{3}{2}}} Y_2$$

and

$$dN_{(x,y,z)}(Y_2) = \frac{1}{\sqrt{x^2 + y^2 + 1}} Y_1.$$

Therefore, $X_1 := Y_1 - \sqrt{x^2 + y^2 + 1} Y_2$ and $X_2 := \sqrt{x^2 + y^2 + 1} Y_1 + Y_2$ are tangent vectors to the helicoid at (x, y, z) . Moreover,

$$dN_{(x,y,z)}(X_1) = -\frac{1}{x^2 + y^2 + 1} X_1$$

and

$$dN_{(x,y,z)}(X_2) = \frac{1}{x^2 + y^2 + 1} X_2.$$

Hence, X_1 and X_2 are the principal directions with $\lambda_1(x, y, z) = -\frac{1}{x^2 + y^2 + 1}$ and $\lambda_2(x, y, z) = \frac{1}{x^2 + y^2 + 1}$. Therefore, $K(x, y, z) = \frac{1}{(x^2 + y^2 + 1)^2}$ and $H(x, y, z) = 0$. This means that the helicoid is a minimal surface.

2. A chart for the catenoid S is

$$\phi(u, v) = (\cosh(u) \cos(v), \cosh(u) \sin(v), u).$$

In particular,

$$\begin{cases} x = \cosh(u) \cos(v) \\ y = \cosh(u) \sin(v) \\ z = u. \end{cases}$$

Observe that

$$\frac{\partial \phi}{\partial u} = (\sinh(u) \cos(v), \sinh(u) \sin(v), 1)$$

and

$$\frac{\partial \phi}{\partial v} = (-\cosh(u) \sin(v), \cosh(u) \cos(v), 0).$$

Hence,

$$\begin{aligned} N(u, v) &= \frac{\frac{\partial \phi}{\partial u}(u, v) \times \frac{\partial \phi}{\partial v}(u, v)}{\left| \frac{\partial \phi}{\partial u}(u, v) \times \frac{\partial \phi}{\partial v}(u, v) \right|} \\ &= \frac{1}{\cosh^2(u)} (-\cosh(u) \cos(v), -\cosh(u) \sin(v), \sinh(u) \cosh(u)). \end{aligned}$$

In particular,

$$N(x, y, z) = \left(-\frac{x}{\cosh^2(z)}, -\frac{y}{\cosh^2(z)}, \tanh(z) \right).$$

For $(v_1, v_2, v_3) \in T_{(x,y,z)}S$, let $\gamma : (-\epsilon, \epsilon) \rightarrow S$ be a smooth map such that $\gamma(0) = (x, y, z)$ and $\gamma'(0) = (v_1, v_2, v_3)$. Note that

$$\begin{aligned} \frac{d}{dt} \left(-\frac{\gamma_1(t)}{\cosh^2(\gamma_3(t))} \right) \Big|_{t=0} &= \left(\frac{\cosh^2(\gamma_3(t))\gamma'_1(t) - 2\cosh^2(\gamma_3(t))\gamma'_3(t)\gamma_1(t)}{\cosh^4(\gamma_3(t))} \right) \\ &= \frac{2v_3x - v_1}{\cosh^2(z)}. \end{aligned}$$

and similarly,

$$\frac{d}{dt} \left(-\frac{\gamma_2(t)}{\cosh^2(\gamma_3(t))} \right) \Big|_{t=0} = \frac{2v_3y - v_2}{\cosh^2(z)}.$$

Moreover,

$$\frac{d}{dt} (\tanh(\gamma_3(t))) \Big|_{t=0} = \left(\frac{\gamma'_3(t)}{\cosh^2(\gamma_3(t))} \right) \Big|_{t=0} = \frac{v_3}{\cosh^2(z)},$$

therefore,

$$dN_{(x,y,z)}(v_1, v_2, v_3) = \left(\frac{2v_3x - v_1}{\cosh^2(z)}, \frac{2v_3y - v_2}{\cosh^2(z)}, \frac{v_3}{\cosh^2(z)} \right).$$

Note that

$$\langle (x, -y, 0), N(x, y, z) \rangle = 0$$

and

$$dN_{(x,y,z)}(x, -y, 0) = -\frac{1}{\cosh^2(z)}(x, -y, 0).$$

Similarly, note that

$$\left\langle \left(\frac{1}{2} \sinh(z) \cosh(z), \frac{1}{2} \sinh(z) \cosh(z), 1 \right), N(x, y, z) \right\rangle = 0$$

and

$$dN_{(x,y,z)} \left(\frac{1}{2} \sinh(z) \cosh(z), \frac{1}{2} \sinh(z) \cosh(z), 1 \right) = \frac{1}{\cosh^2} \left(\frac{1}{2} \sinh(z) \cosh(z), \frac{1}{2} \sinh(z) \cosh(z), 1 \right).$$

Therefore, $\lambda_1(x, y, z) = -\frac{1}{\cosh^2(z)}$ and $\lambda_2(x, y, z) = \frac{1}{\cosh^2(z)}$ and so $K(x, y, z) - \frac{1}{\cosh^4(z)}$ and $H(x, y, z) = 0$. This means that the catenoid is a minimal surface. \square

Exercise 3.8.7

Solution.

1. Let $p = \gamma(t)$ for $t \in I$. Then $\gamma'(t) \in T_p S$ and $|\gamma'(t)| = 1$ and so using Theorem 3.7.1 it follows that $A_p(\gamma'(t), \gamma'(t)) = 0$. Therefore, using the characterisations of the principal curvatures provided by Proposition 3.6.8 it follows that $\lambda_1(p) \leq 0$ and $\lambda_2(p) \geq 0$. Therefore, $K(p) = \lambda_1(p)\lambda_2(p) \leq 0$.
2. Let $\{T_\gamma, N_\gamma, B_\gamma\}$ be the orthonormal frame at $p = \gamma(t_0)$ for $t_0 \in I$. Since γ is parameterised by arc length we have $T_\gamma = \gamma'(t_0)$. Thus, $N_\gamma = \frac{1}{k(t_0)}\gamma''(t_0) = \frac{1}{k(t_0)}\mathbf{k}(t_0)$. Therefore,

$$\langle N_\gamma, N(\gamma(t_0)) \rangle = \frac{1}{k(t_0)} \langle \mathbf{k}(t_0), N(\gamma(t_0)) \rangle = 0.$$

Meaning N_γ is orthogonal to $N(\gamma(t_0))$ and so $\{T_\gamma, N_\gamma\}$ forms an orthonormal basis for $T_p S$. Furthermore, as $N(\gamma(t_0))$ is also orthogonal to T_γ it follows that $N(\gamma(t_0)) = \pm B_\gamma$. Note that

$$\begin{aligned} \langle dN_p(T_\gamma), T_\gamma \rangle &= \left\langle \frac{d}{dt}N(\gamma(t)) \Big|_{t=t_0}, T_\gamma \right\rangle \\ &= \langle \pm B'_\gamma, N_\gamma \rangle \\ &= \mp\tau(t_0) \langle N_\gamma, T_\gamma \rangle \\ &= 0. \end{aligned}$$

Similarly,

$$\begin{aligned} \langle dN_p(T_\gamma), N_\gamma \rangle &= \langle \pm B'_\gamma, N_\gamma \rangle \\ &= \mp\tau(t_0) \langle N_\gamma, N_\gamma \rangle \\ &= \mp\tau(t_0). \end{aligned}$$

Therefore, the matrix of dN_p with respect to the basis $\{T_\gamma, N_\gamma\}$ is

$$S_p = \begin{pmatrix} 0 & \mp\tau(t_0) \\ \mp\tau(t_0) & \langle dN_p(N_\gamma), N_\gamma \rangle \end{pmatrix}.$$

Therefore,

$$K(p) = \det(S_p) = -|\tau(t_0)|$$

and so

$$|\tau(t_0)| = \sqrt{-K(p)},$$

where we have used that M is the identity matrix with respect to the basis $\{T_\gamma, N_\gamma\}$. □

Exercise 3.10.1

Solution. Observe that

$$\begin{aligned} 0 &= \frac{d}{dt} \langle \gamma'(t), N(\gamma(t)) \rangle \\ &= \langle \gamma''(t), N(\gamma(t)) \rangle + \langle \gamma'(t), dN_{\gamma(t)}(\gamma'(t)) \rangle \\ &= \langle \gamma''(t), N(\gamma(t)) \rangle - A_{\gamma(t)}(\gamma'(t), \gamma'(t)). \end{aligned}$$

□

Exercise 3.11.6

Solution.

1. With the chart of Exercise 3.8.4 we have that

$$\frac{\partial \phi}{\partial u} = (\cos(v), \sin(v), 0)$$

and

$$\frac{\partial \phi}{\partial v} = (-u \sin(v), u \cos(v), 1)$$

so that,

$$N(\phi(u, v)) = \frac{1}{\sqrt{u^2 + 1}} (\sin(v), -\cos(v), u).$$

Moreover,

$$\begin{cases} \frac{\partial^2 \phi}{\partial u^2} = (0, 0, 0) \\ \frac{\partial^2 \phi}{\partial u \partial v} = (-\sin(v), \cos(v), 0) \\ \frac{\partial^2 \phi}{\partial v^2} = (-u \cos(v), -u \sin(v), 0) \end{cases}$$

so that,

$$M = \begin{pmatrix} 1 & 0 \\ 0 & u^2 + 1 \end{pmatrix}$$

and

$$\Sigma = \begin{pmatrix} 0 & -\frac{1}{\sqrt{u^2 + 1}} \\ -\frac{1}{\sqrt{u^2 + 1}} & 0 \end{pmatrix}.$$

Therefore,

$$K(p) = \left(-\frac{1}{u^2 + 1} \right) \frac{1}{u^2 + 1} = -\frac{1}{(u^2 + 1)^2}$$

and

$$H(p) = \frac{1}{2} \text{tr} \left(\frac{1}{u^2 + 1} \begin{pmatrix} u^2 + 1 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 0 & -\frac{1}{\sqrt{u^2 + 1}} \\ -\frac{1}{\sqrt{u^2 + 1}} & 0 \end{pmatrix} \right) = 0.$$

2. With the chart of Exercise 3.8.4 we have that

$$\frac{\partial \phi}{\partial u} = (\sinh(u) \cos(v), \sinh(u) \sin(v), 1)$$

and

$$\frac{\partial \phi}{\partial v} = (-\cosh(u) \sin(v), \cosh(u) \cos(v), 0)$$

so that,

$$N(\phi(u, v)) = \frac{1}{\cosh^2(u)} (-\cosh(u) \cos(v), -\cosh(u) \sin(v), \sinh(u) \cosh(u)).$$

Moreover,

$$\begin{cases} \frac{\partial^2 \phi}{\partial u^2} = (\cosh(u) \cos(v), \cosh(u) \sin(v), 0) \\ \frac{\partial^2 \phi}{\partial u \partial v} = (-\sinh(u) \sin(v), \sinh(u) \cos(v), 0) \\ \frac{\partial^2 \phi}{\partial v^2} = (-\cosh(u) \cos(v), -\cosh(u) \sin(v), 0) \end{cases}$$

so that,

$$M = \begin{pmatrix} \cosh^2(u) & 0 \\ 0 & \cosh^2(u) \end{pmatrix}$$

and

$$\Sigma = \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix}.$$

Therefore,

$$K(p) = -\frac{1}{\cosh^4(u)}$$

and

$$H(p) = \frac{1}{2} \operatorname{tr} \left(\frac{1}{\cosh^4(u)} \begin{pmatrix} \cosh^2 & 0 \\ 0 & \cosh^2 \end{pmatrix} \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix} \right) = 0.$$

□

Exercise 3.12.7

Solution. We have the charts $\varphi_1 : \mathbb{R} \times (0, 2\pi) \rightarrow S_1$ given by

$$\varphi_1(u, v) = (\cosh(u) \cos(v), \cosh(u) \sin(v), u)$$

and $\varphi_2 : \mathbb{R} \times (0, 2\pi) \rightarrow S_2$ given by

$$\varphi_2(u, v) = (u \cos(v), u \sin(v), v).$$

Let $\varphi := \varphi_1(u, v) : U \rightarrow S_1$ and $\tilde{\varphi} := (\sinh(u), v) : U \rightarrow S_2$, where $U := \mathbb{R} \times (0, 2\pi)$. Observe that

$$\begin{cases} \varphi_u = (\sinh(u) \cos(v), \sinh(u) \sin(v), 1) \\ \varphi_v = (-\cosh(u) \sin(v), \cosh(u) \cos(v), 0) \end{cases}$$

and

$$\begin{cases} \tilde{\varphi}_u = (\cosh(u) \cos(v), \cosh(u) \sin(v), 0) \\ \tilde{\varphi}_v = (-\cosh(u) \sin(v), \cosh(u) \cos(v), 0). \end{cases}$$

Therefore,

$$\begin{aligned} M &= \begin{pmatrix} \sinh^2(u) + 1 & 0 \\ 0 & \cosh^2(u) \end{pmatrix} \\ &= \begin{pmatrix} \cosh^2(u) & 0 \\ 0 & \sinh^2(u) \end{pmatrix} \\ &= \tilde{M}. \end{aligned}$$

Therefore, using Lemma 3.12.6 it follows that S_1 and S_2 are locally isometric. □

Exercise 3.13.6

Solution.

□

4 Geodesics

4.1 Geodesic Curvature

A geodesic in a surface S is a regular curve $\gamma : (a, b) \rightarrow S$ which is in some sense the straightest line on S . For instance, on \mathbb{R}^n $\gamma : (a, b) \rightarrow \mathbb{R}^n$ given by $\gamma(t) = ct + d$ for $c, d \in \mathbb{R}$ is a straight line. In particular, γ can be characterised by either of the following.

1. γ minimises the distance between points.
2. γ has zero acceleration or curvature. That is, $\gamma''(t) = 0$ for all $t \in (a, b)$.

To extrapolate these ideas beyond \mathbb{R}^n , we utilise the second characteristic property of straight lines in \mathbb{R}^n . More specifically, let S be an oriented surface with Gauss map $N : S \rightarrow S^2$, and let $\gamma : I \rightarrow S \subseteq \mathbb{R}^3$, where $I \subseteq \mathbb{R}^3$ is an interval, be a regular curve parameterised by arc length. Note that $\{\gamma', N \times \gamma', N\}$ is an orthonormal basis for \mathbb{R}^3 where in particular $\{\gamma'(t), (N \times \gamma')(t)\}$ is an orthonormal basis for $T_{\gamma(t)}S$ for all $t \in I$. Recall that the curvature vector for γ is $\mathbf{k}(t) = \gamma''(t)$, which is orthogonal to $\gamma'(t)$. Thus,

$$\mathbf{k}(t) = \langle \mathbf{k}(t), (N \times \gamma')(t) \rangle = \langle \mathbf{k}(t), N(t) \rangle N(t).$$

Definition 4.1.1. With notation as above, $k_g(t) := \langle \mathbf{k}(t), (N \times \gamma')(t) \rangle$ is referred to as the geodesic curvature, and $k_n(t) := \langle \mathbf{k}(t), N(t) \rangle$ is referred to as the normal curvature of γ at t .

Remark 4.1.2.

1. Note that

$$k(t) = |\mathbf{k}(t)| = \sqrt{k_g(t)^2 + k_n(t)^2}.$$

2. The geodesic curvature describes the curvature of γ tangential to S .

Definition 4.1.3. A curve $\gamma : I \rightarrow S \subseteq \mathbb{R}^3$ is a geodesic if $k_g(t) = 0$ for all $t \in I$.

Example 4.1.4.

1. Let S be the x - y plane, such that $N = (0, 0, 1)$. Let $\gamma(t) = (x(t), y(t), 0)$ be parameterised by arc length. Then,

$$\begin{aligned} k_n(t) &= \langle \gamma''(t), N(t) \rangle \\ &= \langle (x''(t), y''(t), 0), (0, 0, 1) \rangle \\ &= 0. \end{aligned}$$

Hence,

$$\mathbf{k}(t) = k_g(N \times \gamma'(t))$$

so that

$$(x''(t), y''(t), 0) = k_g(-y', x', 0).$$

Therefore, $k_g \equiv 0$ if and only if $x''(t) \equiv y''(t) \equiv 0$. In other words, the geodesics of S are straight lines.

2. Let S be the unit sphere in \mathbb{R}^3 , and for $r > 0$ let $\gamma : [0, 2\pi r] \rightarrow S$ be given by

$$\gamma(t) = \left(r \cos\left(\frac{t}{r}\right), r \sin\left(\frac{t}{r}\right), \sqrt{1 - r^2} \right),$$

which is the circle of radius r on S parallel to the x - y plane. Note that γ is parameterised by arc length and recall that $N(p) = p$ for every $p \in S$, hence,

$$\begin{aligned} N(\gamma(t)) \times \gamma'(t) &= \left(r \cos\left(\frac{t}{r}\right), r \sin\left(\frac{t}{r}\right), \sqrt{1-r^2} \right) \times \left(-\sin\left(\frac{t}{r}\right), \cos\left(\frac{t}{r}\right), 0 \right) \\ &= \left(-\sqrt{1-r^2} \cos\left(\frac{t}{r}\right), -\sqrt{1-r^2} \sin\left(\frac{t}{r}\right), r \right). \end{aligned}$$

Moreover,

$$\gamma''(t) = \left(-\frac{1}{r} \cos\left(\frac{t}{r}\right), -\frac{1}{r} \sin\left(\frac{t}{r}\right), 0 \right),$$

so that

$$k_g(t) = \langle \gamma''(t), N(\gamma(t)) \times \gamma'(t) \rangle = \frac{\sqrt{1-r^2}}{r}.$$

Therefore, γ is a geodesic when $r = 1$, that is γ is the equator of the sphere. It follows that all great circles of S^2 are geodesics. A great circle is a path on S^2 obtained by intersecting S^2 with a plane passing through the origin. Using Lemma 2.4.8 we can rotate the curve such that it lies on the equator of the sphere whilst preserving its curvature. Therefore, with the above computations, we deduce that the great circle is a geodesic.

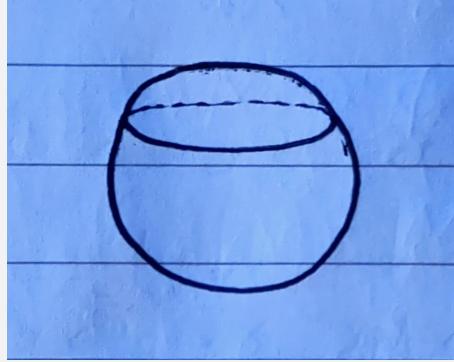


Figure 4.1.1

Exercise 4.1.5. Let S be a regular surface

Let S be a regular oriented surface with chart $\phi : U \rightarrow S$. Let $\gamma : I \rightarrow S \subseteq \mathbb{R}^3$ be a regular curve parameterised by arc length, with $\gamma(I) \subseteq \phi(U)$. Then one can write $\gamma(t) = \phi(x^1(t), x^2(t))$, where $(x^1(t), x^2(t))$ is a curve in U . Recall, that

$$\frac{\partial^2 \phi}{\partial x^i \partial x^j} = \sum_{k=1}^2 \Gamma_{ij}^k \frac{\partial \phi}{\partial x^k} + A_{ij} N,$$

where N is the Gauss map of the surface.

Proposition 4.1.6. For S , ϕ and γ as above, γ is a geodesic if and only if

$$\ddot{x}^k(t) + \sum_{i,j=1}^2 \Gamma_{ij}^k (x^1(t), x^2(t)) \dot{x}^i(t) \dot{x}^j(t) = 0 \quad (4.1.1)$$

for $k = 1, 2$.

Proof. γ is a geodesic if and only if $\gamma''(t)$ is proportional to $N(\gamma(t))$. Note that

$$\gamma'(t) = \sum_{i=1}^2 \dot{x}^i(t) \frac{\partial \phi}{\partial x^i} (x^1(t), x^2(t))$$

and

$$\begin{aligned} \gamma''(t) &= \sum_{i=1}^2 \ddot{x}^i(t) \frac{\partial \phi}{\partial x^i} (x^1(t), x^2(t)) + \sum_{i,j=1}^2 \dot{x}^i(t) x^j(t) \frac{\partial^2}{\partial x^i \partial x^j} (x^1(t), x^2(t)) \\ &= \sum_{k=1}^2 \left(\ddot{x}^k(t) \frac{\partial \phi}{\partial x^k} + \sum_{i,j=1}^2 \dot{x}^i(t) x^j(t) \Gamma_{ij}^k (x^1(t), x^2(t)) \frac{\partial \phi}{\partial x^k} \right) + \sum_{i,j=1}^2 \dot{x}^i(t) \dot{x}^j(t) A_{ij} N. \end{aligned}$$

Hence, γ is a geodesic if and only if

$$\ddot{x}^k(t) \frac{\partial \phi}{\partial x^k} + \sum_{i,j=1}^2 \dot{x}^i(t) x^j(t) \Gamma_{ij}^k (x^1(t), x^2(t)) \frac{\partial \phi}{\partial x^k} = 0.$$

Therefore, since the vectors $\left\{ \frac{\partial \phi}{\partial x^1}, \frac{\partial \phi}{\partial x^2} \right\}$ are linearly independent it follows that equations (4.1.1) hold. \square

Remark 4.1.7. Equations (4.1.1) are referred to as the geodesic equations.

Corollary 4.1.8. Local isometries maps geodesics to geodesics.

Proof. If $F : S \rightarrow \tilde{S}$ is a local isometry, then, shrinking U if necessary, $F \circ \phi : U \rightarrow \tilde{S}$ is a chart for \tilde{S} . Therefore, we conclude by recalling that $\tilde{\Gamma}_{ij}^k(u, v) = \Gamma_{ij}^k(u, v)$ for all $(u, v) \in U$ which implies that the geodesic equations hold in \tilde{S} . \square

Exercise 4.1.9. For a surface S let $\phi : U \rightarrow S$ be a chart with first fundamental form

$$M = \begin{pmatrix} E & F \\ F & G \end{pmatrix}.$$

Show that a curve $\gamma : (-\epsilon, \epsilon) \rightarrow S$ given by $\gamma(t) = \phi(u(t), v(t))$ is a geodesic if and only if

$$\begin{cases} (Eu' + Fv')' = \frac{1}{2} \left(E_u (u')^2 + 2F_u (u'v') + G_u (v')^2 \right) \\ (Fu' + Gv')' = \frac{1}{2} \left(E_v (u')^2 + 2F_v (u'v') + G_v (v')^2 \right). \end{cases}$$

Example 4.1.10. Let $C = \{(x, y, z) \in \mathbb{R}^3 : x^2 + y^2 = 1\}$. Recall, from statement 2 of Example 3.12.5 that C is isometric to the plane $\Pi = \{(x, y, z) \in \mathbb{R}^3 : z = 0\}$ plane through the isometry

$$F(x, y, 0) = (\cos(x), \sin(x), y).$$

From statement 1 of Example 4.1.4 the geodesics of Π are of the form $\gamma(t) = (at + b, ct + d, 0)$, with $a^2 + c^2 = 1$ ensuring the geodesic is parameterised by arc length. Thus, using Corollary 4.1.8 it follows that the geodesics of S are of the form

$$\gamma(t) = F(at + b, ct + d) = (\cos(at + b), \sin(at + b), ct + d).$$

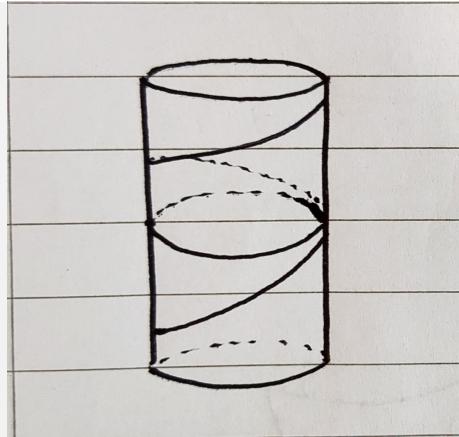


Figure 4.1.2

4.2 Minimising Arc Length

Example 4.2.1. Note that geodesics do not necessarily minimise the arc length between two points. Consider S^2 , then distinct non-antipodal points can be connected by a small arc and a longer arc along the equator. Both these arcs are geodesics, statement 2 of Example 4.1.4, however, one does not minimise the arc length between these points.

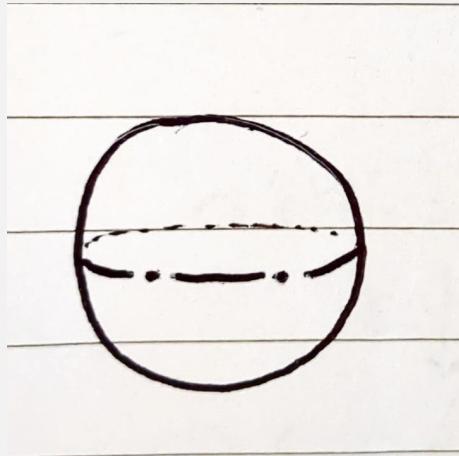


Figure 4.2.1

Definition 4.2.2. Let $S \subseteq \mathbb{R}^3$ be a regular surface, and let $\gamma : [0, L] \rightarrow S$ be a regular curve. A variation of γ is a smooth map $A : [0, L] \times (-\epsilon, \epsilon) \rightarrow S$ such that the following hold.

1. $A(t, 0) = \gamma(t)$ for all $t \in [0, L]$.
2. $A(0, s) = \gamma(0)$ for all $s \in (-\epsilon, \epsilon)$.
3. $A(L, s) = \gamma(L)$ for all $s \in (-\epsilon, \epsilon)$.

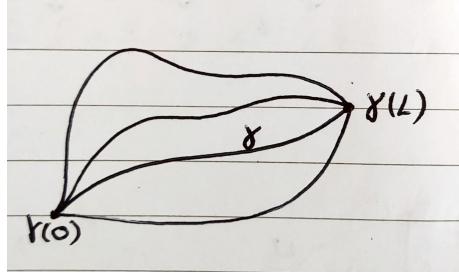


Figure 4.2.2

Proposition 4.2.3. Let $S \subseteq \mathbb{R}^3$ be a regular surface. Let $\gamma : [0, L] \rightarrow S$ be a regular curve parameterised by arc length such that if regular curve $\tilde{\gamma} : [a, b] \rightarrow S$ is a regular curve with $\tilde{\gamma}(a) = \gamma(0)$ and $\tilde{\gamma}(b) = \gamma(L)$ then $L(\gamma) \leq L(\tilde{\gamma})$. Then γ is a geodesic.

Proof. Let $A : [0, L] \times (-\epsilon, \epsilon) \rightarrow S$ be a variation of γ , with $\gamma_s : [0, L] \rightarrow S$ given by $\gamma_s(t) = A(t, s)$. As $s \mapsto L(\gamma_s)$ is minimised at $s = 0$, it follows that the derivative of this map is zero at $s = 0$. Therefore,

$$\begin{aligned}
\frac{d}{ds} L(\gamma_s) \Big|_{s=0} &= \frac{d}{ds} \int_0^L |\gamma'_s(t)| dt \Big|_{s=0} \\
&= \frac{d}{ds} \int_0^L \sqrt{\langle \gamma'_s(t), \gamma'_s(t) \rangle} dt \Big|_{s=0} \\
&\stackrel{(1)}{=} \int_0^L \frac{d}{ds} \sqrt{\langle \gamma'_s(t), \gamma'_s(t) \rangle} \Big|_{s=0} dt \\
&= \int_0^L \frac{\frac{d}{ds} \langle \gamma'_s(t), \gamma'_s(t) \rangle \Big|_{s=0}}{2\sqrt{\langle \gamma'_s(t), \gamma'_s(t) \rangle \Big|_{s=0}}} dt \\
&\stackrel{(2)}{=} \int_0^L \frac{1}{2} \frac{d}{ds} \langle \gamma'_s(t), \gamma'_s(t) \rangle \Big|_{s=0} dt \\
&= \int_0^L \left\langle \frac{d}{ds} \left(\frac{d\gamma_s(t)}{dt} \right) \Big|_{s=0}, \frac{d\gamma_0(t)}{dt} \right\rangle dt \\
&= \int_0^L \left\langle \frac{d}{dt} \left(\frac{d\gamma_s(t)}{ds} \right) \Big|_{s=0}, \frac{d\gamma(t)}{dt} \right\rangle dt \\
&= \left[\left\langle \frac{d\gamma_s(t)}{ds} \Big|_{s=0}, \frac{d\gamma(t)}{dt} \right\rangle \right]_{t=0}^{t=L} - \int_0^L \left\langle \frac{d\gamma_s(t)}{ds} \Big|_{s=0}, \gamma''(t) \right\rangle dt \\
&\stackrel{(3)}{=} - \int_0^L \left\langle \frac{d\gamma_s(t)}{ds} \Big|_{s=0}, \gamma''(t) \right\rangle dt \\
&= - \int_0^L \left\langle \frac{d\gamma_s(t)}{ds} \Big|_{s=0}, (k_n(t)N(\gamma(t)) + k_g(t)(N(\gamma(t)) \times \gamma'(t))) \right\rangle dt \\
&\stackrel{(4)}{=} - \int_0^L k_g(t) \left\langle \frac{d\gamma_s(t)}{ds} \Big|_{s=0}, N(\gamma(t)) \times \gamma'(t) \right\rangle dt. \tag{4.2.1}
\end{aligned}$$

Equality (1) follows as $s \mapsto \sqrt{\langle \gamma'_s(t), \gamma'_s(t) \rangle}$ is smooth in s and t , so that the order of integration can be interchanged. Equality (2) is because γ is parameterised by arc length. Equality (3) is because $\gamma_s(0) = \gamma(0)$, $\gamma_s(L) = \gamma(L)$ and $\frac{d\gamma_s(t)}{ds} \Big|_{s=0}$ is zero for $t = 0, L$. Equality (4) is because $\frac{d\gamma_s(t)}{ds} \Big|_{s=0}$ belongs to the tangent space of $\gamma(t)$ as $\gamma_s(t) \in S$ for all s and t . Therefore,

$$\int_0^L k_g(t) \left\langle \frac{d\gamma_s(t)}{ds} \Big|_{s=0}, N(\gamma(t)) \times \gamma'(t) \right\rangle dt = 0 \tag{4.2.2}$$

for any variation A of γ . Suppose that there exists $t_0 \in (0, L)$ such that $k_g(t_0) > 0$, with the case $k_g(t_0) < 0$ being similar. Since k_g is continuous there exists a $\delta > 0$ such that $k_g(t) > 0$ for all $t \in (t_0 - \delta, t_0 + \delta) \subseteq (0, L)$. Let $\phi : U \rightarrow S$ be a chart around $\gamma(t_0)$ with $\gamma((t_0 - \delta, t_0 + \delta)) \subseteq \phi(U)$, shrinking δ if necessary. Write $\gamma(t) = \phi(u(t), v(t))$ for all $t \in (t_0 - \delta, t_0 + \delta)$. Note that given any $V : (t_0 - \delta, t_0 + \delta) \rightarrow \mathbb{R}^3$ such that $V(t) \in T_{\gamma(t)}S$ for all $t \in (t_0 - \delta, t_0 + \delta)$ there exists a variation A of γ such that

$$V(t) = \frac{dA(s, t)}{ds} \Big|_{s=0}.$$

Indeed, let $V(t) = V_u(t) \frac{\partial \phi}{\partial u} + V_v(t) \frac{\partial \phi}{\partial v}$ and $A(t, s) = \phi(u(t) + sV_u(t), v(t) + sV_v(t))$. Then,

$$\frac{dA(s, t)}{ds} \Big|_{s=0} = V(t).$$

So take $V(t) = f(t)(N \times \gamma')(t)$ where f is smooth such that $f(t_0) = 1$, $f(t) \leq 1$ and $f(t) = 0$ for $t \in [0, L] \setminus (t_0 - \delta, t_0 + \delta)$. Then,

$$0 = \int_0^L k_g(t) \left\langle \frac{d\gamma_s(t)}{ds} \Big|_{s=0}, (N \times \gamma')(t) \right\rangle dt = \int_{t_0-\delta}^{t_0+\delta} k_g(t) f(t) dt > 0$$

which contradicts (4.2.2). Therefore, $k_g \equiv 0$ and thus a geodesic. \square

Example 4.2.4. Note there may exist points on a regular surface for which no connecting geodesic exists. Consider a plane punctured at a point, then there exist distinct points that cannot be connected by a straight line since the straight line traverses the removed point.

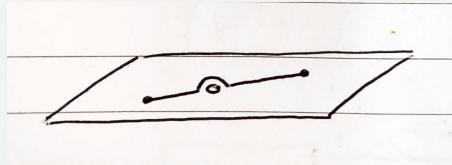


Figure 4.2.3

4.3 Solution to Exercises

Exercise 4.1.9

Solution. Recall, that γ is a geodesic if and only if $\langle \gamma''(t), \phi_u \rangle = 0$ and $\langle \gamma''(t), \phi_v \rangle = 0$. Note that

$$\gamma'(t) = \phi_u u'(t) + \phi_v v'(t).$$

Using

$$\langle \gamma''(t), \phi_u \rangle = (\langle \gamma'(t), \phi_u \rangle)' - \langle \gamma'(t), (\phi_u)' \rangle$$

it follows that

$$\begin{aligned} 0 &= (\langle \phi_u u' + \phi_v v', \phi_u \rangle)' - \langle \phi_u u' + \phi_v v', \phi_{uu} u' + \phi_{uv} v' \rangle \\ &= (Eu' + Fv')' - \left(\langle \phi_u, \phi_{uu} \rangle (u')^2 + (\langle \phi_u, \phi_{uv} \rangle + \langle \phi_v, \phi_{uu} \rangle) (u'v') + \langle \phi_v, \phi_{vv} \rangle (v')^2 \right). \end{aligned} \quad (4.3.1)$$

Note that

$$\begin{cases} \langle \phi_u, \phi_{uu} \rangle = \frac{1}{2} \frac{\partial}{\partial u} \langle \phi_u, \phi_u \rangle = \frac{1}{2} E_u \\ \langle \phi_u, \phi_{uv} \rangle + \langle \phi_v, \phi_{uu} \rangle = \frac{\partial}{\partial u} \langle \phi_u, \phi_v \rangle = F_u \\ \langle \phi_v, \phi_{uv} \rangle = \frac{1}{2} \frac{\partial}{\partial u} \langle \phi_v, \phi_v \rangle = \frac{1}{2} G_u. \end{cases}$$

Therefore, (4.3.1) becomes

$$0 = (Eu' + Fv')' - \frac{1}{2} \left(E_u (u')^2 + 2F_u (u'v') + G_u (v')^2 \right).$$

Similarly, using

$$\langle \gamma''(t), \phi_v \rangle = (\langle \gamma'(t), \phi_v \rangle)' - \langle \gamma'(t), (\phi_v)' \rangle$$

it follows that

$$(Fu' + Gv')' - \frac{1}{2} \left(E_v (u')^2 + 2F_v (u'v') + G_v (v')^2 \right).$$

□

5 Gauss-Bonnet Theorem

5.1 The Local Gauss-Bonnet Theorem

Definition 5.1.1. A regular surface with boundary $S \subseteq \mathbb{R}^3$ is such that for all $p \in S$ either of the following occur.

1. There is a chart $\phi : U \rightarrow S$ for S at p . That is, there is an open set $V \subseteq \mathbb{R}^3$ such that $p \in V$ and $S \cap V$ is a regular surface.
2. There is an open set $U \subseteq \mathbb{R}^2$ such that $(0, 0) \in U$, an open neighbourhood $V \subseteq \mathbb{R}^3$ of p , and a smooth map $\phi : U \rightarrow V$ such that the following hold.
 - $\phi(0, 0) = p$.
 - $\phi : \{(x, y) \in U : y \geq 0\} \rightarrow V \cap S$ is a homeomorphism.
 - For every $q \in U$, the differential $d\phi_q : \mathbb{R}^2 \rightarrow \mathbb{R}^3$ is injective.

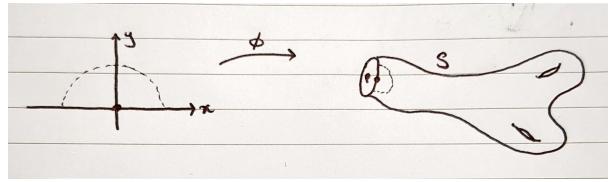


Figure 5.1.1: A chart at a boundary point of S .

Remark 5.1.2.

1. Statement 1 of Definition 5.1.1 says that locally at p the subset S looks like a regular surface.
2. The smooth map ϕ of statement 2 of Definition 5.1.1 is still referred to as a chart.
3. Note that a regular surface is a regular surface with a boundary, just that in this case the boundary is empty.

Definition 5.1.3. Let S be a regular surface with a boundary.

1. Points $p \in S$ satisfying statement 1 of Definition 5.1.1 are referred to as interior points.
2. Points $p \in S$ satisfying statement 2 of Definition 5.1.1 are referred to as boundary points. The set of boundary points of S is denoted ∂S .

Remark 5.1.4. Note that ∂S in the sense of statement 2 of Definition 5.1.3 is distinct from ∂S in the sense of topology. Indeed, ∂S in the sense of statement 2 of Definition 5.1.3 is a union of regular curves. On the other hand, the topological boundary of the set $S \subseteq \mathbb{R}^3$ is S .

Definition 5.1.5. Let S be a regular surface with boundary S . For $p \in \partial S$ let

$$T_p S := \{\gamma'(0) \in \mathbb{R}^3 : \gamma : [0, \epsilon) \rightarrow S \text{ or } \gamma : (-\epsilon, 0] \rightarrow S \text{ smooth such that } \gamma(0) = p\}.$$

Remark 5.1.6. Note that for $p \in \partial S$, if ϕ is a chart in the sense of statement 2 of Definition 5.1.1, then $T_p S = d\phi_{(0,0)}(\mathbb{R}^2)$.

An orientation of a regular surface with boundary S induces an orientation on ∂S . Indeed, if $N : S \rightarrow S^2$ is a Gauss map for S and $\gamma : [a, b] \rightarrow \partial S$ is a regular curve, then γ is positively oriented if $N \times \gamma'$ points into S . Therefore, one can consider integrals on regular surfaces with boundary. In particular, if ∂S has a single connected component let $\gamma : [a, b] \rightarrow S$ be a positively oriented arc length parameterisation of ∂S . Then for $f : \partial S \rightarrow \mathbb{R}$ let

$$\int_{\partial S} f := \int_a^b f(\gamma(t)) dt.$$

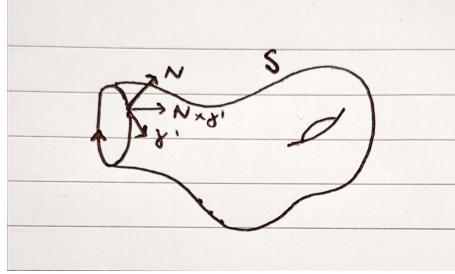


Figure 5.1.2: Orienting the boundary of an oriented surface.

Theorem 5.1.7 (Green's). Let $F = (F^u, F^v)$ be a real vector field on \mathbb{R}^2 . Then

$$\int_{\partial U} F \cdot dS = \int_U \operatorname{curl} F du dv.$$

Theorem 5.1.8 (Local Gauss-Bonnet). Let S be a regular surface with a boundary such that there is a chart $\phi : U \rightarrow S$ satisfying the following.

1. $\bar{U} \subseteq \mathbb{R}^2$ is diffeomorphic to a closed disc, and ϕ is smooth on a neighbourhood on a neighbourhood of $\bar{U} \subseteq \mathbb{R}^2$.
2. $S = \phi(\bar{U})$ with $\partial S = \phi(\partial U)$, where ∂S is as in statement 2 of Definition 5.1.3 and ∂U is the topological boundary of $U \subseteq \mathbb{R}^2$.

Then

$$\int_{\partial S} k_g + \int_S K dA = 2\pi,$$

where k_g is the geodesic curvature of S , and K is the Gauss curvature of S .

Proof. Let $E_1 : \bar{U} \rightarrow \mathbb{R}^3$ be given by

$$E_1(u, v) = \frac{\phi_u(u, v)}{|\phi_u(u, v)|}$$

and $E_2 : \bar{U} \rightarrow \mathbb{R}^3$ be given by

$$E_2(u, v) = N(\phi(u, v)) \times E_1(u, v).$$

Then for every $(u, v) \in \bar{U}$ the set $\{E_1(u, v), E_2(u, v)\}$ is a basis for $T_{\phi(u,v)} S$. Moreover, $\{E_1, E_2, N\}$ forms an orthonormal basis for \mathbb{R}^3 at each point. Let $\gamma : [0, L] \rightarrow \partial S$ be a parameterisation of ∂S by arc length, with positive orientation. Then there is a regular curve $\sigma : [0, L] \rightarrow \partial U$ such that $\gamma = \phi \circ \sigma$. Moreover, there is a smooth function $\theta : [0, L] \rightarrow \mathbb{R}$ such that

$$\gamma'(t) = \cos(\theta(t))E_1(\sigma(t)) + \sin(\theta(t))E_2(\sigma(t)) \in T_{\gamma(t)} S. \quad (5.1.1)$$

Step 1: For every $t \in [0, L]$, we have $k_g(\gamma(t)) = \theta'(t) - \langle E_1 \circ \sigma(t), (E_2 \circ \sigma)'(t) \rangle$.

Differentiating (5.1.1) with respect to t gives

$$\gamma''(t) = \theta'(t) (-\sin(\theta(t))E_1(\sigma(t)) + \cos(\theta(t))E_2(\sigma(t))) + \cos(\theta(t))(E_1 \circ \sigma)'(t) + \sin(\theta(t))(E_2 \circ \sigma)'(t).$$

Also using (5.1.1) we have

$$\begin{aligned} N(\gamma) \times \gamma' &= N(\gamma) \times (\cos(\theta)(E_1 \circ \sigma) + \sin(\theta)(E_2 \circ \sigma)) \\ &= -\sin(\theta)(E_1 \circ \sigma) + \cos(\theta)(E_2 \circ \sigma) \end{aligned}$$

Note the relation

$$\langle E_1 \circ \sigma, E_1 \circ \sigma \rangle = \langle E_2 \circ \sigma, E_2 \circ \sigma \rangle = 1$$

and

$$\langle E_1 \circ \sigma, E_2 \circ \sigma \rangle = 0.$$

Differentiating these with respect to t produces the relations

$$\langle E_1 \circ \sigma, (E_1 \circ \sigma)' \rangle = \langle E_2 \circ \sigma, (E_2 \circ \sigma)' \rangle = 0$$

and

$$\langle E_1 \circ \sigma, (E_2 \circ \sigma)' \rangle = -\langle (E_1 \circ \sigma)', E_2 \circ \sigma \rangle.$$

Therefore,

$$\begin{aligned} k_g(\gamma(t)) &= \langle \gamma''(t), N(\gamma(t)) \times \gamma'(t) \rangle \\ &= \langle \gamma''(t), -\sin(\theta(t))E_1 \circ \sigma(t) + \cos(\theta(t))E_2 \circ \sigma(t) \rangle \\ &= \theta'(t) + \langle \cos(\theta(t))(E_1 \circ \sigma)'(t) + \sin(\theta(t))(E_2 \circ \sigma)'(t), -\sin(\theta(t))E_1 \circ \sigma(t) + \cos(\theta(t))E_2 \circ \sigma(t) \rangle \\ &= \theta'(t) + \cos^2(\theta(t)) \langle (E_1 \circ \sigma)'(t), E_2 \circ \sigma(t) \rangle - \sin^2(\theta(t)) \langle (E_2 \circ \sigma)'(t), E_1 \circ \sigma(t) \rangle \\ &= \theta'(t) - (\cos^2(\theta) + \sin^2(\theta)) \langle (E_2 \circ \sigma)'(t), E_1 \circ \sigma(t) \rangle \\ &= \theta'(t) - \langle E_1 \circ \sigma(t), (E_2 \circ \sigma)'(t) \rangle. \end{aligned}$$

Step 2: $\int_0^L \langle E_1 \circ \sigma(t), (E_2 \circ \sigma)'(t) \rangle dt = \int_U (K \circ \phi) |\phi_u \times \phi_v| du dv$.

Note that

$$\left\langle E_1, \frac{\partial E_1}{\partial u} \right\rangle = \frac{1}{2} \frac{\partial}{\partial u} \langle E_1, E_1 \rangle = 0$$

and

$$\left\langle E_1, \frac{\partial E_1}{\partial v} \right\rangle = \left\langle E_2, \frac{\partial E_2}{\partial u} \right\rangle = \left\langle E_2, \frac{\partial E_2}{\partial v} \right\rangle = 0.$$

Moreover,

$$\begin{aligned} 0 &= \frac{\partial}{\partial u} \langle E_1, N \circ \phi \rangle \\ &= \left\langle \frac{\partial E_1}{\partial u}, N \circ \phi \right\rangle + \left\langle E_1, \frac{\partial N \circ \phi}{\partial u} \right\rangle \\ &= \left\langle \frac{\partial E_1}{\partial u}, N \circ \phi \right\rangle + \left\langle E_1, dN_\phi \left(\frac{\partial \phi}{\partial u} \right) \right\rangle \\ &= \left\langle \frac{\partial E_1}{\partial u}, N \circ \phi \right\rangle - A \left(E_1, \frac{\partial \phi}{\partial u} \right). \end{aligned}$$

Therefore, there exists a real function $a : U \rightarrow \mathbb{R}$ such that

$$\begin{aligned} \frac{\partial E_1}{\partial u} &= 0E_1 + aE_2 + \left\langle \frac{\partial E_1}{\partial u}, N \circ \phi \right\rangle N \circ \phi \\ &= aE_2 + A \left(E_1, \frac{\partial \phi}{\partial u} \right) N \circ \phi. \end{aligned}$$

Similarly, there exists a real function b such that

$$\frac{\partial E_1}{\partial v} = bE_2 + A \left(E_1, \frac{\partial \phi}{\partial v} \right) N \circ \phi,$$

a real function c such that

$$\frac{\partial E_2}{\partial u} = cE_1 + A \left(E_2, \frac{\partial \phi}{\partial u} \right) N \circ \phi,$$

and a real function d such that d such that

$$\frac{\partial E_2}{\partial v} = dE_1 + A \left(E_2, \frac{\partial \phi}{\partial v} \right) N \circ \phi.$$

For $i, j = 1, 2$ let the real functions c_{ij} be such that

$$\frac{\partial \phi}{\partial u} = c_{11}E_1 + c_{12}E_2$$

and

$$\frac{\partial \phi}{\partial v} = c_{21}E_1 + c_{22}E_2.$$

Then

$$\begin{aligned} \left\langle \frac{\partial E_1}{\partial u}, \frac{\partial E_2}{\partial v} \right\rangle - \left\langle \frac{\partial E_2}{\partial u}, \frac{\partial E_1}{\partial v} \right\rangle &= A \left(E_1, \frac{\partial \phi}{\partial u} \right) A \left(E_2, \frac{\partial \phi}{\partial v} \right) - A \left(E_2, \frac{\partial \phi}{\partial u} \right) A \left(E_1, \frac{\partial \phi}{\partial v} \right) \\ &= (c_{11}A(E_1, E_1) + c_{12}A(E_1, E_2))(c_{21}A(E_2, E_1) + c_{22}A(E_2, E_2)) \\ &\quad - (c_{11}A(E_2, E_1) + c_{12}A(E_2, E_2))(c_{21}A(E_1, E_1) + c_{22}A(E_1, E_2)) \\ &= (c_{11}c_{22} - c_{12}c_{21})(A(E_1, E_1)A(E_2, E_2) - A(E_1, E_2)A(E_2, E_1)) \\ &= \left| \frac{\partial \phi}{\partial u} \times \frac{\partial \phi}{\partial v} \right| \det(\Sigma) \\ &= |\phi_u \times \phi_v| K \circ \phi, \end{aligned}$$

where we have used the fact that the first fundamental form M in the basis $\{E_1, E_2\}$ is the identity matrix and so has determinant 1. Under a change of basis, P , the first and second fundamental forms change to $P^\top MgP$ and $P^\top \Sigma P$ respectively. Thus, the quantity $\frac{\det(\Sigma)}{\det(M)}$ is independent of the choice of basis. Now let $\sigma(t) = (u(t), v(t))$, where $u(t)$ and $v(t)$ are some smooth functions. Then

$$\begin{aligned} \frac{\partial}{\partial t}(E_2 \circ \sigma)(t) &= \frac{\partial}{\partial t}(E_2(u(t), v(t))) \\ &= \frac{\partial E_2}{\partial u}(u(t), v(t))v'(t) + \frac{\partial E_2}{\partial v}(u(t), v(t))v'(t). \end{aligned}$$

Hence,

$$\begin{aligned} \int_0^L \langle E_1 \circ \sigma(t), (E_2 \circ \sigma)'(t) \rangle dt &= \int_0^L \left\langle E_1(u(t), v(t)), \frac{\partial E_2}{\partial u}(u(t), v(t)) \right\rangle u'(t) dt \\ &\quad + \int_0^L \left\langle E_1(u(t), v(t)), \frac{\partial E_2}{\partial v}(u(t), v(t)) \right\rangle v'(t) dt \\ &= \int_{\partial U} \left\langle E_1(u, v), \frac{\partial E_2}{\partial u}(u, v) \right\rangle du + \int_{\partial U} \left\langle E_1(u, v), \frac{\partial E_2}{\partial v}(u, v) \right\rangle dv \\ &\stackrel{(1)}{=} \int_U \frac{\partial}{\partial u} \left(\left\langle E_1(u, v), \frac{\partial E_2}{\partial v}(u, v) \right\rangle \right) - \frac{\partial}{\partial v} \left(\left\langle E_1(u, v), \frac{\partial E_2}{\partial u}(u, v) \right\rangle \right) du dv \\ &= \int_U \left(\left\langle \frac{\partial E_1}{\partial u}, \frac{\partial E_2}{\partial v} \right\rangle + \left\langle E_1, \frac{\partial^2 E_2}{\partial u \partial v} \right\rangle \right) - \left(\left\langle \frac{\partial E_1}{\partial v}, \frac{\partial E_2}{\partial u} \right\rangle + \left\langle E_1, \frac{\partial^2 E_2}{\partial v \partial u} \right\rangle \right) du dv \\ &= \int_U \left\langle \frac{\partial E_1}{\partial u}, \frac{\partial E_2}{\partial v} \right\rangle - \left\langle \frac{\partial E_1}{\partial v}, \frac{\partial E_2}{\partial u} \right\rangle du dv \\ &= \int_U |\phi_u \times \phi_v| K \circ \phi du dv, \end{aligned}$$

where in (1) we have applied Theorem 5.1.7 by noting that

$$\int_{\partial U} F \cdot dS = \int_0^L F^u u'(t) + F^v v'(t) dt$$

and

$$\operatorname{curl}(F) = \partial_u F^v - \partial_v F^u.$$

Step 3: $\int_0^L \theta'(s) ds = 2\pi$.

Note that

$$\int_0^L \theta'(s) ds = \theta(L) - \theta(0). \quad (5.1.2)$$

For a closed curve γ we have $\gamma'(0) = \gamma'(L)$, and thus from (5.1.1) we have that $\theta(L) - \theta(0)$ is a multiple of 2π . By assumption, we have a diffeomorphism $\Psi : B(0, 1) \rightarrow \bar{U}$, which can be used to construct a family of regular curves $(\sigma_s : [0, L] \rightarrow \bar{U})_{s \in [0, 1]}$ such that $\sigma_0 \equiv \sigma$ and σ_1 is a circle of radius ϵ in U . Then the continuous family of curves $(\gamma_s)_{s \in [0, 1]}$, where $\gamma_s := \phi \circ \sigma_s$, can be considered as a continuous perturbation of γ to some small closed curve in S . Note that the left-hand side of depends continuously on the curves γ_s . Since the value of the integral of the left-hand side is an integer multiple of 2π for all γ_s , it must be the case that the value of the left-hand side for γ_s is equal to the value of the left-hand side for γ_1 . Since the curve σ_1 is small, the map E_1 on σ_1 is essentially constant, since E is smooth. Observe that $\theta_1(t)$ is the angle between $\gamma'_1(t)$ and $E_1 \circ \sigma_1(t)$. Since, γ_1 revolves counter-clockwise around a small circle, and $E_1 \circ \sigma$ is near constant on that circle, the change in angle is 2π .

Step 4: Conclude.

Using step 1, step 2 and step 3 we have

$$\begin{aligned} \int_{\partial S} k_g ds + \int_S K dA &= \int_0^L k_g(\gamma(t)) dt + \int_U (K \circ \phi) |\phi_u \times \phi_v| du dv \\ &= \int_0^L \theta'(t) dt - \int_0^L \langle E_1 \circ \sigma(t), (E_2 \circ \sigma)'(t) \rangle dt + \int_U (K \circ \phi) |\phi_u \times \phi_v| du dv \\ &= \int_0^L \theta'(t) dt \\ &= 2\pi. \end{aligned}$$

□

Remark 5.1.9. Theorem 5.1.8 links curvatures, an intrinsic and extrinsic form of curvature, to a topological quantity.

5.2 The n -gon Gauss Bonnet

Definition 5.2.1. Given $n \geq 1$, a continuous map $\beta : [0, L] \rightarrow \mathbb{R}^2$ is a curvilinear n -gon if the following hold.

1. $\beta(0) = \beta(L)$.
2. $\beta|_{[0, L]}$ is injective.
3. There exists a subdivision $0 = t_0 < \dots < t_n = L$ such that the following hold.
 - (a) $\beta|_{(t_i, t_{i+1})}$ is a regular curve for $i = 0, \dots, n-1$.
 - (b) $\beta'(t_i^-) = \lim_{t \nearrow t_i} \beta'(t)$ exists for $i = 1, \dots, n$.
 - (c) $\beta'(t_i^+) = \lim_{t \searrow t_i} \beta'(t)$ exists for $i = 0, \dots, n$.

(d) Each pair $(\beta'(t_0^+), \beta'(t_n^-)), (\beta'(t_1^-), \beta'(t_1^+)), \dots, (\beta'(t_{n-1}^-), \beta'(t_{n-1}^+))$ is linear independent.

Remark 5.2.2.

1. A curvilinear 3-gon is referred to as a curvilinear triangle.
2. The points $\beta(t_i)$ are referred to as the vertices and the curves $\beta((t_i, t_{i+1}))$ are referred to as edges.

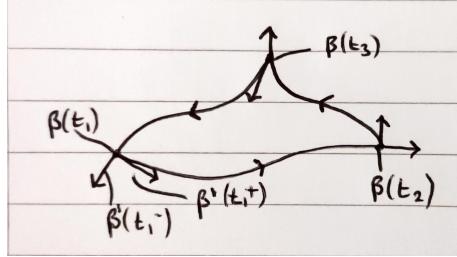


Figure 5.2.1: A curvilinear triangle.

If S is a regular surface with chart $\phi : U \rightarrow S$, and $N \subseteq U$ is a curvilinear n -gon. Then $\phi(N)$ is referred to as a curvilinear n -gon in S . Where we assume that the linear independence of the vectors of statement 3(d) of Definition 5.2.1 is preserved.

Definition 5.2.3. Let S be a regular surface with chart $\phi : U \rightarrow S$. Let N be a curvilinear n -gon and set $\gamma := \phi \circ \beta$. Then the exterior angle θ_i for $i = 1, \dots, n$, between $\gamma'(t_i^-)$ and $\gamma'(t_i^+)$ is $\theta_i \in (-\pi, \pi)$ such that

$$\cos(\theta_i) = \frac{\langle \gamma'(t_i^-), \gamma'(t_i^+) \rangle}{|\gamma'(t_i^-)| |\gamma'(t_i^+)|}$$

with

- $\theta_i > 0$ if $\{\gamma'(t_i^-), \gamma'(t_i^+), N\}$ is a positively oriented basis of \mathbb{R}^3 , and
- $\theta_i < 0$ if $\{\gamma'(t_i^-), \gamma'(t_i^+), N\}$ is a negatively oriented basis of \mathbb{R}^3 .

Remark 5.2.4.

1. Note suitable adjustments are to be made to Definition 5.2.3 when $i = n$.
2. The interior angle is given by $\alpha_i = \pi - \theta_i$.

Theorem 5.2.5 (n -gon Gauss-Bonnet). Let $S' \subseteq \mathbb{R}^3$ be a regular oriented surface. Suppose $S \subset S'$ is a regular surface with boundary such that ∂S is a curvilinear n -gon, with edges whose arc length parameterisations are $\gamma_i = \gamma|_{(t_{i-1}, t_i)}$ for $i = 1, \dots, n$ and meet at exterior angles θ_i . Then,

$$\sum_{i=1}^n \int_{\gamma_i} k_g \, dS + \sum_{i=1}^n \theta_i + \int_S K \, dA = 2\pi.$$

Proof. Recall the proof of Theorem 5.1.8. The identity of step 1 holds on the intervals (t_{i-1}, t_i) for $i = 1, \dots, n$.

Step 2 remains unchanged. Then using similar arguments as those made in step 3 we deduce that

$$\int_{t_0}^{t_1} \theta'(t) dt + \cdots + \int_{t_{n-1}}^{t_n} \theta'(t) dt = 2\pi - \sum_{i=1}^n \theta_i,$$

since γ' still rotates by 2π , however, the left-hand side does not include the rotations that occur at the vertices. \square

Corollary 5.2.6. *In the context of Theorem 5.2.5, if $n = 3$ and the edges are geodesics, then*

$$\begin{aligned} \int_S K dA &= 2\pi - (\theta_1 + \theta_2 + \theta_3) \\ &= \alpha_1 + \alpha_2 + \alpha_3 - \pi. \end{aligned}$$

Remark 5.2.7. *We can consider particular cases of Corollary 5.2.6.*

1. *If S' is a plane, then $\alpha_1 + \alpha_2 + \alpha_3 = \pi$.*
2. *If S' is a unit sphere, then $\alpha_1 + \alpha_2 + \alpha_3 = \pi + \text{area}(T)$.*
3. *If $K_{S'} < 0$, then $\alpha_1 + \alpha_2 + \alpha_3 < \pi$.*

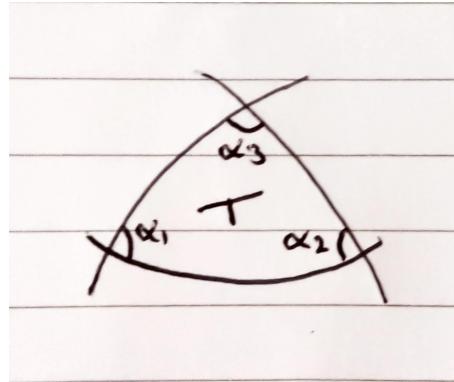


Figure 5.2.2: Curvilinear triangle and its interior angles on a sphere.