

Differential Geometry I

Lecture notes

Andriy Haydys

November 22, 2023

This is a draft. If you spot a mistake, please let me know.

Contents

1	Smooth surfaces	2
1.1	The notion of a smooth surface	2
1.2	The change of coordinates maps	8
1.3	Smooth functions on surfaces	9
1.4	The tangent plane	16
1.5	The differential of a smooth map	18
1.6	Orientability	23
1.7	Partitions of unity	27
1.8	Integration on surfaces	30
1.9	Quadratic forms on surfaces	35
1.10	The geometric meaning of the sign of the Gauss curvature	38
1.11	Surfaces of positive curvature and the Gauss–Bonnet theorem	41
1.11.1	A solution of Exercise 1.142	46
2	Manifolds	47
2.1	Abstract manifolds	47
2.2	Smooth maps	50
2.3	The tangent space	51
2.4	The differential of a smooth map	54
2.5	Submanifolds	55

Chapter 1

Smooth surfaces

1.1 The notion of a smooth surface

Let $U \subset \mathbb{R}^n$ be an open subset and $f \in C^1(U)$. It is known from analysis that $x_0 \in U$ is a point of extremum for f if

$$\frac{\partial f}{\partial x_i}(x_0) = 0$$

holds for all $i = 1, \dots, n$. Notice that this is a necessary condition, which is not sufficient in general.

A more general type of problems does not fit into this scheme. For example, consider the following.

Problem. Among all rectangular parallelepipeds, whose diagonal has a fixed length, say 1, find the one with maximal volume.

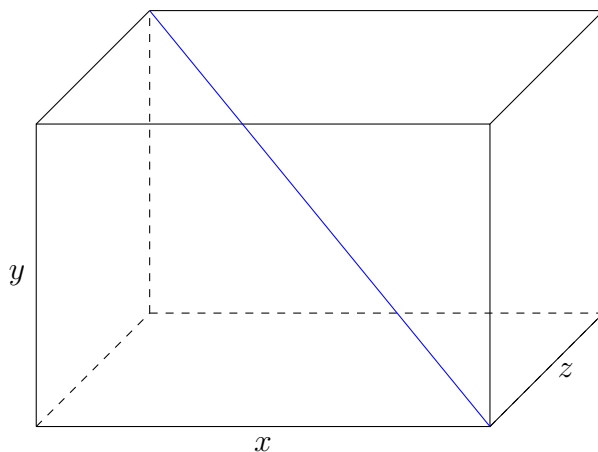


Figure 1.1: A parallelepiped

Thus, we want to find a point of maximum of the function $f(x, y, z) = xyz$ on the set

$$V = \{(x, y, z) \in \mathbb{R}^3 \mid x > 0, y > 0, z > 0 \text{ and } x^2 + y^2 + z^2 = 1\} \subset S^2. \quad (1.1)$$

However, V is *not* an open subset of \mathbb{R}^3 so that the receipt known from the analysis course is not readily applicable.

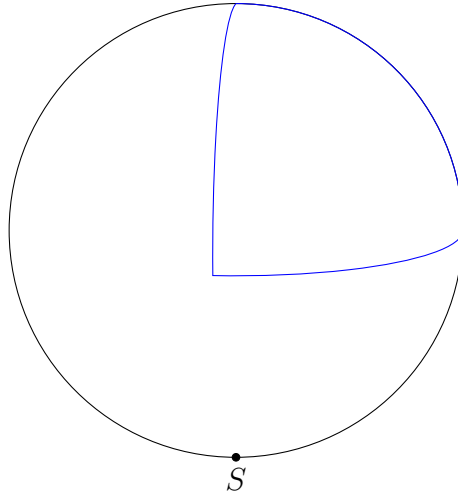


Figure 1.2: The spherical triangle $x, y, z > 0$

This problem is relatively easy to solve, however. Indeed, since $z > 0$, we obtain $z = \sqrt{1 - x^2 - y^2}$ so that we are essentially interested in the function

$$F(x, y) := f(x, y, \sqrt{1 - x^2 - y^2}) = xy\sqrt{1 - x^2 - y^2}.$$

More precisely, we want to find points of maximum of F on the set $\{(x, y) \mid x^2 + y^2 < 1, x > 0, y > 0\}$, which is an open subset of \mathbb{R}^2 .

We compute

$$\begin{aligned} \frac{\partial F}{\partial x} &= y\sqrt{1 - x^2 - y^2} - xy \frac{x}{\sqrt{1 - x^2 - y^2}} = 0, \\ \frac{\partial F}{\partial y} &= x\sqrt{1 - x^2 - y^2} - xy \frac{y}{\sqrt{1 - x^2 - y^2}} = 0. \end{aligned} \tag{1.2}$$

Since $x \neq 0$ and $y \neq 0$, we have

$$\begin{aligned} (1.2) \quad &\Longleftrightarrow \begin{aligned} 1 - x^2 - y^2 &= x^2 \\ 1 - x^2 - y^2 &= y^2 \end{aligned} \implies x^2 = y^2 \implies x = y \\ &\implies 3x^2 = 1 \implies x = y = \frac{1}{\sqrt{3}} \\ &\implies z = \frac{1}{\sqrt{3}}. \end{aligned}$$

Hence, if there is a parallelepiped maximizing the volume among all rectangular parallelepipeds with the given length of the diagonal, this must be the cube.

Exercise 1.3. Show that $\left(\frac{1}{\sqrt{3}}, \frac{1}{\sqrt{3}}, \frac{1}{\sqrt{3}}\right)$ is a point of maximum indeed.

Consider a more general problem of constrained maximum/minimum. Given $f, \varphi \in C^\infty(\mathbb{R}^n)$ find a point of maximum/minimum of f on the set

$$S := \{x \in \mathbb{R}^n \mid \varphi(x) = 0\}.$$

Proposition 1.4. Assume that for $p \in S$ we have

$$\frac{\partial \varphi}{\partial x_n}(p) \neq 0. \quad (1.5)$$

Then there is a neighbourhood W of p in \mathbb{R}^n , an open subset $V \subset \mathbb{R}^{n-1}$, and a smooth function $\psi: V \rightarrow \mathbb{R}$ such that for $x = (y, z) \in \mathbb{R}^{n-1} \times \mathbb{R}$ we have

$$x \in S \cap W \iff y \in V \text{ and } z = \psi(y).$$

This is a celebrated implicit function theorem, whose proof was given in the analysis course.

Theorem 1.6. Let $p \in S$ be a point of (local) maximum of f on S . If (1.5) holds, then there exists some $\lambda \in \mathbb{R}$ such that

$$\frac{\partial f}{\partial x_j}(p) = \lambda \frac{\partial \varphi}{\partial x_j}(p) \iff \nabla f(p) = \lambda \nabla \varphi(p) \quad (1.7)$$

holds for each $j = 1, \dots, n$.

Proof. Let $p = (y_0, z_0)$ be a local maximum for f on S . Hence, y_0 is a local maximum for the function

$$F: V \rightarrow \mathbb{R}, \quad F(y) := f(y, \psi(y))$$

This yields

$$\frac{\partial F}{\partial y_j}(y_0) = \frac{\partial f}{\partial y_j}(p) + \frac{\partial f}{\partial x_n}(p) \frac{\partial \psi}{\partial y_j}(y_0) = 0$$

for all $j \leq n-1$.

Furthermore, since $\varphi(y, \psi(y)) \equiv 0$, we have

$$\frac{\partial \varphi}{\partial y_j} + \frac{\partial \varphi}{\partial x_n} \frac{\partial \psi}{\partial y_j} \equiv 0.$$

This yields in turn

$$\frac{\partial \psi}{\partial y_j}(y_0) = -\frac{\partial \varphi}{\partial y_j}(p) / \frac{\partial \varphi}{\partial x_n}(p) \implies \frac{\partial f}{\partial y_j}(p) = \left(\frac{\partial f}{\partial x_n}(p) / \frac{\partial \varphi}{\partial x_n}(p) \right) \cdot \frac{\partial \varphi}{\partial y_j}(p).$$

Thus, (1.7) holds for all $j \leq n-1$ with $\lambda := \frac{\partial f}{\partial x_n}(p) / \frac{\partial \varphi}{\partial x_n}(p)$ independent of j .

For $j = n$ we have

$$\frac{\partial f}{\partial x_n}(p) = \left(\frac{\partial f}{\partial x_n}(p) / \frac{\partial \varphi}{\partial x_n}(p) \right) \cdot \frac{\partial \varphi}{\partial x_n}(p) = \lambda \frac{\partial \varphi}{\partial x_n}(p).$$

Thus, (1.7) holds also for $j = n$ with the same λ . □

Let us come back to the example about maximal value of parallelepipeds with a fixed length of the diagonal. Thus, if (x, y, z) is a point of maximum of f on (1.1), then there exists $\lambda \in \mathbb{R}$ such that

$$\begin{aligned} yz &= 2\lambda x \\ xz &= 2\lambda y \\ xy &= 2\lambda z \end{aligned} \implies (xyz)^2 = 8\lambda^3 xyz \implies xyz = 8\lambda^3.$$

This yields in turn

$$8\lambda^3 = xyz = x(yz) = 2\lambda x^2.$$

Notice that $\lambda \neq 0$, since otherwise $x = 0$ or $y = 0$ or $z = 0$. Hence, we obtain $x = 2\lambda$.

A similar argument yields also $y = 2\lambda$ and $z = 2\lambda$. Therefore we obtain

$$4\lambda^2 + 4\lambda^2 + 4\lambda^2 = 1 \quad \implies \quad \lambda = \frac{1}{2\sqrt{3}} \quad \implies \quad x = y = z = \frac{1}{\sqrt{3}},$$

which is in agreement with our previous computation.

Coming back to **Proposition 1.4**, it is clear that it is only important that one of the partial derivatives of φ does not vanish. This leads to the following definition.

Definition 1.8 (Surface). A non-empty set $S \subset \mathbb{R}^3$ is called a (smooth) *surface*, if for any $p \in S$ there exists an open set $V \subset \mathbb{R}^2$ and a smooth map $\psi : V \rightarrow \mathbb{R}^3$ such that the following holds:

- (i) $\psi(V) =: U$ is a neighbourhood of p in S ; in particular, $\psi(V) \subset S$.
- (ii) $\psi : V \rightarrow U$ is a homeomorphism.
- (iii) $D_q\psi : \mathbb{R}^2 \rightarrow \mathbb{R}^3$ is injective $\forall q \in V$.

Example 1.9. Assume $\varphi \in C^\infty(\mathbb{R}^3)$ satisfies

$$\frac{\partial \varphi}{\partial z}(p) \neq 0 \quad \text{for all } p \in S := \varphi^{-1}(0).$$

Let ψ be as in **Proposition 1.28**. Define $\Psi(x, y) := (x, y, \psi(x, y))$. If U and V are also as in **Proposition 1.28**, then $\Psi : V \rightarrow S \cap U$ is a homeomorphism, since $\pi : S \cap U \rightarrow V$, $\pi(x, y, z) = (x, y)$ is a continuous inverse. Furthermore,

$$D\Psi = \begin{pmatrix} 1 & 0 \\ 0 & 1 \\ \partial_x \psi & \partial_y \psi \end{pmatrix}$$

is clearly injective at all points. Hence, S is a surface.

Again, the same conclusion holds if we assume only that $\nabla \varphi(p) \neq 0$ for all $p \in \varphi^{-1}(0)$. In particular,

- the sphere $S^2 = \{x^2 + y^2 + z^2 = 1\}$
- the cylinder $C = \{(x, y, z) \mid x^2 + y^2 = 1\}$
- the hyperboloid $H = \{x^2 + y^2 - z^2 = 1\}$

are surfaces

Example 1.10 (Torus). Let C be the circle of radius r in the yz -plane centered at the point $(0, a, 0)$ as shown on Fig. 1.4, where $a > r$.

More formally,

$$T := \{(\sqrt{x^2 + y^2} - a)^2 + z^2 = r^2\}.$$

Exercise 1.11. Check that T is a surface indeed.

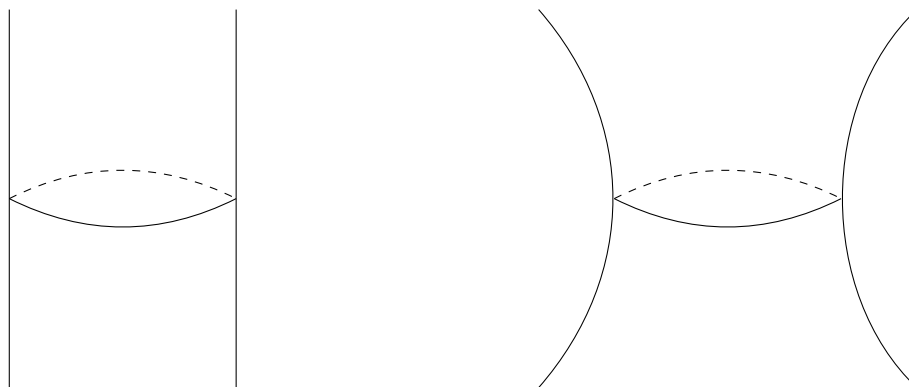


Figure 1.3: The cylinder and hyperboloid

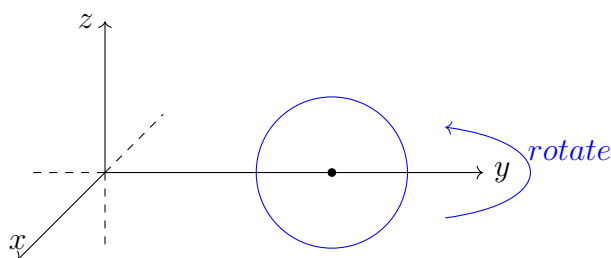


Figure 1.4: The torus as a circle rotated with respect to an axis

Example 1.12 (A non-example). The double cone $C_0 := \{x^2 + y^2 - z^2 = 0\}$ is not a surface. Indeed, assume C_0 is a surface. Then the tip of the cone p must have a neighbourhood U homeomorphic to an open disc in \mathbb{R}^2 .

Let $f: U \rightarrow D$ be a homeomorphism. Then $f: U \setminus \{p\} \rightarrow D \setminus \{f(p)\}$ is also a homeomorphism. However, this is impossible, since the punctured disc is connected but $U \setminus \{p\}$ is disconnected. Hence, p does not have a neighbourhood homeomorphic to a disc (or any open subset of \mathbb{R}^2).

Exercise 1.13. Show that a straight line is not a surface.

Remark 1.14.

- 1) The map ψ in the definition of the surface is called a *parametrization*.
- 2) Condition (iii) is equivalent to the following:

$$\partial_u \psi \quad \text{and} \quad \partial_v \psi \quad \text{are linearly independent}$$

at each point $(u, v) \in V$.

Proposition 1.15. Let S be a surface. For any $p \in S$ there exists a neighbourhood $W \subset \mathbb{R}^3$ and $\varphi \in C^\infty(W)$ such that

$$S \cap W = \{x \in W \mid \varphi(x) = 0\} \quad \text{and} \quad \nabla \varphi(x) \neq 0$$

for any $x \in S \cap W$.

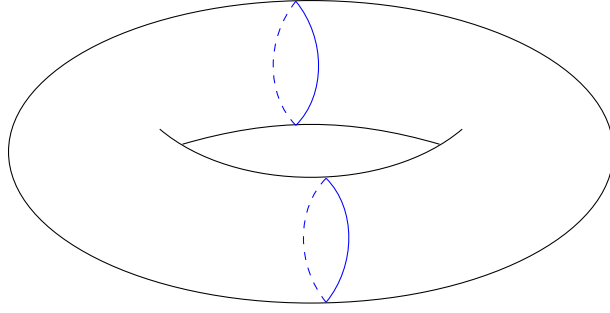


Figure 1.5: The torus

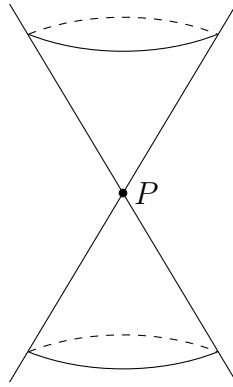


Figure 1.6: The double cone

Proof. Choose a parametrization $\psi: V \rightarrow U \subset S$. Let $(u_0, v_0) \in V$ be a unique point such that $\psi(u_0, v_0) = p$. Choose a vector $n \in \mathbb{R}^3$ such that

$$\partial_u \psi(u_0, v_0), \quad \partial_v \psi(u_0, v_0), \quad n \quad (1.16)$$

are linearly independent. Consider the map

$$\Psi: V \times \mathbb{R} \rightarrow \mathbb{R}^3, \quad \Psi(u, v, w) = \psi(u, v) + w \cdot n$$

The linear independence of (1.16) yields $\det D\Psi(u_0, v_0, 0) \neq 0$. By the inverse map theorem, there exists an open neighbourhood $W \subset \mathbb{R}^3$ of p and a smooth map $\Phi: W \rightarrow V \times \mathbb{R} \subset \mathbb{R}^3$ such that

$$\Psi \circ \Phi(x) = x \quad \forall x \in W.$$

If $\Phi = (\varphi_1, \varphi_2, \varphi_3)$, then

$$\Psi \circ \Phi(x) = \psi(\varphi_1(x), \varphi_2(x)) + \varphi_3(x) \cdot n = x.$$

Observe that

$$x \in S \cap W \iff \exists (u, v) \in V \text{ such that } \psi(u, v) = x$$

and consequently

$$\Psi(u, v, 0) = \psi(u, v) = x = \Psi(\varphi_1(x), \varphi_2(x), \varphi_3(x)).$$

Since Ψ is injective (on an open neighbourhood of $(u_0, v_0, 0)$), we have

$$x \in S \cap W \iff \varphi_3(x) = 0.$$

Furthermore, since $\det D\Phi(x) \neq 0$ for all $x \in W$, the vectors $\nabla\varphi_1(x), \nabla\varphi_2(x), \nabla\varphi_3(x)$ are linearly independent at each $x \in W$. In particular, $\nabla\varphi_3(x) \neq 0$ for all $x \in W$. \square

The following corollary follows immediately from **Proposition 1.15**.

Corollary 1.17. *Any surface is locally the graph of a smooth function.* \square

Example 1.18 (A non-example). The union of two intersecting planes in \mathbb{R}^3 is *not* a surface. Indeed, assume that

$$S := \{z = 0\} \cup \{x = 0\}$$

is a surface. Then there exists a smooth function φ defined in a neighbourhood W of the origin such that φ vanishes on S and $\nabla\varphi(0) \neq 0$ by **Proposition 1.15**. Notice that φ vanishes identically along S , hence φ vanishes identically along all three coordinate axes (at least in a neighbourhood of the origin). This yields in turn $\nabla\varphi(0) = 0$, which is a contradiction.

Exercise 1.19. Show that the cone $C := \{x^2 + y^2 - z^2 = 0, z \geq 0\}$ is not a smooth surface, cf. Example 1.12 above.

1.2 The change of coordinates maps

Neither parametrizations, nor local functions as in the **Proposition 1.15** are unique. Our next goal is to understand a relation between different parametrizations.

Thus, let

$$\psi_1: V_1 \longrightarrow U_1 \subset S \quad \text{and} \quad \psi_2: V_2 \longrightarrow U_2 \subset S$$

be two parametrizations such that $U_1 \cap U_2 \neq \emptyset$. Since both ψ_1 and ψ_2 are homeomorphisms, we have a well-defined continuous map

$$\psi_{21} := \psi_2^{-1} \circ \psi_1: V_{12} \longrightarrow V_{21}$$

which is called "a transition map" or "a change of coordinates map".

Notice that ψ_{21} is a map $\mathbb{R}^2 \longrightarrow \mathbb{R}^2$ defined on an open subset. Therefore, transition maps can be studied by the tools familiar from the analysis course.

Example 1.20. Consider the sphere S^2 , which can be covered by the images of two parametrizations as follows. The inverse of the stereographic projection from the north pole N is given by

$$(u, v) \longmapsto \psi_N(u, v) = \frac{1}{1 + u^2 + v^2} (2u, 2v, -1 + u^2 + v^2)$$

This is a homeomorphism viewed as a map $\mathbb{R}^2 \longrightarrow S^2 \setminus \{N\}$ and is clearly smooth.

Exercise 1.21. Show that $D\psi_N$ is injective at each point.

Thus, ψ_N is a parametrization (at each point $p \in S^2 \setminus \{N\}$). Of course, we have also the inverse ψ_S of the stereographic projection from the south pole S . The images of these two parametrizations cover together the whole sphere S^2 . A straightforward computation shows that the change of coordinates map $\psi_{SN} := \psi_S^{-1} \circ \psi_N: \mathbb{R}^2 \setminus \{0\} \longrightarrow \mathbb{R}^2 \setminus \{0\}$ is given by

$$\psi_{SN}(u, v) = \frac{1}{u^2 + v^2} (u, v)$$

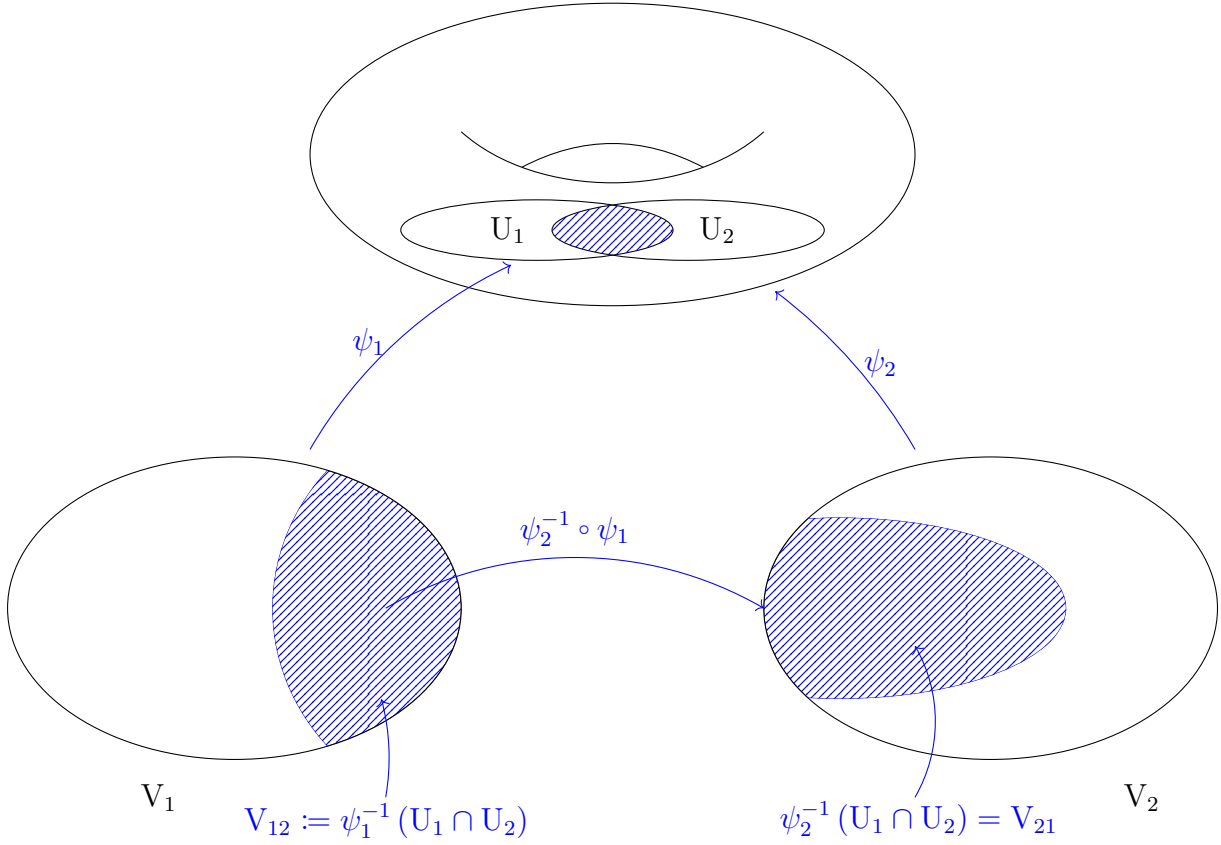


Figure 1.7: The transition map

Exercise 1.22. Show that the sphere can not be covered by the image of a single parametrization.

Theorem 1.23. Let S be a surface. For any two parametrizations ψ_1 and ψ_2 as above, the change of coordinates map ψ_{12} is smooth.

Proof. Since smoothness is a local property, it suffices to show that for all $(u_0, v_0) \in V_{12}$ there exists a neighbourhood $V_0 \subset V_{12}$ such that $\psi_{21}|_{V_0}$ is smooth.

Thus, set $p_0 := \psi_1(u_0, v_0)$. For this p_0 and ψ_2 construct a smooth map $\Phi_2: W \rightarrow V_2 \times \mathbb{R}$ as in the proof of the [Proposition 1.15](#). Recall that

$$\Phi_2|_{S \cap W}: S \cap W \rightarrow V_2 \times \{0\} = V_2$$

equals ψ_2^{-1} .

The map $\Phi_2 \circ \psi_1: \psi_1^{-1}(S \cap W) \rightarrow V_2$ is clearly smooth as a composition of smooth maps. Set $V_0 := V_{12} \cap \psi_1^{-1}(S \cap W)$. Since the image of ψ_1 lies in S , we obtain that

$$\Phi_2 \circ \psi_1|_{V_0} = \psi_2^{-1} \circ \psi_1|_{V_0} = \psi_{21}|_{V_0}$$

is smooth. □

1.3 Smooth functions on surfaces

Definition 1.24. Let S be a surface. A function $f: S \rightarrow \mathbb{R}$ is said to be smooth, if for any parametrization $\psi: V \rightarrow U$ the composition

$$F := f \circ \psi: V \rightarrow \mathbb{R}$$

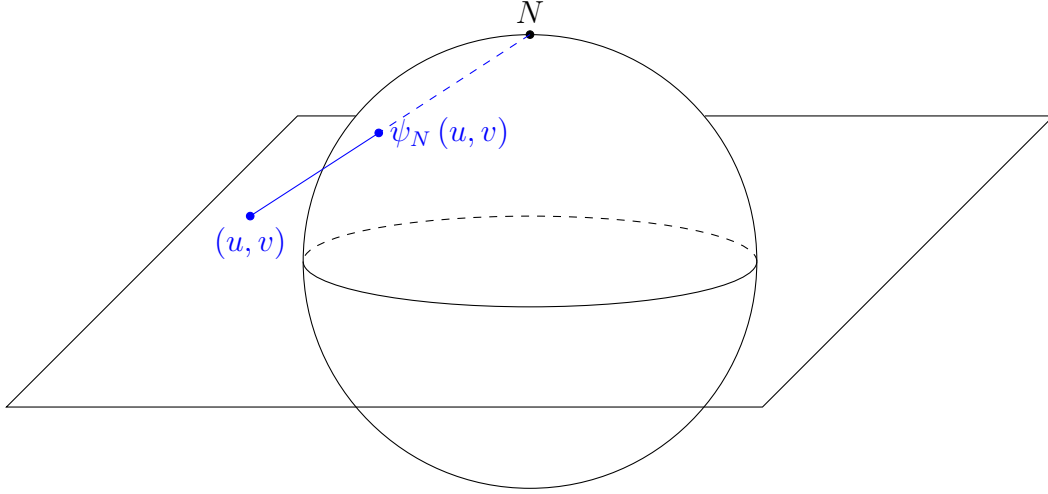


Figure 1.8: The inverse of the stereographic projection

is smooth. The function $F := f \circ \psi$ is called a local (coordinate) representation of f .

Remark 1.25. **Theorem 1.23** implies that if $f \circ \psi_1$ is smooth, then $f \circ \psi_2$ is also smooth on $V_{21} = \psi_2^{-1}(U_1 \cap U_2)$. Indeed,

$$f \circ \psi_2 = f \circ \psi_1 \circ (\psi_1^{-1} \circ \psi_2) = (f \circ \psi_1) \circ \psi_{12}$$

$f \circ \psi_1$ and ψ_{12} are smooth. Hence, if (V_i, ψ_i) is a collection of parametrizations such that $\psi_i(V_i)$ covers all of S , it suffices to check that $f \circ \psi_i$ is smooth for all i .

Example 1.26. Let $h: \mathbb{R}^3 \rightarrow \mathbb{R}$ be an arbitrary smooth function. Define $f: S \rightarrow \mathbb{R}$ as the restriction of h . Then f is smooth, since for any parametrization ψ we have $f \circ \psi = h \circ \psi$ and the right hand side is clearly smooth.

For example, for any fixed $a \in \mathbb{R}^3$ the height function

$$f_a(x) = \langle a, x \rangle \quad x \in S$$

is a smooth function on S . In particular, set $S = S^2$ and $h(x, y, z) = z$. Then the coordinate representation of $f = h|_{S^2}$ with respect to ψ_N is

$$F(u, v) = f \circ \psi_N(u, v) = \frac{-1 + u^2 + v^2}{1 + u^2 + v^2}.$$

This can be seen as a sanity check: This function is smooth indeed.

Example 1.27. Let $\psi: V \rightarrow U$ be a parametrization of a surface S . Since ψ is a homeomorphism, we have the inverse map

$$\varphi := \psi^{-1}: U \rightarrow V.$$

Since U itself is a surface (with a single parametrization ψ), it makes sense to ask if φ viewed as a map $U \rightarrow \mathbb{R}^2$ is smooth, which means by definition that both components of φ are smooth functions. This is the case indeed, since the local representation of φ is nothing else but $\varphi \circ \psi = \text{id}$, which is surely smooth. Any such pair (U, φ) is called a *chart* on S .

Proposition 1.28. *Let S be a surface. Then the set $C^\infty(S)$ of all smooth functions on S is a vector space, that is*

$$\begin{array}{ccc} f, g \in C^\infty(S) & \implies & \lambda f + \mu g \in C^\infty(S) \\ \lambda, \mu \in \mathbb{R} & & \end{array}$$

In fact, we also have

$$f, g \in C^\infty(S) \implies f \cdot g \in C^\infty(S),$$

where $f \cdot g$ is the product-function $p \mapsto f(p) \cdot g(p)$.

Proof. We prove the last statement only, while the first one is left as an exercise to the reader. If $\psi: U \rightarrow V$ is a parametrization, then $(f \cdot g) \circ \psi = (f \circ \psi) \cdot (g \circ \psi)$. Since $(f \circ \psi) \in C^\infty(V)$ and $(g \circ \psi) \in C^\infty(V)$, the function $(f \cdot g) \circ \psi$ is smooth as the product of smooth functions of two variables. \square

Let $W \subset \mathbb{R}^n$ be an open set.

Definition 1.29. A continuous map $f: W \rightarrow S$, where S is a surface, is called *smooth*, if for any parametrization $\psi: V \rightarrow U \subset S$ the map

$$\varphi \circ f = \psi^{-1} \circ f: f^{-1}(U) \rightarrow V \subset \mathbb{R}^2$$

is smooth.

In the above definition we require that f is continuous to ensure that $f^{-1}(U)$ is an open subset so that it makes sense to talk about smoothness of the coordinate representation $\varphi \circ f$.

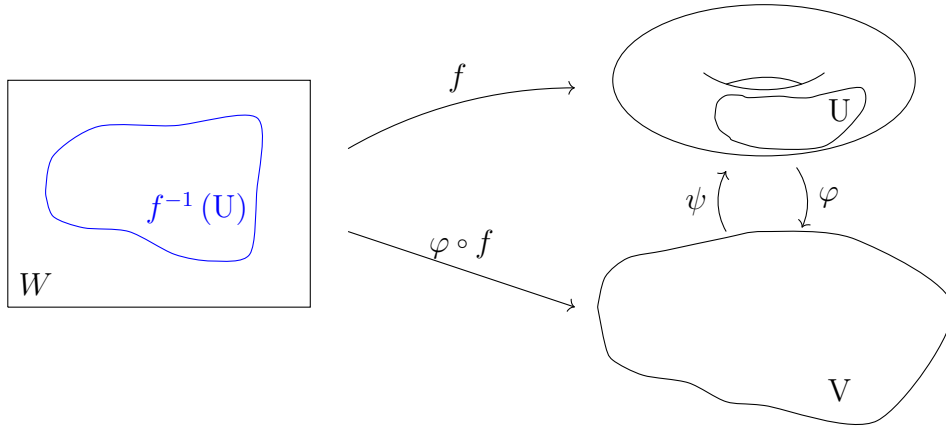


Figure 1.9: A map into a surface and its coordinate representation

Proposition 1.30. *$f: W \rightarrow S$ is smooth if and only if f is smooth as a map $W \rightarrow \mathbb{R}^3$. More formally, this means the following: If $\iota: S \rightarrow \mathbb{R}^3$ denotes the natural inclusion map, then*

$$f \in C^\infty(W; S) \iff \iota \circ f \in C^\infty(W; \mathbb{R}^3)$$

Proof. Pick a parametrization ψ of S and construct a smooth map $\Phi: X \rightarrow \mathbb{R}^3$ just as in the proof of **Proposition 1.15**, where $X \subset \mathbb{R}^3$ is an open set. Assume $f: W \rightarrow \mathbb{R}^3$ is smooth. Then $\Phi \circ f$ is also smooth as the composition of smooth maps. However, since f takes values in S and $\Phi|_S = \varphi = \psi^{-1}$, we obtain that $\varphi \circ f = \Phi \circ f: \mathbb{R}^2 \rightarrow \mathbb{R}^2$ is smooth.

Conversely, assume that $f: W \rightarrow S$ is smooth. Then

$$f|_{f^{-1}(U)} = (\psi \circ \varphi) \circ f|_{f^{-1}(U)} = \psi \circ (\varphi \circ f)|_{f^{-1}(U)}$$

is again smooth as the composition of smooth maps. \square

The following class of maps will be particularly important in the sequel.

Definition 1.31. Let $I \subset \mathbb{R}$ be an (open) interval. A smooth map $\gamma: I \rightarrow S$ is called a smooth curve on S .

If $0 \in I$, we say that γ is a smooth curve through $p := \gamma(0) \in S$.

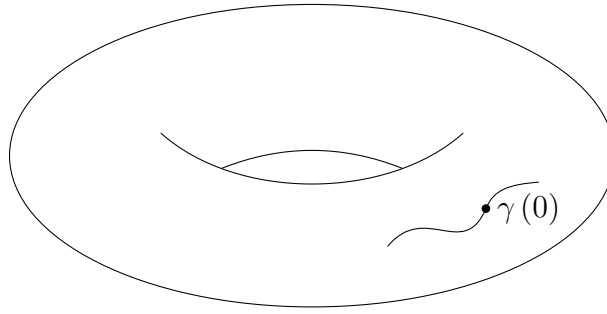


Figure 1.10: A smooth curve on a surface

Example 1.32. Let $p \in S^2$ and $v \in \mathbb{R}^3$ such that $\langle p, v \rangle = 0$ and $\|v\| = 1$. Define $\gamma_v: \mathbb{R} \rightarrow \mathbb{R}^3$ by $\gamma_v(t) = (\cos t) \cdot p + (\sin t) \cdot v$. Since

$$\begin{aligned} \|\gamma_v(t)\|^2 &= \langle \cos t \cdot p + \sin t \cdot v, \cos t \cdot p + \sin t \cdot v \rangle \\ &= \cos^2 t \cdot \|p\|^2 + 0 + \sin^2 t \cdot \|v\|^2 \\ &= \cos^2 t + \sin^2 t = 1, \end{aligned}$$

we obtain that $\gamma_v: \mathbb{R} \rightarrow S^2$ is a smooth curve through p . Of course, the image of γ_v is a great circle on S^2 .

Even more generally, we can define smooth maps between surfaces as follows.

Definition 1.33. Let S_1 and S_2 be two surfaces. A continuous map $f: S_1 \rightarrow S_2$ is said to be smooth, if for any parametrizations $\psi: V \rightarrow U \subset S_1$ and $\chi: W \rightarrow X \subset S_2$ the map

$$\chi^{-1} \circ f \circ \psi: \psi^{-1}(f^{-1}(X)) \rightarrow W \quad (1.34)$$

is smooth. Just like in the case of functions, (1.34) is called the coordinate (or local) representation of f .

Remark 1.35. Since parametrizations and charts contain the same amount of information, we can also define smoothness of a map $f: S_1 \rightarrow S_2$ in terms of charts as follows: f is smooth if and only if for any chart (U, φ) on S_1 and any chart (X, ξ) on S_2 the map

$$\xi \circ f \circ \varphi^{-1}: \mathbb{R}^2 \rightarrow \mathbb{R}^2$$

is smooth (on an open subset where defined). The map $\xi \circ f \circ \varphi^{-1}$ is also called a coordinate representation of f (with respect to charts (U, φ) and (X, ξ)).

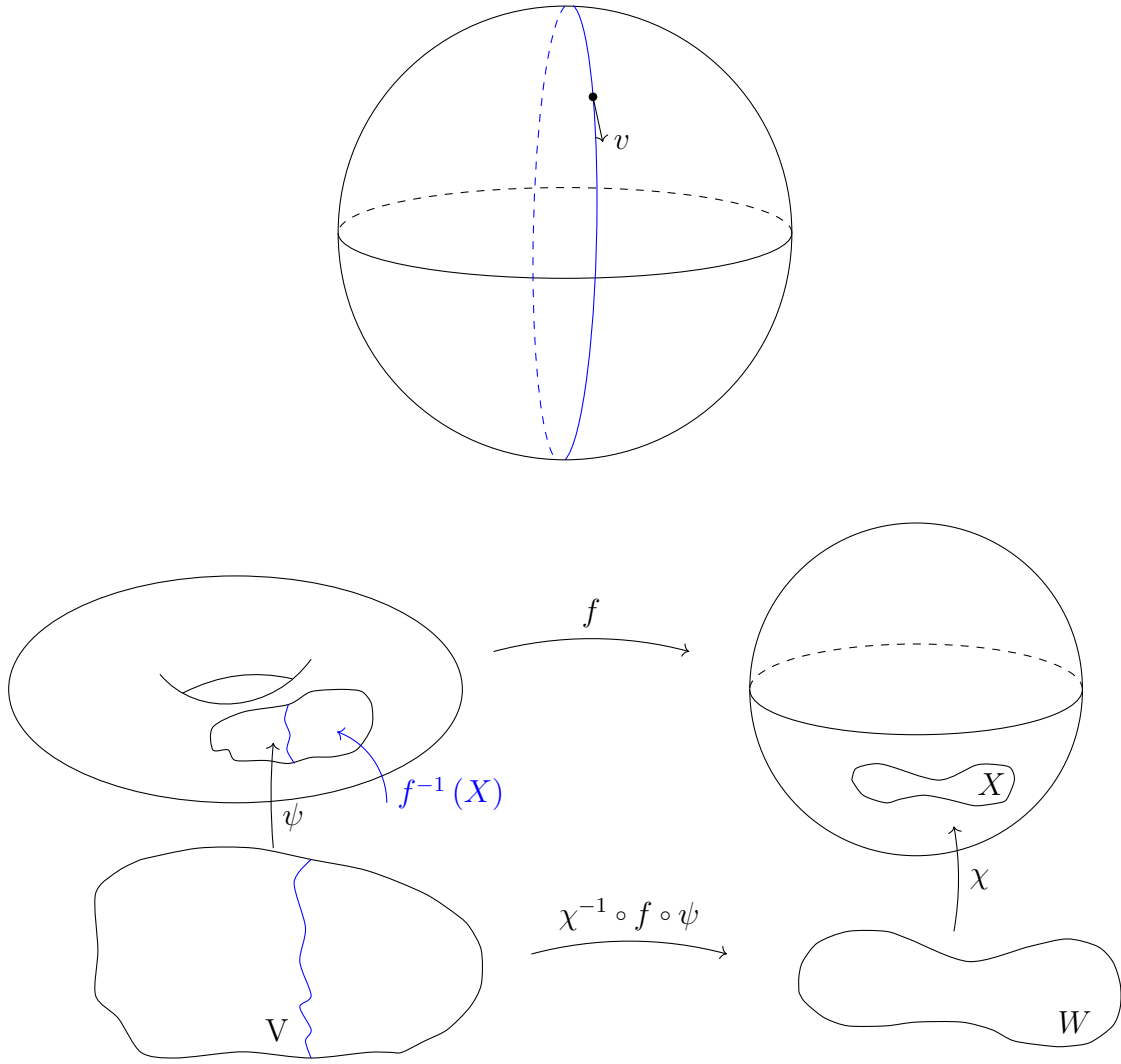


Figure 1.11: A smooth map between surfaces and its coordinate representation

Remark 1.36. Just like in the case of functions, it suffices to find two collections $\{\psi_i: V_i \rightarrow U_i\}$ and $\{\chi_j: W_j \rightarrow X_j\}$ of parametrizations such that

$$\bigcup_i U_i = S_1 \quad \text{and} \quad \bigcup_j X_j = S_2$$

and check that all coordinate representations $\chi_j^{-1} \circ f \circ \psi_i$ are smooth.

Consider the antipodal map

$$a: S^2 \rightarrow S^2, \quad a(x) = -x.$$

For any $(u, v) \in \mathbb{R}^2$ we have

$$a \circ \psi_N(u, v) = -\frac{1}{1 + u^2 + v^2} (2u, 2v, -1 + u^2 + v^2)$$

Since $\psi_S^{-1}: S^2 \setminus \{S\} \rightarrow \mathbb{R}^2$ is given by

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

we obtain

$$\begin{aligned}\psi_S^{-1} \circ a \circ \psi_N(u, v) &= \frac{1}{1 + \frac{1-u^2-v^2}{1+u^2+v^2}} \left(-\frac{2u}{1+u^2+v^2}, -\frac{2v}{1+u^2+v^2} \right) \\ &= -\frac{1+u^2+v^2}{2} \left(\frac{2u}{1+u^2+v^2}, \frac{-2v}{1+u^2+v^2} \right) \\ &= -(u, v)\end{aligned}$$

It follows in a similar manner, that $\psi_S^{-1} \circ a \circ \psi_S$, $\psi_N^{-1} \circ a \circ \psi_N$, and $\psi_N^{-1} \circ a \circ \psi_S$ are also smooth. Hence, a is smooth.

Proposition 1.37. *Let $h: \mathbb{R}^3 \rightarrow \mathbb{R}^3$ be a smooth map such that $h(S_1) \subset S_2$, where S_1 and S_2 are surfaces. Then $h|_{S_1}: S_1 \rightarrow S_2$ is also smooth.*

The proof of this proposition is similar to the proof of [Proposition 1.30](#) and is left as an exercise to the reader.

To construct a more interesting example, pick a polynomial

$$p(z) := z^n + a_{n-1}z^{n-1} + \dots + a_1z + a_0$$

with complex coefficients. Identifying \mathbb{R}^2 with \mathbb{C} , we can view p as a smooth map $\mathbb{R}^2 \rightarrow \mathbb{R}^2$. Define $f: S^2 \rightarrow S^2$ by

$$f(p) = \begin{cases} \psi_N \circ p \circ \psi_N^{-1}(p) & \text{if } p \neq N, \\ N & \text{if } p = N. \end{cases} \quad (1.38)$$

I claim that f is smooth. Indeed, since by the construction of f , the coordinate representation of f with respect to the pair (\mathbb{R}^2, ψ_N) and (\mathbb{R}^2, ψ_N) of parametrizations (the first one on the source of f , the second one on the target), is

$$\psi_N^{-1} \circ f \circ \psi_N = \underbrace{\psi_N^{-1} \circ \psi_N}_{\text{id}} \circ p \circ \underbrace{\psi_N^{-1} \circ \psi_N}_{\text{id}} = p.$$

Hence f is smooth at each point $p \in S^2 \setminus \{N\}$. To check that f is also smooth at N too, consider

$$\psi_S \circ f \circ \psi_S^{-1}(z) = \begin{cases} \psi_S \circ \psi_N^{-1} \circ p \circ \psi_N \circ \psi_S^{-1} & \text{if } z \neq 0, \\ 0 & \text{if } z = 0. \end{cases}$$

We know that

$$\begin{aligned}\psi_{SN}(z) &= \psi_S \circ \psi_N^{-1}(z) = \frac{1}{|z|^2}z = \frac{1}{z \cdot \bar{z}} \cdot z = \frac{1}{\bar{z}} \\ \implies \psi_{NS}(z) &= \psi_{SN}^{-1}(z) = \frac{1}{\bar{z}}.\end{aligned}$$

Hence, we compute

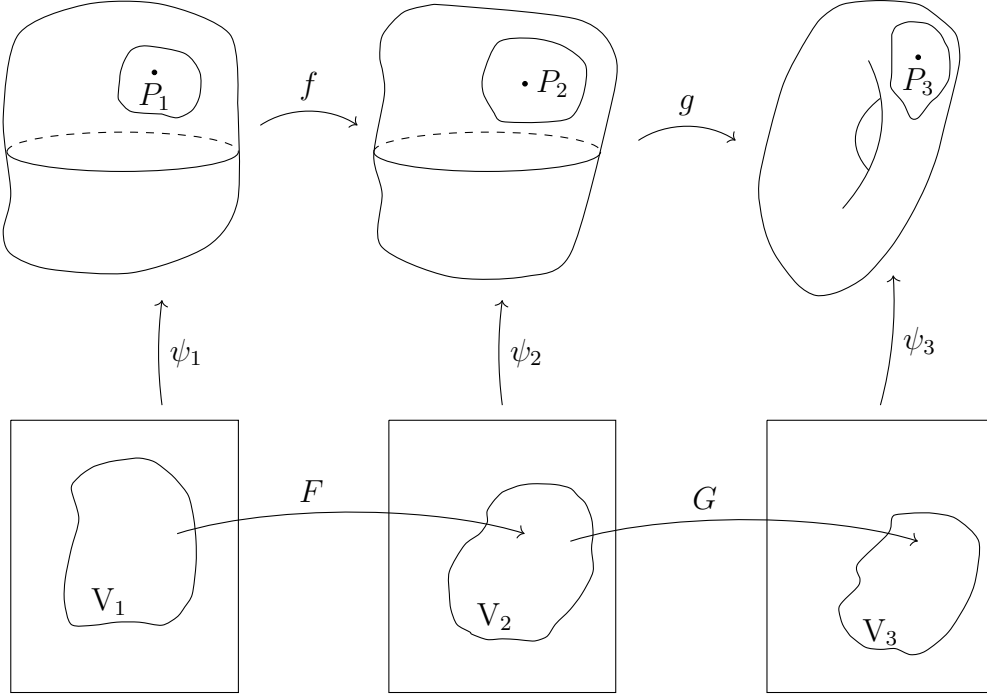
$$\begin{aligned}\psi_{SN} \circ p \circ \psi_{NS}(z) &= \psi_{SN} \left(\frac{1}{\bar{z}^n} + \frac{a_{n-1}}{\bar{z}^{n-1}} + \dots + a_0 \right) \\ &= \psi_{SN} \left(\frac{1 + a_{n-1}\bar{z} + \dots + a_0\bar{z}^n}{\bar{z}^n} \right) \\ &= \frac{z^n}{1 + \bar{a}_{n-1}z + \dots + \bar{a}_0z^n}, \quad \text{if } z \neq 0.\end{aligned}$$

This yields that $\psi_S \circ f \circ \psi_S^{-1}$ is smooth even at $z = 0$, that is f is smooth everywhere on S (or, simply, f is smooth).

Theorem 1.39. Suppose $f: S_1 \rightarrow S_2$ and $g: S_2 \rightarrow S_3$ are smooth maps between surfaces. Then $g \circ f: S_1 \rightarrow S_3$ is also smooth.

Proof. Pick a point $p_1 \in S_1$ and denote $p_2 := f(p_1) \in S_2$, $p_3 := g(p_2) = g(f(p_1)) \in S_3$. Pick parametrizations

$$\psi_j: V_j \rightarrow U_j \subset S_j.$$



In a sufficiently small neighbourhood of p_1 we have

$$\psi_3^{-1} \circ (g \circ f) \circ \psi_1 = \underbrace{\psi_3^{-1} \circ g \circ \psi_2}_{G \in C^\infty} \circ \underbrace{\psi_2^{-1} \circ f \circ \psi_1}_{F \in C^\infty}.$$

Hence, $g \circ f$ is smooth in a neighbourhood of p_1 . Since p_1 was arbitrary, $g \circ f$ is smooth everywhere. \square

Remark 1.40. The proof shows that the coordinate representation of the composition is the composition of coordinate representations.

Notice that **Theorem 1.39** yields in particular the following: If $\gamma: I \rightarrow S_1$ is a smooth curve and $f: S_1 \rightarrow S_2$ is a smooth map, then $f \circ \gamma: I \rightarrow S_2$ is also a smooth curve.

Definition 1.41. A smooth map $f: S_1 \rightarrow S_2$ is called a diffeomorphism, if there exists a smooth map $g: S_2 \rightarrow S_1$ such that

$$g \circ f = \text{id}_{S_1} \quad \text{and} \quad f \circ g = \text{id}_{S_2}$$

Example 1.42. The antipodal map $a: S^2 \rightarrow S^2$ is a diffeomorphism.

Example 1.43. The hyperboloid $H = \{x^2 + y^2 - z^2 = 1\}$ and cylinder $C = \{x^2 + y^2 = 1\}$ are diffeomorphic, that is there exists a diffeomorphism $f: H \rightarrow C$. Explicitly, define

$$h: \mathbb{R}^3 \rightarrow \mathbb{R}^3 \quad \text{by} \quad h(x, y, z) = \left(\frac{x}{\sqrt{1+z^2}}, \frac{y}{\sqrt{1+z^2}}, z \right)$$

Clearly, $h \in C^\infty(\mathbb{R}^3; \mathbb{R}^3)$. If $(x, y, z) \in H$, then $\left(\frac{x}{\sqrt{1+z^2}}\right)^2 + \left(\frac{y}{\sqrt{1+z^2}}\right)^2 = \frac{x^2+y^2}{1+z^2} = 1$, that is $f := h|_H: H \rightarrow C$ is smooth.

Exercise 1.44. Show that the restriction of $h^{-1}: \mathbb{R}^3 \rightarrow \mathbb{R}^3$ given explicitly by

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

yields a smooth inverse of f .

Remark 1.45. A map $f: S_1 \rightarrow S_2$ may fail to be a diffeomorphism in the following two ways: either f^{-1} does not exist or f^{-1} exists but is not smooth.

Example 1.46 (A non-example). Consider a map

$$f: C \longrightarrow C, \quad f(x, y, z) = (x, y, z^3),$$

which is smooth. The inverse $f^{-1}: C \rightarrow C$ exists:

$$f^{-1}(x, y, z) = (x, y, \sqrt[3]{z}).$$

It is continuous, but fails to be smooth.

Exercise 1.47. Compute a coordinate representation of f^{-1} and check that this fails to be smooth indeed.

Example 1.48. Let S be a smooth surface and let $\psi: V \rightarrow U$ be any parametrization. Consider U as a surface covered by the image of a single parametrization ψ . Then $\varphi = \psi^{-1}$ exists and is smooth as we have seen in Example 1.27. That is U is diffeomorphic to V , which is an open subset of \mathbb{R}^2 . Summing up, we see that any surface is locally diffeomorphic to an open subset of \mathbb{R}^2 .

Exercise 1.49.

- (i) Show that the disc $D := \{(x, y) \in \mathbb{R}^2 \mid x^2 + y^2 < 1\}$ is diffeomorphic to \mathbb{R}^2 , that is there exists a smooth bijective map $f: D \rightarrow \mathbb{R}^2$ such that $f^{-1}: \mathbb{R}^2 \rightarrow D$ is also smooth.
- (ii) Show that any smooth surface is locally diffeomorphic to \mathbb{R}^2 , that is any point $p \in S$ has a neighbourhood U diffeomorphic to \mathbb{R}^2 .

1.4 The tangent plane

Let S be a surface.

Definition 1.50. A vector $v \in \mathbb{R}^3$ is said to be tangent to S at p , if there exists a smooth curve $\gamma: (-\varepsilon, \varepsilon) \rightarrow S$ such that

$$\gamma(0) = p \quad \text{and} \quad \dot{\gamma}(0) = v.$$

Notice that when computing the tangent vector of γ we think of γ as a curve in \mathbb{R}^3 .

The set $T_p S$ of all vectors tangent to S at the point p is called *the tangent space* of S at p .

Example 1.51. For $S = S^2$ and an arbitrary point p we have the curve

$$\gamma: \mathbb{R} \rightarrow S^2, \quad \gamma_v(t) = \cos t \cdot p + \sin t \cdot v,$$

where $\|v\| = 1$ and $v \perp p$ just as in in Example 1.32. Then $\dot{\gamma}_v(0) = v$. Hence, v is tangent to S^2 at p .

In fact, any vector v which is orthogonal to p is tangent to S^2 at p . Indeed, set $\lambda := \|v\|$ and $v_1 := \lambda^{-1}v$, and

$$\gamma: \mathbb{R} \rightarrow S^2, \quad \gamma(t) = \gamma_{v_1}(\lambda t).$$

Then $\gamma(0) = p$ and $\dot{\gamma}(0) = \lambda \dot{\gamma}_{v_1}(0) = v$.

Proposition 1.52. Let $\psi: V \rightarrow U$ be a parametrization such that $\psi(u_0, v_0) = p$. Then

$$T_p S = \text{Im } D_{(u_0, v_0)} \psi.$$

In particular, $T_p S$ is a vector space of dimension 2.

Proof. The proof consists of the following steps.

Step 1. We have $\text{Im } D_{(u_0, v_0)} \psi \subset T_p S$.

Assume $v \in \text{Im } D_{(u_0, v_0)} \psi$. Then there exists a vector $w \in \mathbb{R}^2$ such that $D_{(u_0, v_0)} \psi(w) = v$. Consider the smooth curve $\beta: (-\varepsilon, \varepsilon) \rightarrow V$

$$\beta(t) = (u_0, v_0) + t \cdot w.$$

Then $\gamma(t) := \psi \circ \beta(t)$ is a smooth curve in S such that

$$\gamma(0) = \psi(\beta(0)) = \psi(u_0, v_0) = p \quad \text{and} \quad \dot{\gamma}(0) = D_{(u_0, v_0)} \psi(w) = v.$$

Hence, $v \in T_p S$.

Step 2. $T_p S \subset \text{Im } D_{(u_0, v_0)} \psi$

If $v \in T_p S$, then there exists $\gamma: (-\varepsilon, \varepsilon) \rightarrow S$ such that $\gamma(0) = p$ and $\dot{\gamma}(0) = v$. Can assume $\text{Im } \gamma \subset U$ by choosing ε smaller if necessary. If $\varphi = \psi^{-1}$, then $\beta(t) := \varphi \circ \gamma(t)$ is a smooth curve in $V \subset \mathbb{R}^2$ such that $\beta(0) = (u_0, v_0)$. Denote $w := \dot{\beta}(0) \in \mathbb{R}^2$. Then we have

$$\begin{aligned} v = \dot{\gamma}(0) &= \left. \frac{d}{dt} \right|_{t=0} (\psi \circ \beta)(t) = (D_{(u_0, v_0)} \psi) (\dot{\beta}(0)) \\ &= D_{(u_0, v_0)} \psi(w) \in \text{Im } D_{(u_0, v_0)} \psi. \end{aligned}$$

Step 3. $\dim T_p S = 2$.

This follows immediately from the injectivity of $D_{(u_0, v_0)} \psi$. □

Proposition 1.53. Pick $p \in S$ and recall that there exists a neighbourhood $W \subset \mathbb{R}^3$ of p and a smooth function $\varphi: W \rightarrow \mathbb{R}$ such that

$$S \cap W = \{q \in W \mid \varphi(q) = 0\} \quad \text{and} \quad \nabla \varphi(q) \neq 0 \quad \forall q \in W.$$

Then $T_p S = \nabla \varphi(p)^\perp$.

Proof. If γ is any curve in S through p , then

$$\varphi \circ \gamma(t) = 0 \quad \forall t \quad \implies \quad \left. \frac{d}{dt} \right|_{t=0} \varphi(\gamma(t)) = 0.$$

Therefore, we obtain

$$0 = \left. \frac{d}{dt} \right|_{t=0} \varphi(\gamma(t)) = \langle \nabla \varphi(p), \dot{\gamma}(0) \rangle \quad \implies \quad T_p S \subset \nabla \varphi(p)^\perp.$$

Since both $T_p S$ and $\nabla \varphi(p)^\perp$ are two-dimensional, these spaces must be equal in fact. \square

Example 1.54. Set $\varphi(x, y, z) = (x^2 + y^2 + z^2 - 1)/2$. Then $\varphi^{-1}(0) = S^2$ and

$$\nabla \varphi(p) = p \neq 0 \text{ if } p \in S^2 \quad \implies \quad T_p S^2 = p^\perp.$$

This is consistent with Example 1.51.

Example 1.55. Set $\varphi(x, y, z) = (x^2 + y^2 - z^2 - 1)/2$. If $p = (x, y, z) \in H =: \varphi^{-1}(0)$, then $\nabla \varphi(p) = (x, y, -z) \neq 0$ and therefore

$$T_p H = (x, y, -z)^\perp = \{v = (v_1, v_2, v_3) \in \mathbb{R}^3 \mid xv_1 + yv_2 - zv_3 = 0\}.$$

Example 1.56. Set $\varphi(x, y, z) := (x^2 + y^2 - 1)/2$, $C = \varphi^{-1}(0) \ni p = (x, y, z)$. Then

$$T_p C = \{v = (v_1, v_2, v_3) \mid xv_1 + yv_2 = 0, v_3 \text{ is arbitrary}\}.$$

1.5 The differential of a smooth map

Just as in calculus of several variables, we wish to study smooth functions, or, more generally, smooth maps, by approximating those by linear ones. This leads to the concept of the differential, which we define first for the case of functions. The more general case of smooth maps is considered below.

Definition 1.57 (Differential of a smooth function). Let S be a surface and $f \in C^\infty(S)$. Define a map $d_p f: T_p S \rightarrow \mathbb{R}$ as follows: for $v \in T_p S$ choose a smooth curve γ through p with $\dot{\gamma}(0) = v$ and set

$$d_p f(v) = \left. \frac{d}{dt} \right|_{t=0} f \circ \gamma(t). \quad (1.58)$$

Proposition 1.59. $d_p f$ is a well-defined linear map.

Proof. Pick a parametrization $\psi: V \rightarrow U \ni p$. Without loss of generality we can assume that $\psi^{-1}(p) = 0 \in V$.

If γ_1 and γ_2 are two curves through p such that $\dot{\gamma}_1(0) = v = \dot{\gamma}_2(0)$, then for $\beta_j := \psi^{-1} \circ \gamma_j$ we have

$$\gamma_j(t) = \psi \circ \beta_j(t) \quad \implies \quad v = D_0 \psi(\dot{\beta}_1(0)) = D_0 \psi(\dot{\beta}_2(0)).$$

Since $D_0 \psi$ is injective, we obtain $\dot{\beta}_1(0) = \dot{\beta}_2(0) =: w$. Furthermore,

$$\left. \frac{d}{dt} \right|_{t=0} f \circ \gamma_1(t) = \left. \frac{d}{dt} \right|_{t=0} (f \circ \psi \circ \psi^{-1} \circ \gamma_1(t)) = \left. \frac{d}{dt} \right|_{t=0} (f \circ \beta_1(t)) = D_0 f(w).$$

Likewise, we obtain

$$\left. \frac{d}{dt} \right|_{t=0} f \circ \gamma_2(t) = D_0 F(w) \quad \implies \quad \left. \frac{d}{dt} \right|_{t=0} (f \circ \gamma_1(t)) = \left. \frac{d}{dt} \right|_{t=0} (f \circ \gamma_2(t)).$$

Hence, $d_p f$ is well-defined and, moreover, we have the equality

$$d_p f \circ D_0 \psi = D_0 F,$$

where $F := f \circ \psi$ is the coordinate representation of f . Since both $D_0 \psi$ and $D_0 F$ are linear, so is $d_p f$. \square

Exercise 1.60. Think of \mathbb{R}^2 as a surface in \mathbb{R}^3 (for example, as $\mathbb{R}^2 \times \{0\} \subset \mathbb{R}^3$). Let $f: \mathbb{R}^2 \rightarrow \mathbb{R}^2$ be any smooth map. Show that the differential of f in the sense of Definition 1.57 coincides with the one known from the analysis course.

Exercise 1.61. If $h \in C^\infty(\mathbb{R}^3)$ and $f = h|_S$, then for all $p \in S$ we have

$$d_p f = D_p h|_{T_p S}.$$

Definition 1.62. A point $p \in S$ is called critical for $f \in C^\infty(S)$, if $d_p f = 0$, that is $d_p f(v) = 0$ for all $v \in T_p S$.

Proposition 1.63. If p is a point of local maximum (minimum) for f , then p is critical for f .

Proof. If p is a point of local maximum for f , then for any curve γ through p , 0 is a point of local maximum for $f \circ \gamma$. Hence, $\left. \frac{d}{dt} \right|_{t=0} f \circ \gamma(t) = 0$. \square

Proposition 1.64. Let $h, \varphi \in C^\infty(\mathbb{R}^3)$. Assume $\nabla \varphi(p) \neq 0$ for any $p \in S = \varphi^{-1}(0)$. If $p \in S$ is a point of local maximum for $f = h|_S$, then

$$\nabla h(p) = \lambda \nabla \varphi(p) \tag{1.65}$$

for some $\lambda \in \mathbb{R}$.

Proof. Our hypothesis implies that S is a surface and $T_p S = (\nabla \varphi(p))^\perp$, see Example 1.9 and Proposition 1.53. Hence,

$$d_p f = 0 \quad \iff \quad D_p h|_{T_p S} = 0 \quad \iff \quad \langle v, \nabla h(p) \rangle = 0 \quad \forall v \in T_p S.$$

In other words, $\nabla h(p)$ is orthogonal to $T_p S$. However, $T_p S^\perp$ is one-dimensional and contains $\nabla \varphi(p) \neq 0$. This implies (1.65). \square

Remark 1.66. This proof is in a sense more conceptual than the proof of Theorem 1.6.

More generally, for any $f \in C^\infty(S; \mathbb{R}^n)$ the differential $d_p f: T_p S \rightarrow \mathbb{R}^n$ is defined by (1.58) too. This yields immediately the following: If f is written in components as $f = (f_1, \dots, f_n)$, then $d_p f$ can be written in components as

$$d_p f = (d_p f_1, \dots, d_p f_n).$$

Also, the differential is well-defined for maps $f: \mathbb{R}^n \rightarrow S$ and is a linear map of the form $d_p f: \mathbb{R}^n \rightarrow T_{f(p)} S$. For maps $f: S_1 \rightarrow S_2$ between surfaces we define

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

essentially by the same rule: If $\dot{\gamma}(0) = v \in T_p S_1$, then $d_p f(v) := \left. \frac{d}{dt} \right|_{t=0} (f \circ \gamma(t))$. This yields again a well-defined linear map as the reader can easily check.

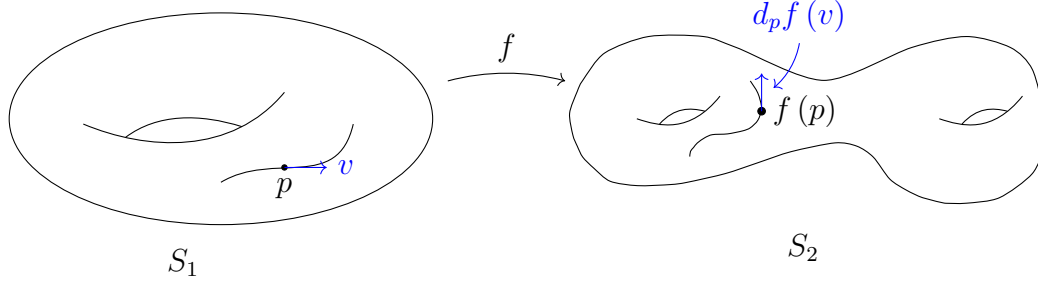


Figure 1.12: The differential of a smooth map

Proposition 1.67. Let S_1, S_2, S_3 be smooth surfaces. For any smooth maps $f: S_1 \rightarrow S_2$ and $g: S_2 \rightarrow S_3$ and any point $p \in S_1$ we have

$$D_p(g \circ f) = D_{f(p)}g \circ D_p f.$$

This also holds if any of S_i is replaced by an open subset of \mathbb{R}^n .

Proof. Let γ_1 be any smooth curve in S_1 through p . Denote $\gamma_2 = f \circ \gamma_1$, which is a smooth curve in S_2 through $f(p)$. If $\dot{\gamma}_1(0) = v_1$, then $v_2 := \dot{\gamma}_2(0) = D_p f(v_1)$ by the definition of $D_p f$. Hence,

$$\begin{aligned} D_p(g \circ f)(v_1) &= \left. \frac{d}{dt} \right|_{t=0} \left(g \circ \underbrace{f \circ \gamma_1}_{\gamma_2}(t) \right) = \left. \frac{d}{dt} \right|_{t=0} (g \circ \gamma_2(t)) = D_{f(p)}g(v_2) \\ &= D_{f(p)}g(D_p f(v_1)). \end{aligned}$$

□

Corollary 1.68. If $f: S_1 \rightarrow S_2$ is a diffeomorphism, then $d_p f: T_p S_1 \rightarrow T_{f(p)} S_2$ is an isomorphism for any $p \in S_1$. □

Definition 1.69. A map $f: S_1 \rightarrow S_2$ is called a *local diffeomorphism* if for any $p \in S_1$ there exists a neighbourhood $U_1 \subset S_1$ and a neighbourhood $U_2 \subset S_2$ of $f(p)$ such that $f: U_1 \rightarrow U_2$ is a diffeomorphism.

Theorem 1.70. Let $f: S_1 \rightarrow S_2$ be a smooth map such that $d_p f: T_p S_1 \rightarrow T_{f(p)} S_2$ is an isomorphism for all $p \in S_1$. Then f is a local diffeomorphism.

Proof. Pick any $p \in S_1$ and parametrizations $\psi_1: V_1 \rightarrow W_1 \subset S_1$ and $\psi_2: V_2 \rightarrow W_2 \subset S_2$. Without loss of generality we can assume that $\psi_1(0) = p$ and $\psi_2(0) = f(p)$.

Recall that the coordinate representation of f is $F = \psi_2^{-1} \circ f \circ \psi_1$, see Fig. 1.13. Hence, by Proposition 1.67 we obtain $d_0 F = d_{f(p)} \psi_2^{-1} \circ d_p f \circ d_0 \psi_1$. Furthermore, since all of the following linear maps

$$d_0 \psi_1: \mathbb{R}^2 \rightarrow T_p S_1, \quad d_{f(p)} \psi_2: T_{f(p)} S_2 \rightarrow \mathbb{R}^2, \quad \text{and} \quad d_p f: T_p S_1 \rightarrow T_{f(p)} S_2$$

are isomorphisms, we conclude that $d_0 F$ is an isomorphism too.

From the analysis course it is known that there exists a neighbourhood $\tilde{V}_1 \subset V_1$ of the origin and a neighbourhood $\tilde{V}_2 \subset V_2$ of the origin such that $F: \tilde{V}_1 \rightarrow \tilde{V}_2$ is a diffeomorphism. Denoting $U_1 = \psi_1(\tilde{V}_1)$ and $U_2 = \psi_2(\tilde{V}_2)$, we have

$$f|_{U_1} = \psi_2 \circ F \circ \psi_1^{-1}|_{U_1}: U_1 \rightarrow U_2$$

is a diffeomorphism, since it is a composition of diffeomorphisms. □

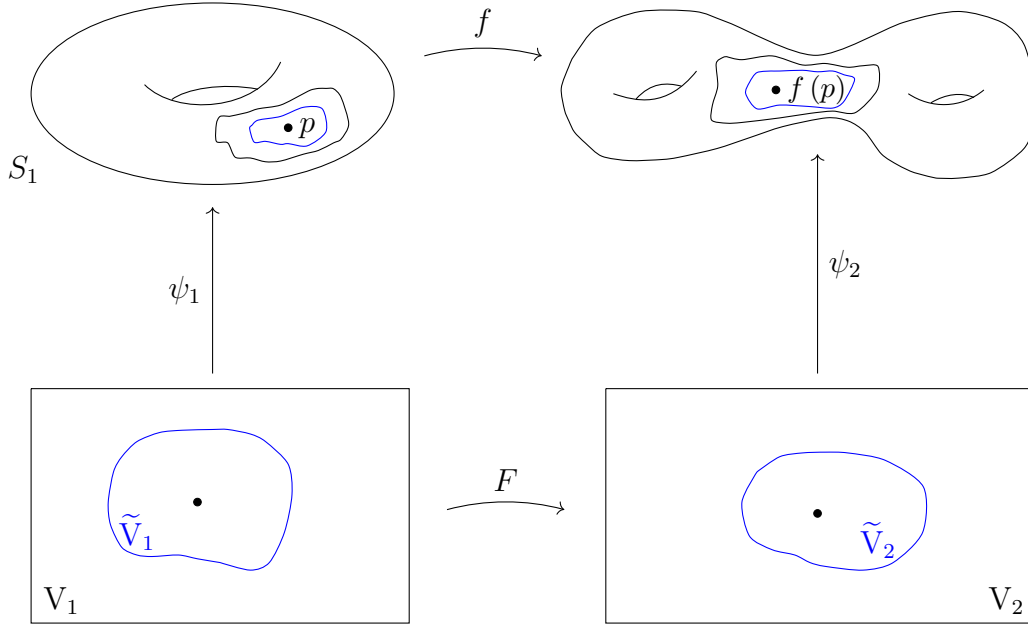


Figure 1.13: Illustration for the proof of Theorem 1.70

Remark 1.71. It follows from the proof of Theorem 1.70, that

$$d_p f = d_0 \psi_2 \circ d_0 F \circ d_p \psi_1^{-1},$$

where both $d_0 \psi_2$ and $d_p \psi_1^{-1}$ are linear isomorphisms.

In particular, this implies that the following holds:

- $d_p f$ is injective $\iff D_{\psi_1(p)} F$ is injective;
- $d_p f$ is surjective $\iff D_{\psi_1(p)} F$ is surjective;
- $d_p f$ is an isomorphism $\iff D_{\psi_1(p)} F$ is an isomorphism.

Definition 1.72. For $f \in C^\infty(S_1; S_2)$ a point $p \in S_1$ is called a *critical point* of f if $d_p f$ is not surjective.

Since $\dim T_p S_1 = \dim T_{f(p)} S_2$, a simple argument from linear algebra yields:

$$d_p f \text{ is non-surjective} \iff d_p f \text{ is non-injective} \iff d_p f \text{ is not an isomorphism.} \quad (1.73)$$

Notice, however, that Definition 1.72 makes sense in more general situations where, for example, the target S_2 (and/or the source S_1) is replaced by \mathbb{R}^n . However, (1.73) is false in general for those more general cases.

To see that Definition 1.72 coincides with the previous one in the case of function, suppose p is a critical point of a smooth function $f: S_1 \rightarrow \mathbb{R}$ in the sense of Definition 1.72. If there exists $v \in T_p S_1$ such that $d_p f(v) \neq 0$, then the linearity of $d_p f$ yields immediately that $d_p f$ is surjective. Hence, $d_p f$ is non-surjective if and only if it vanishes, cf. Definition 1.62.

Definition 1.74. A point $q \in S_2$ is called a *regular value* of f , if any $p \in f^{-1}(q)$ is a regular (that is non-critical) point of f , i.e., if for all $p \in f^{-1}(q)$ the differential $d_p f$ is surjective.

The argument demonstrating (1.73) yields also the following:

$$d_p f \text{ is surjective} \iff d_p f \text{ is injective} \iff d_p f \text{ is an isomorphism.}$$

Example 1.75. Identify \mathbb{C} with \mathbb{R}^2 and consider the map $f: \mathbb{C} \rightarrow \mathbb{C}$, $f(z) = z^n$, where $n \in \mathbb{Z}$, $n \geq 2$. It is known from analysis that $d_z f: \mathbb{C} \rightarrow \mathbb{C}$ can be identified with the map $h \mapsto f'(z) \cdot h$. Hence, z is critical if and only if $f'(z) = 0 \Leftrightarrow nz^{n-1} = 0 \Leftrightarrow z = 0$. Hence, f has a single critical point $z = 0$ and a single critical value, the zero. All other points are regular and any non-zero value is also regular.

Viewing f as a map $\mathbb{C} \setminus \{0\} \rightarrow \mathbb{C} \setminus \{0\}$, we obtain an example of a local diffeomorphism, which is not a diffeomorphism (assuming $n \geq 2$).

Theorem 1.76 (The fundamental theorem of algebra). *Let $q(z) = z^n + a_{n-1}z^{n-1} + \dots + a_1z + a_0$ be a polynomial of degree $n \geq 1$ with complex coefficients. Then q has at least one complex root.*

Proof. First recall that the map $f: S^2 \rightarrow S^2$,

$$f(p) = \begin{cases} N & p = N, \\ \psi_N \circ q \circ \psi_N^{-1}, & p \neq N, \end{cases}$$

is smooth. Indeed, the details of this claim are spelled on Page 14. The rest of the proof consists of the following steps.

Step 1. f has at most n critical points (values).

Indeed, a point $p \in S^2 \setminus \{N\}$ is critical for f if and only if $z := \psi_N(p)$ is critical for q . Hence, in this case $q'(z) = 0$, that is z is a root of the polynomial $nz^{n-1} + (n-1)a_{n-1}z^{n-2} + \dots + a_1$, which can have at most $(n-1)$ roots.

Step 2. Denote by $R(f)$ the set of regular values of f . Then for any $r \in R(f)$ the set $f^{-1}(r)$ is finite and the map $R(f) \rightarrow \mathbb{Z}_{\geq 0}$, $r \mapsto \#f^{-1}(r)$ is constant.

Pick any $r \in R(f)$ and any $p \in f^{-1}(r)$. Then $f(p) = r$ and $d_p f$ is an isomorphism. Hence, by Theorem 1.70 there exists a neighbourhood U_p of p and a neighbourhood W_r such that $f: U_p \rightarrow W_r$ is a diffeomorphism. In particular, $f^{-1}(r) \cap U_p = \{p\}$, that is $f^{-1}(r)$ is discrete. Since $f^{-1}(r)$ is a closed subset of S^2 , $f^{-1}(r)$ is compact. But a compact discrete set must be finite.

Denote $f^{-1}(r) = \{p_1, \dots, p_m\}$ and the corresponding neighbourhoods U_1, \dots, U_m and W_1, \dots, W_m . Set $W := W_1 \cap \dots \cap W_m$ and $\tilde{U}_j := f^{-1}(W) \cap U_j$. Then for each $j \leq m$ the map $f: \tilde{U}_j \rightarrow W$ is a diffeomorphism. In particular, for all $r' \in W$ there exists a unique $p'_j \in \tilde{U}_j$ such that $f(p'_j) = r'$. Hence, $\#f^{-1}(r') = \#f^{-1}(r)$ for all $r' \in W$, so that the function

$$R(f) \longrightarrow \mathbb{Z}, \quad r \longmapsto \#f^{-1}(r) \quad (1.77)$$

is locally constant.

However $R(f)$ is the complement of a finite number of points in S^2 , hence connected. Therefore (1.77) is (globally) constant.

Step 3. We prove this theorem.

Pick any pairwise distinct points $p_1, \dots, p_{n+1} \in S^2 \setminus \{N\}$ such that $f(p_1), \dots, f(p_{n+1})$ are also pairwise distinct. Since f has at most n critical values, at least one of those points is a regular value of f and (1.77) does not vanish at this point. Hence, (1.77) vanishes nowhere on $R(f)$.

If the south pole S is a critical value of f , then $f^{-1}(S) \neq \emptyset$, since $f^{-1}(S)$ contains a critical point. However,

$$f^{-1}(S) \neq \emptyset \iff q^{-1}(0) \neq \emptyset.$$

If S is a regular value, then **Step 2** yields $\#f^{-1}(S) \geq 1$. This yields in turn $q^{-1}(0) \neq \emptyset$, which finishes this proof. \square

1.6 Orientability

Let $S \subset \mathbb{R}^3$ be a (smooth) surface.

Definition 1.78. A (smooth) map $v: S \rightarrow \mathbb{R}^3$ is called a (smooth) tangent vector field on S , if $v(p) \in T_p S$ for all $p \in S$.

Definition 1.79. A (smooth) map $n: S \rightarrow \mathbb{R}^3$ is called a (smooth) *normal field* on S , if $n(p) \perp T_p S$ for all $p \in S$.

Example 1.80. Set $S = S^2$, $n(x) = x$. Then n is a normal vector field on S^2 .

Lemma 1.81. Let $\psi: V \rightarrow U \subset S$ be a parametrization. Then U admits a unit normal field n on U , that is $n(p) \perp T_p S$ and $|n(p)| = 1$ holds for all $p \in U$.

Proof. Since ψ is a parametrization, for any $p \in U$ there exists $q \in V$ such that $\psi(q) = p$ and $D_q \psi: \mathbb{R}^2 \rightarrow T_p S = \text{Im}(D_q \psi)$ is an isomorphism. Hence, $D_q \psi$ maps a basis of \mathbb{R}^2 onto a basis of $T_p S$. In particular, the image of the standard basis $(\partial_u \psi, \partial_v \psi)|_q$ is a basis of $T_p S$.

Define

$$n(p) = \frac{\partial_u \psi \times \partial_v \psi}{|\partial_u \psi \times \partial_v \psi|},$$

where " \times " means the cross-product in \mathbb{R}^3 . This is well-defined, since $\partial_u \psi \times \partial_v \psi \neq 0$. \square

Exercise 1.82. Check that n is a smooth normal field on U .

Lemma 1.83. If S is connected, then there are at most 2 non-equal unit normal fields on S .

Proof. Let n_1 and n_2 be unit normal fields. Since for any $p \in S$ both $n_1(p)$ and $n_2(p)$ are orthogonal to $T_p S$ and $|n_1(p)| = |n_2(p)|$, we must have $n_2(p) = \pm n_1(p)$.

Denote $S_{\pm} := \{p \in S \mid n_2(p) = \pm n_1(p)\}$. Then both S_+ and S_- are closed and $S = S_+ \cup S_-$. Hence, either

$$\begin{aligned} S_+ &= \emptyset & \iff & n_2(p) = -n_1(p) & \text{for any } p \in S & \text{ or} \\ S_- &= \emptyset & \iff & n_2(p) = +n_1(p) & \text{for any } p \in S. \end{aligned}$$

\square

Definition 1.84. A surface S is said to be *orientable*, if S admits a unit normal field.

It should be intuitively clear that any unit normal field "selects a side" of the surface. A choice of the unit normal field ("a side of S ") is called an orientation of S . Thus, any surface S admits at most 2 distinct orientations.

Proposition 1.85 (Preimages are orientable). *If 0 is a regular value of $\varphi: \mathbb{R}^3 \rightarrow \mathbb{R}$, then $S := \varphi^{-1}(0)$ admits a unit normal field.*

Here, just like in the Definition 1.74, 0 is said to be the regular value of φ if for any $p \in S = \varphi^{-1}(0)$ we have

$$D_p\varphi: \mathbb{R}^3 \longrightarrow \mathbb{R} \text{ is surjective} \iff \nabla\varphi(p) \neq 0,$$

since $D_p\varphi(v) = \langle \nabla\varphi(p), v \rangle$, where $v \in \mathbb{R}^3$.

Proof. Since $T_pS = \nabla\varphi(p)^\perp$, we see that $\nabla\varphi$ is a normal field. Since 0 is a regular value of φ , $\nabla\varphi$ vanishes nowhere on S . Hence, $n(p) := \frac{\nabla\varphi(p)}{|\nabla\varphi(p)|}$ is a unit normal field. \square

Remark 1.86. In the definition of orientability, it is only important, that the normal field exists, is non-vanishing and continuous. Smoothness can be deduced from this.

Example 1.87 (A non-example: the Möbius band). One can obtain the Möbius band from the strip by gluing the opposite sides as shown on the figure.

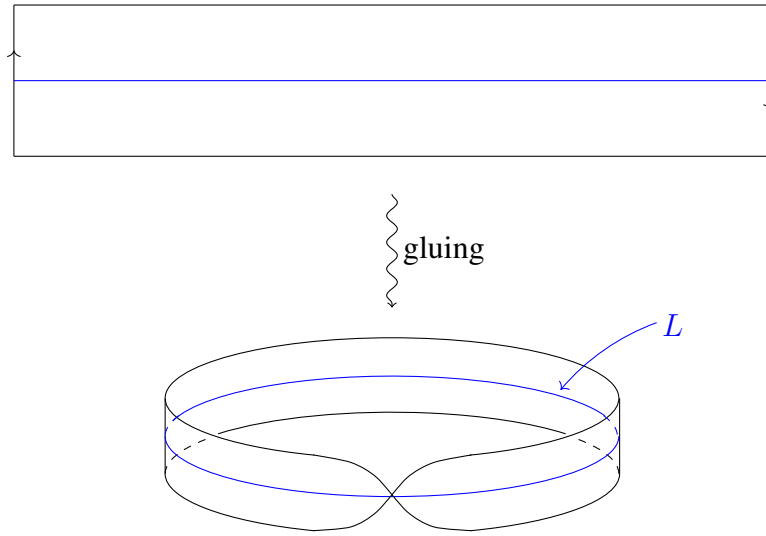


Figure 1.14: The Möbius band from the strip

More formally, the Möbius band is the image of the map

$$\begin{aligned} \Psi: [0, 2\pi] \times (-1, 1) &\longrightarrow \mathbb{R}^3, \\ \Psi(u, v) &= \left(\left(2 - v \sin \frac{u}{2} \right) \sin u, \left(2 - v \sin \frac{u}{2} \right) \cos u, v \cos \frac{u}{2} \right). \end{aligned}$$

Exercise 1.88. Show that the image of Ψ is a surface indeed.

To see that the Möbius band is non-orientable, recall that we showed in Lemma 1.81 that any point on a surface admits an orientable neighbourhood U . Moreover, it follows from the proof that given $0 \neq n_0 \perp T_{p_0}S$ at some $p_0 \in U$, there is a unique orientation n of U such that $n(p_0) = \frac{n_0}{|n_0|}$. With this understood, for all $p \in L$ pick an orientable neighbourhood U_p . Since L is compact, there is a finite collection U_1, \dots, U_n covering L . Choose a point $p_1 \in L \cap U_1$ and a vector $n_1 \in T_{p_1}S^\perp$, $|n_1| = 1$. This determines uniquely a normal field n on U_1 such that $n(p_1) = n_1$. If $U_2 \cap U_1 \neq \emptyset$, then there exists a unique smooth extension of n to $U_1 \cup U_2$. After finitely many steps we obtain a normal field n on $U_1 \cup \dots \cup U_n \supset L$. However, as one travels once along L , this normal field must change its direction, that is $n(p_1) = -n(p_1)$, which is impossible. Hence, the Möbius band does not admit a unit normal field, that is the Möbius band is non-orientable.

Let S be a surface.

Definition 1.89. A collection $\mathcal{A} = \{(\psi_a, V_a, U_a) \mid a \in A\}$ of parametrizations of S is said to be an atlas, if $\bigcup_{a \in A} U_a = S$.

Recall that for $a, b \in A$ the map

$$\theta_{ab} := \psi_a^{-1} \circ \psi_b : V_{ab} = \psi_b^{-1}(U_a \cap U_b) \longrightarrow \mathbb{R}^2$$

is called the change of coordinates map.

Definition 1.90. An atlas \mathcal{A} on S is said to be oriented, if $\det(D_{(u,v)}\theta_{ab}) > 0$ for any $(u, v) \in V_{ab}$.

Example 1.91. For $S = S^2$, $\mathcal{A} = \{(\psi_N, \mathbb{R}^2, S^2 \setminus \{N\}), (\psi_S, \mathbb{R}^2, S^2 \setminus \{S\})\}$ is an atlas. We have

$$\theta_{SN}(u, v) = \frac{1}{u^2 + v^2}(u, v)$$

A computation yields $\det(D\theta_{SN}) < 0$, so that \mathcal{A} is *not* an oriented atlas.

Consider, however

$$\mathcal{B} = \{(\psi_N, \mathbb{R}^2, S^2 \setminus \{N\}), (\hat{\psi}_S, \mathbb{R}^2, S^2 \setminus \{S\})\},$$

where $\hat{\psi}_S(u, v) = \psi_S(-u, v) = \psi_S \circ \sigma(u, v)$, where $\sigma(u, v) = (-u, v)$. Then

$$\hat{\theta}_{SN} = \hat{\psi}_S^{-1} \circ \psi_N = (\psi_S \circ \sigma)^{-1} \circ \psi_N = \sigma^{-1} \circ \theta_{SN} = \sigma \circ \theta_{SN},$$

since $\sigma^{-1} = \sigma$. By the linearity of σ , we have $D\hat{\theta}_{SN} = \sigma \circ D\theta_{SN}$, which yields

$$\det D\hat{\theta}_{SN} = \det \sigma \cdot \det D\theta_{SN} > 0,$$

since $\det \sigma = -1$ and $\det D\theta_{SN} < 0$. Thus, \mathcal{B} is an oriented atlas on S^2 .

Proposition 1.92. A surface S is orientable if and only if S admits an oriented atlas.

Proof. The proof consists of the following steps.

Step 1. If S is orientable, then S admits an oriented atlas.

Choose a unit normal field n on S and an atlas \mathcal{A} on S . Define a new atlas \mathcal{B} as follows: If $\psi_a : V_a \rightarrow U_a$ belongs to \mathcal{A} and $\det(\partial_u \psi_a, \partial_v \psi_a, n(\psi_a(u, v))) > 0$, then (ψ_a, V_a, U_a) belongs to \mathcal{B} . If $\det(\partial_u \psi_a, \partial_v \psi_a, n(\psi_a(u, v))) < 0$, then $(\psi_a \circ \sigma, \sigma(V_a), U_a) = (\hat{\psi}_a, \hat{V}_a, U_a)$ belongs to \mathcal{B} , where $\sigma : \mathbb{R}^2 \rightarrow \mathbb{R}^2, \sigma(u, v) = (-u, v)$. This yields

$$\det(\partial_u \hat{\psi}_a, \partial_v \hat{\psi}_a, n(\hat{\psi}_a(u, v))) = \det(-\partial_u \psi_a, \partial_v \psi_a, n(\psi_a(u, v))) > 0.$$

Therefore, we obtain:

- (a) Suppose both $\psi_a : V_a \rightarrow U_a$ and $\psi_b : V_b \rightarrow U_b$ belong to \mathcal{B} . Denote by (x_1, x_2) and (y_1, y_2) coordinates on V_a and V_b respectively. Write the transition map $\theta = \theta_{ab} : V_b \rightarrow V_a$, which is defined on an open subset of V_b , in components as $\theta = (\theta_1, \theta_2)$. Then from $\psi_b = \psi_a \circ \theta$ we obtain

$$\begin{aligned} \partial_{y_1} \psi_b &= \partial_{x_1} \psi_a(\theta(y)) \partial_{y_1} \theta_1 + \partial_{x_2} \psi_a(\theta(y)) \partial_{y_1} \theta_2, \\ \partial_{y_2} \psi_b &= \partial_{x_1} \psi_a(\theta(y)) \partial_{y_2} \theta_1 + \partial_{x_2} \psi_a(\theta(y)) \partial_{y_2} \theta_2. \end{aligned}$$

In matrix notations this can be written more briefly as

$$(\partial_{y_1}\psi_b, \partial_{y_2}\psi_b) = (\partial_{x_1}\psi_a, \partial_{x_2}\psi_a) \cdot \partial_y\theta, \quad \text{where} \quad \partial_y\theta = \begin{pmatrix} \partial_{y_1}\theta_1 & \partial_{y_2}\theta_1 \\ \partial_{y_1}\theta_2 & \partial_{y_2}\theta_2 \end{pmatrix}$$

is the Jacobi matrix of $\theta = \theta_{ab}$. Hence,

$$(\partial_{y_1}\psi_b, \partial_{y_2}\psi_b, n) = (\partial_{x_1}\psi_a, \partial_{x_2}\psi_a, n) \left(\begin{array}{c|c} \partial_y\theta & \begin{smallmatrix} 0 \\ 0 \end{smallmatrix} \\ \hline 0 & 1 \end{array} \right),$$

which yields in turn

$$\det(\partial_{y_1}\psi_b, \partial_{y_2}\psi_b, n) = \det(\partial_{x_1}\psi_a, \partial_{x_2}\psi_a, n) \cdot \det \left(\begin{array}{c|c} \partial_y\theta & \begin{smallmatrix} 0 \\ 0 \end{smallmatrix} \\ \hline 0 & 1 \end{array} \right). \quad (1.93)$$

By the assumption, we have $\det(\partial_{y_1}\psi_b, \partial_{y_2}\psi_b, n) > 0$ and $\det(\partial_{x_1}\psi_a, \partial_{x_2}\psi_a, n) > 0$. Hence, using (1.93) and

$$\det \left(\begin{array}{c|c} \partial_y\theta & \begin{smallmatrix} 0 \\ 0 \end{smallmatrix} \\ \hline 0 & 1 \end{array} \right) = \det(\partial_y\theta)$$

we obtain $\det(\partial_y\theta) > 0$.

(b) If $\hat{\psi}_a$ and $\hat{\psi}_b$ belong to \mathcal{B} , essentially the same computation as above yields

$$\det(\partial_y\theta_{ab}) > 0.$$

Furthermore,

$$\psi_b = \psi_a \circ \theta_{ab} \quad \implies \quad \psi_b \circ \sigma = \psi_a \circ \theta_{ab} \circ \sigma = (\psi_a \circ \sigma) \circ \sigma \circ \theta_{ab} \circ \sigma$$

where $\psi_b \circ \sigma = \hat{\psi}_b$ and $\psi_a \circ \sigma = \hat{\psi}_a$. Hence, the change of coordinates map between $\hat{\psi}_a$ and $\hat{\psi}_b$ is $\hat{\theta}_{ab} := \sigma \circ \theta_{ab} \circ \sigma$. This yields

$$\det(\partial_y\hat{\theta}_{ab}) = \det\sigma \cdot \det\partial_y\theta_{ab} \cdot \det\sigma = (\det\sigma)^2 \det\partial_y\theta_{ab} > 0.$$

(c) Suppose finally that ψ_a and $\hat{\psi}_b$ belong to \mathcal{B} . By the same argument as above, we obtain $\det(\partial_y\theta_{ab}) < 0$. If $\hat{\theta}_{ab}$ denotes the change of coordinates between ψ_a and $\hat{\psi}_b$, then

$$\hat{\theta}_{ab} = \theta_{ab} \circ \sigma \quad \implies \quad \det\partial_y\hat{\theta}_{ab} = \det(\partial_y\theta_{ab}) \cdot \det\sigma > 0,$$

since both $\det(\partial_y\theta_{ab})$ and $\det\sigma$ are negative.

Thus, \mathcal{B} is an oriented atlas.

Step 2. If S admits an oriented atlas, then S admits a unit normal field.

Let \mathcal{A} be an oriented atlas on S and $\psi_a: V_a \rightarrow U_a$ a parametrization from \mathcal{A} . If $\psi_a(q) = p \in U_a$, define $n(p)$ by

$$n(p) = \frac{\partial_u\psi_a \times \partial_v\psi_a}{|\partial_u\psi_a \times \partial_v\psi_a|} \Big|_q.$$

Assume ψ_b is another parametrization from \mathcal{A} such that $p \in U_b$. Then $\psi_b = \psi_a \circ \theta$, where $\theta = \theta_{ab}$, so that

$$(\partial_{y_1}\psi_b, \partial_{y_2}\psi_b) = (\partial_{x_1}\psi_a, \partial_{x_2}\psi_a) \cdot \partial_y\theta \quad \implies \quad \partial_{y_1}\psi_b \times \partial_{y_2}\psi_b = \det(\partial_y\theta) \cdot \partial_{x_1}\psi_a \times \partial_{x_2}\psi_a,$$

where $\det(\partial_y\theta) > 0$. Hence $n(p)$ does not depend on the choice of parametrization near p . Since n is smooth in a neighbourhood of p , n is smooth everywhere. \square

1.7 Partitions of unity

Recall that the function $\lambda: \mathbb{R} \rightarrow \mathbb{R}$

$$\lambda(t) = \begin{cases} 0 & \text{if } t \leq 0, \\ e^{-\frac{1}{t}} & \text{if } t > 0 \end{cases}$$

is smooth.

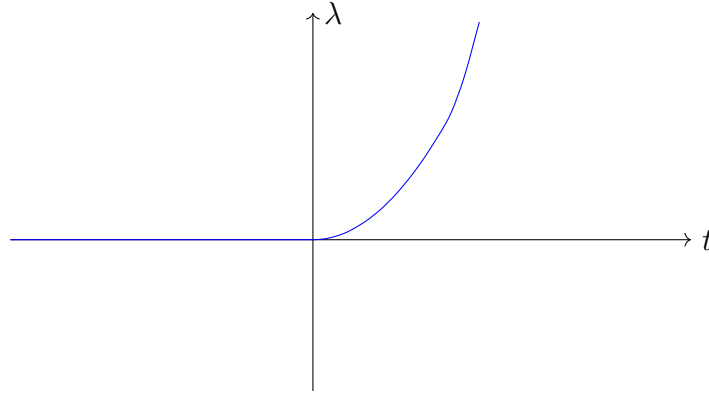


Figure 1.15: The graph of λ

For any fixed $r > 0$ and all $t \in \mathbb{R}$ we have

$$\lambda(t) + \lambda(r - t) > 0,$$

because $\lambda(t)$ is positive for $t > 0$ and $\lambda(r - t)$ is positive for $t < r$. Define

$$\hat{\chi}_r(t) := \frac{\lambda(r - t)}{\lambda(t) + \lambda(r - t)},$$

which is smooth everywhere on \mathbb{R} . Denote also

$$\chi_r(t) := \chi_r(t - 1)$$

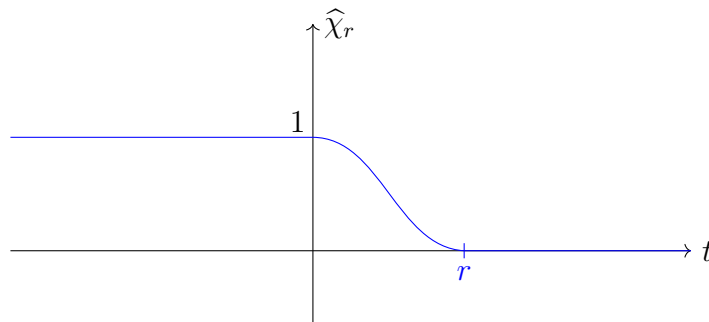
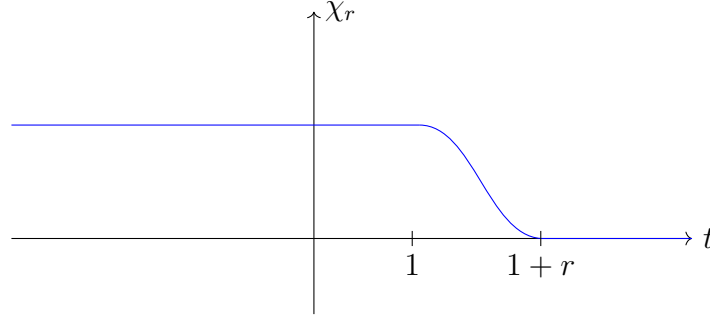


Figure 1.16: The graph of $\hat{\chi}_r$

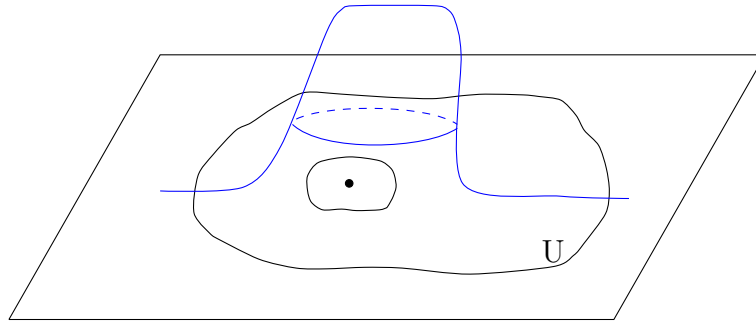
Lemma 1.94. *For any point $p \in \mathbb{R}^n$ and any neighbourhood $U \ni p$ there exists a neighbourhood $V \subset U$ and $\rho \in C^\infty(\mathbb{R}^n)$ such that the following holds:*


 Figure 1.17: The graph of χ_r

- $0 \leq \rho(x) \leq 1$ for all $x \in \mathbb{R}^n$;
- $\rho|_U \equiv 1$ and $\rho|_{\mathbb{R}^n \setminus U} \equiv 0$.

Proof. For any $R > 0$, consider

$$\rho(x) := \chi_1\left(\frac{|x - p|}{R}\right).$$


 Figure 1.18: Schematic graph of ρ

If $B_{2R}(p) \subset U$, then ρ vanishes outside of $B_{2R}(p)$, so vanishes outside of U . Also, $\rho(x) \equiv 1$ on $B_{2R}(p)$ and $\rho \in C^\infty$. Here $B_{2R}(p)$ is the ball of radius $2R$ centered at p . \square

Definition 1.95. For a continuous function f on a topological space X define *the support* of f by

$$\text{supp } f := \overline{\{x \in X \mid f(x) \neq 0\}}.$$

Notice in particular, that for $x \notin \text{supp } f$ we have $f(x) = 0$. However, a function may still have zeros in its support. For example, $\text{supp } \lambda = [0, +\infty)$ so that $0 \in \text{supp } \lambda$ and $\lambda(0) = 0$.

In fact, unwinding the definition in full details, we obtain that $x \in \text{supp } f$ if and only if there exists a sequence $x_n \rightarrow x$ such that $f(x_n) \neq 0$. In other words,

$$x \notin \text{supp } f \iff \exists \text{ a neighbourhood } U \text{ of } x \text{ such that } f|_U \equiv 0.$$

Example 1.96. If ρ is as in the above lemma, then $\text{supp } \rho \subset U$.

Example 1.97. For $f(x) = |x|^2 - 1$, $f: \mathbb{R}^n \rightarrow \mathbb{R}$, $\text{supp } f = \mathbb{R}^n$.

Definition 1.98. A (smooth) partition of unity on \mathbb{R}^n is a family of smooth functions $\{\rho_\alpha \mid \alpha \in A\}$ such that

- (i) $0 \leq \rho_\alpha(x) \leq 1$ for all $x \in \mathbb{R}^n$ and all $\alpha \in A$;
- (ii) For any $x \in \mathbb{R}^n$ the set $\{\alpha \in A \mid \rho_\alpha(x) \neq 0\}$ is finite;
- (iii) $\sum_{\alpha \in A} \rho_\alpha(x) = 1$ for all $x \in \mathbb{R}^n$.

Remark 1.99. More precisely, (ii) in the above definition should be replaced by the following condition: $\forall x \in \mathbb{R}^n$ there exists a neighbourhood $V \ni x$ such that the set $\{\alpha \in A \mid \text{supp } \rho_\alpha \cap V \neq \emptyset\}$ is finite. However, we consider mostly finite partitions of unity so that this condition (and therefore, also (ii)) will be satisfied automatically.

Example 1.100 (A partition of unity on \mathbb{R}). Consider $\{\hat{\rho}_j(x) \mid j \in \mathbb{Z}\}$, where $\hat{\rho}_j(x) = \chi_1(|x - j|)$. Notice that $\text{supp } \hat{\rho}_j \subset [j - 2, j + 2]$ so that the function $\hat{\rho}(x) := \sum_{j \in \mathbb{Z}} \hat{\rho}_j(x)$ well-defined, smooth and positive everywhere on \mathbb{R} . Hence,

$$\{\rho_j = \hat{\rho}_j / \hat{\rho} \mid j \in \mathbb{Z}\}$$

is a partition of unity on \mathbb{R}^1 .

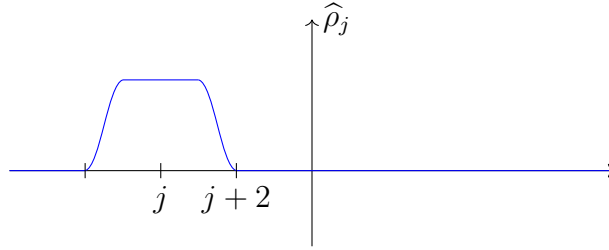


Figure 1.19: The schematic graph of ρ_j

Partitions of unity for surfaces are defined just like for \mathbb{R}^n .

Theorem 1.101 (Existence of a partition of unity). Let $\mathcal{U} = \{U_\alpha \mid \alpha \in A\}$ be any open covering of a surface S . Then there exists a partition of unity $\{\rho_\beta \mid \beta \in B\}$ such that for each $\beta \in B$ there exists an $\alpha \in A$ so that

$$\text{supp } \rho_\beta \subset U_\alpha.$$

Proof. The proof is given for compact surfaces only.

Step 1. Let S be any surface. For any $p \in S$ and any open subset $W \subset S$ such that $p \in W$, there exist $\rho \in C^\infty(S)$ such that

- (i) $0 \leq \rho(q) \leq 1$ for $q \in S$;
- (ii) $\text{supp } \rho \subset W$;
- (iii) There exists an open subset $X \subset W$ such that $p \in X$ and $\rho|_X \equiv 1$.

Let (U, φ) be a chart on S such that $\varphi(p) = 0 \in V \subset \mathbb{R}^2$ and $U \subset W$. Pick a function $\hat{\rho} \in C^\infty(\mathbb{R}^2)$ such that $0 \leq \hat{\rho} \leq 1$, $\hat{\rho}|_{B_r(0)} \equiv 1$, and $\hat{\rho}|_{\mathbb{R}^2 \setminus B_{2r}(0)} \equiv 0$ for some $r > 0$ such that $B_{2r}(0) \subset V$. Define

$$\rho(p) := \begin{cases} \hat{\rho} \circ \varphi(p) & \text{if } p \in U, \\ 0 & \text{otherwise.} \end{cases}$$

Then ρ is smooth everywhere and with $X := \varphi^{-1}(B_r(0))$ satisfies (i)–(iii).

Remark 1.102. Alternatively, one can first define a suitable function $\tilde{\rho}$ on a neighbourhood of p in \mathbb{R}^3 and define ρ as the restriction of $\tilde{\rho}$ to S .

Remark 1.103. Any function satisfying Properties (i)–(iii) of **Step 1** is called a bump function.

Step 2. We prove this theorem assuming S is compact.

Pick any U_α and any $p \in U_\alpha$. By **Step 1**, there exists $X_{p,\alpha} \subset U_\alpha$ and a function $\hat{\rho}_{p,\alpha}$ satisfying (i)–(iii).

Consider the family $\{X_{p,\alpha} \mid p \in S, \alpha \in A\}$, which is an open covering of S . By the compactness of S , there exists a finite subcovering $\{X_{p_1,\alpha_1}, \dots, X_{p_n,\alpha_n}\}$. To simplify notations, redenote $X_j := X_{p_j,\alpha_j}$ and $\hat{\rho}_j := \hat{\rho}_{p_j,\alpha_j}$ so that $\hat{\rho}_j|_{X_j} \equiv 1$. Just as in **Example 1.100**, we have

$$\hat{\rho}(p) := \sum_{j=1}^n \hat{\rho}_j(p) > 0$$

for any $p \in S$. Then $\rho_j := \hat{\rho}_j / \hat{\rho}$ is a partition of unity on S . Moreover, $\text{supp } \rho_j = \text{supp } \hat{\rho}_j \subset U_{\alpha_j}$. \square

Remark 1.104. A partition of unity as in the above theorem is called *subordinate* to \mathcal{U} .

Example 1.105. Consider the case $S = S^2$ with the covering $\mathcal{U} = \{S^2 \setminus \{N\}, S^2 \setminus \{S\}\}$. Albeit the above theorem yields a partition of unity subordinate to \mathcal{U} , we can construct this by hands as follows. Let ρ be a bump function on \mathbb{R}^2 such that $\rho|_{B_1(0)} \equiv 1$ and $\text{supp } \rho \subset B_2(0)$. Define

$$\rho_N := \rho \circ \varphi_N \quad \text{and} \quad \rho_S := 1 - \rho_N.$$

Then $\{\rho_N, \rho_S\}$ is the partition of unity we are looking for.

1.8 Integration on surfaces

The aim of this section is to define a map $\int : C^\infty(S) \longrightarrow \mathbb{R}$ with "the usual" properties of the integral, e.g.

$$\int_S (\lambda f + \mu g) = \lambda \int_S f + \mu \int_S g \quad \lambda, \mu \in \mathbb{R} \quad f, g \in C^\infty(S). \quad (1.106)$$

To this end, assume that S is compact and choose an atlas $\mathcal{A} = \{(U_\alpha, \varphi_\alpha) \mid \alpha \in A\}$ on S . Let $\{\rho_j \mid j = 1, \dots, J\}$ be a partition of unity on S such that $\text{supp } \rho_j \subset U_{\alpha_j} =: U_j$. For any $f \in C^\infty(S)$ we have

$$f = f \cdot 1 = \sum_{j=1}^J f \cdot \rho_j = \sum_j f_j,$$

where $f_j := f \cdot \rho_j$ and $\text{supp } f_j \subset \text{supp } \rho_j \subset U_j$. Hence, by (1.106) it suffices to define $\int_S f_j$, that is we want to define $\int_S f$ provided $\text{supp } f \subset U$, where (U, φ) is a chart.

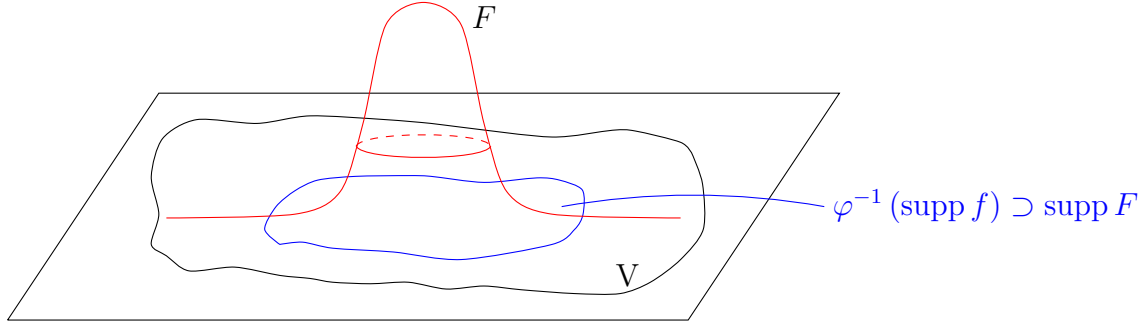
Viewing φ as an identification between U and $V \subset \mathbb{R}^2$, we can identify f with its coordinate representation

$$F := f \circ \varphi^{-1} = f \circ \psi : V \longrightarrow \mathbb{R}.$$

Then F vanishes outside of $\varphi^{-1}(\text{supp } f)$, which is compact.

It is tempting to define

$$\int_S f := \int_{\mathbb{R}^2} F(u, v) du dv. \quad (1.107)$$


 Figure 1.20: The coordinate representation of f

Notice that the integrand on the right hand side of the above equality vanishes outside of a compact set so that in fact we do not need to worry about the convergence of this integral. It may happen, however, that there is another chart $(\hat{U}, \hat{\varphi})$ on S such that $\text{supp } f \subset \hat{U}$. To show that $\int_S f$ is well-defined, we must show the equality

$$\int_{\mathbb{R}^2} F(u, v) du dv \stackrel{?}{=} \int_{\mathbb{R}^2} \hat{F}(x, y) dx dy, \quad (1.108)$$

where $\hat{F} = f \circ \hat{\varphi}^{-1}$ is the coordinate representation of f with respect to $\hat{\varphi}$.

Let $\theta = \varphi \circ \hat{\varphi}^{-1} \Leftrightarrow (u, v) = \theta(x, y)$ denote the change of coordinates map. Then

$$\hat{F} = f \circ \hat{\varphi}^{-1} = f \circ \varphi^{-1} \circ \varphi \circ \hat{\varphi}^{-1} = F \circ \theta,$$

so that (1.108) is equivalent to

$$\int_{\mathbb{R}^2} F(u, v) du dv \stackrel{?}{=} \int_{\mathbb{R}^2} F \circ \theta(x, y) dx dy$$

The last equality is false in general, since by a well-known theorem from analysis we have

$$\int_{\mathbb{R}^2} F(u, v) du dv = \int_{\mathbb{R}^2} F \circ \theta(x, y) |\det D\theta| dx dy.$$

Thus, our naïve approach to define $\int_S f$ by (1.107) does not work in general.

To solve this problem, recall the following fact. Suppose $V \subset \mathbb{R}^3$ is a bounded open set such that $S := \partial V$ is a smooth oriented surface. Then by the divergence theorem we have

$$\int_V \text{div } v = \int_S \langle v, n \rangle dS,$$

where n is the unit normal field pointing outwards. If $\psi = \psi(u, v)$ is a parametrization of S , the right hand side is defined by

$$\int \langle v, n \rangle |\partial_u \psi \times \partial_v \psi| du dv.$$

Following this hint, for $f \in C^\infty(S)$ with $\text{supp } f \subset U$, where U is a coordinate chart, we define

$$\int_S f := \int_{\mathbb{R}^2} F(u, v) |\partial_u \psi \times \partial_v \psi| du dv. \quad (1.109)$$

Then, if $(\widehat{U}, \widehat{\varphi})$ is another chart just like above and $\theta = \varphi \circ \widehat{\varphi}^{-1} = \psi^{-1} \circ \widehat{\psi}$, we have

$$\begin{aligned} \widehat{\psi} &= \psi \circ \theta &\implies & (\partial_x \widehat{\psi}, \partial_y \widehat{\psi}) = (\partial_u \psi, \partial_v \psi) \cdot D\theta \\ & &\implies & |\partial_x \widehat{\psi} \times \partial_y \widehat{\psi}| = |\partial_u \psi \times \partial_v \psi| \cdot |\det D\theta|. \end{aligned}$$

Hence, we have

$$\begin{aligned} \int_{\mathbb{R}^2} \widehat{F}(x, y) |\partial_x \widehat{\psi} \times \partial_y \widehat{\psi}| dx dy &= \int_{\mathbb{R}^2} F \circ \theta(x, y) |\partial_u \psi \times \partial_v \psi| |\det D\theta| dx dy \\ &= \int_{\mathbb{R}^2} F(u, v) |\partial_u \psi \times \partial_v \psi| du dv. \end{aligned}$$

That is (1.109) does not depend on the choice of the parametrization of S .

Definition 1.110. Let S be a compact surface and f a smooth function on S . Pick an atlas $\mathcal{U} = \{(U_\alpha, \varphi_\alpha)\}$ and a finite partition of unity $\{\rho_j \mid 1 \leq j \leq J\}$ subordinate to \mathcal{U} . Denote by F_j the coordinate representation of $f_j := \rho_j \cdot f$. Then the integral of f over S is defined by

$$\int_S f := \sum_j \int_S f_j = \sum_j \int_{\mathbb{R}^2} F_j(u, v) |\partial_u \psi_j \times \partial_v \psi_j| du dv.$$

Proposition 1.111. $\int_S f$ is well-defined, that is $\int_S f$ does not depend on the choice of an atlas.

Proof. Let $\widehat{\mathcal{U}} = \{(\widehat{U}_\beta, \widehat{\varphi}_\beta) \mid \beta \in B\}$ be another atlas on S . Choose a partition of unity $\{\mu_k \mid k = 1, \dots, K\}$ subordinate to $\widehat{\mathcal{U}}$. We need to show that

$$\sum_j \int_S (\rho_j f) \stackrel{?}{=} \sum_k \int_S (\mu_k f). \quad (1.112)$$

Notice that $\{\lambda_{jk} := \rho_j \lambda_k \mid j = 1, \dots, J, k = 1, \dots, K\}$ is also a partition of unity and $\text{supp } \lambda_{jk} \subset U_j \cap \widehat{U}_k$.

With this understood, for a fixed j consider

$$\sum_{k=1}^K \int_S \lambda_{jk} f = \int_S \left(\rho_j \sum_{k=1}^K \mu_k f \right) = \int_S \rho_j f,$$

where the first equality follows by the linearity of the integral on the space of compactly supported functions on \mathbb{R}^2 . Summing the above equality over j , we arrive at

$$\sum_{j=1}^J \sum_{k=1}^K \int_S \lambda_{jk} f = \sum_{j=1}^J \int_S \left(\rho_j \sum_{k=1}^K \mu_k f \right) = \sum_{j=1}^J \int_S \rho_j f.$$

Similarly, we have

$$\sum_{k=1}^K \sum_{j=1}^J \int_S \lambda_{jk} f = \sum_k \int_S \left(\mu_k \sum_{j=1}^J \rho_j f \right) = \sum_k \int_S \mu_k f.$$

Comparing the above two equalities we see that (1.112) holds indeed. \square

It follows immediately from the definition that \int_S has the usual properties known from the analysis course, for example:

- $\int_S (\lambda f + \mu g) = \lambda \int_S f + \mu \int_S g$;
- $f \geq 0 \implies \int_S f \geq 0$;
- $\int_S f = 0$ and $f \geq 0 \implies f \equiv 0$

and so on, where in the last property I assume that f is at least continuous.

Example 1.113. Let $f: S^2 \rightarrow \mathbb{R}$ be any (smooth) function. Let $\mathcal{U} = \{S^2 \setminus \{N\}, S^2 \setminus \{S\}\}$ be just as in [Example 1.105](#). Choose $\varepsilon > 0$ and set

$$\rho_N^\varepsilon(p) := \rho(\varepsilon \varphi_N(p)), \quad \text{and} \quad \rho_S^\varepsilon := 1 - \rho_N^\varepsilon,$$

where ρ is just as in [Example 1.105](#). Notice the following:

$$\begin{aligned} \rho|_{B_1(0)} &\equiv 1 &\implies & \rho_N^\varepsilon|_{\varphi_N^{-1}(B_{\varepsilon^{-1}}(0))} \equiv 1, \\ \rho|_{\mathbb{R}^2 \setminus B_2(0)} &&\implies & \rho_N^\varepsilon|_{S^2 \setminus \varphi_N^{-1}(B_{2\varepsilon^{-1}}(0))} \equiv 0. \end{aligned}$$

If $F_N = f \circ \psi_N$ and $F_S := f \circ \psi_S$ are coordinate representations of f , then by the definition of the integral we have

$$\begin{aligned} \int_S f &= \int_{\mathbb{R}^2} (\rho_N^\varepsilon \circ \psi_N(u, v)) F_N(u, v) |\partial_u \psi_N \times \partial_v \psi_N| du dv \\ &\quad + \int_{\mathbb{R}^2} (\rho_S^\varepsilon \circ \psi_S(u, v)) \cdot F_S(u, v) |\partial_u \psi_S \times \partial_v \psi_S| du dv \\ &= \int_{\mathbb{R}^2} \rho(\varepsilon u, \varepsilon v) F_N(u, v) |\partial_u \psi_N \times \partial_v \psi_N| du dv \\ &\quad + \int_{\mathbb{R}^2} \rho_S^\varepsilon \circ \psi_S(u, v) F_S(u, v) |\partial_u \psi_S \times \partial_v \psi_S| du dv. \end{aligned}$$

The last term converges to 0 as $\varepsilon \rightarrow 0$, since

- the measure of the support of $\rho_S^\varepsilon \circ \psi_S$ converges to zero;
- the integrand is uniformly bounded with respect to ε .

For the first term, we have

$$\begin{aligned} &\int_{\mathbb{R}^2} \rho(\varepsilon u, \varepsilon v) F_N(u, v) |\partial_u \psi_N \times \partial_v \psi_N| du dv \\ &= \int_{B_{\varepsilon^{-1}}(0)} F_N(u, v) |\partial_u \psi_N \times \partial_v \psi_N| du dv \\ &\quad + \int_{B_{2\varepsilon^{-1}}(0) \setminus B_{\varepsilon^{-1}}(0)} \rho(\varepsilon u, \varepsilon v) F_N(u, v) |\partial_u \psi_N \times \partial_v \psi_N| du dv. \end{aligned}$$

The last summand of this expression converges to zero, since

- $|\rho(\varepsilon u, \varepsilon v) F_N(u, v)| \leq \sup_{S^2} |f|$;
- $\int_{B_{2\varepsilon^{-1}}(0) \setminus B_{\varepsilon^{-1}}(0)} |\partial_u \psi \times \partial_v \psi| du dv \leq \text{Area}(S^2 \setminus \psi_N(B_{\varepsilon^{-1}}(0))) \rightarrow 0$.

Summing up, we obtain

$$\int_{S^2} f = \int_{\mathbb{R}^2} F_N(u, v) |\partial_u \psi_N \times \partial_v \psi_N| du dv \quad (1.114)$$

just as it is well-known from the analysis course.

Of course, a similar argument yields also

$$\int_{S^2} f = \int_{\mathbb{R}^2} F_S(u, v) |\partial_u \psi_S \times \partial_v \psi_S| du dv. \quad (1.115)$$

The reader should check directly that the right hand sides of (1.114) and (1.115) are equal indeed.

Theorem 1.116. *Let $h: S_1 \rightarrow S_2$ be a diffeomorphism, where S_1 and S_2 are compact surfaces. Then for any $f \in C^\infty(S)$ we have*

$$\int_{S_2} f = \int_{S_1} (f \circ h) \cdot |\det dh|. \quad (1.117)$$

To explain the right hand side of (1.117), let V and W be Euclidean vector spaces such that $\dim V = \dim W = n$. Choose an orthonormal basis $e = (e_1, \dots, e_n)$ of V and an orthonormal basis $g = (g_1, \dots, g_n)$ of W . A linear map $\varphi: V \rightarrow W$ can be represented by a matrix $A_\varphi = (a_{ij}) \in M_n(\mathbb{R})$, where

$$\varphi(e_i) = \sum_{j=1}^n a_{ij} g_j \iff (\varphi(e_1), \dots, \varphi(e_n)) = (g_1, \dots, g_n) \cdot A \iff \varphi(e) = g \cdot A.$$

If e' is another basis of V , then there exists an orthogonal $n \times n$ matrix B such that

$$e' = e \cdot B \iff e'_i = \sum_{j=1}^n b_{ij} e_j.$$

Similarly, if g' is another basis of W , then there exists an orthogonal $n \times n$ matrix $C = (c_{ij})$ such that

$$g' = g \cdot C \iff g'_i = \sum_{j=1}^n c_{ij} g_j.$$

Let A'_φ be the matrix of φ with respect to e' and g' . Then

$$\begin{aligned} \varphi(e') &= g' \cdot A'_\varphi = g C A'_\varphi \iff \varphi(e \cdot B) = \varphi(e) \cdot B = g \cdot A_\varphi B \\ &\implies C A'_\varphi = A_\varphi B \implies A'_\varphi = C^{-1} A_\varphi B. \end{aligned}$$

Therefore,

$$\det A'_\varphi = \det(C^{-1}) \det A_\varphi \det B = \pm \det A_\varphi \implies |\det A'_\varphi| = |\det A_\varphi|,$$

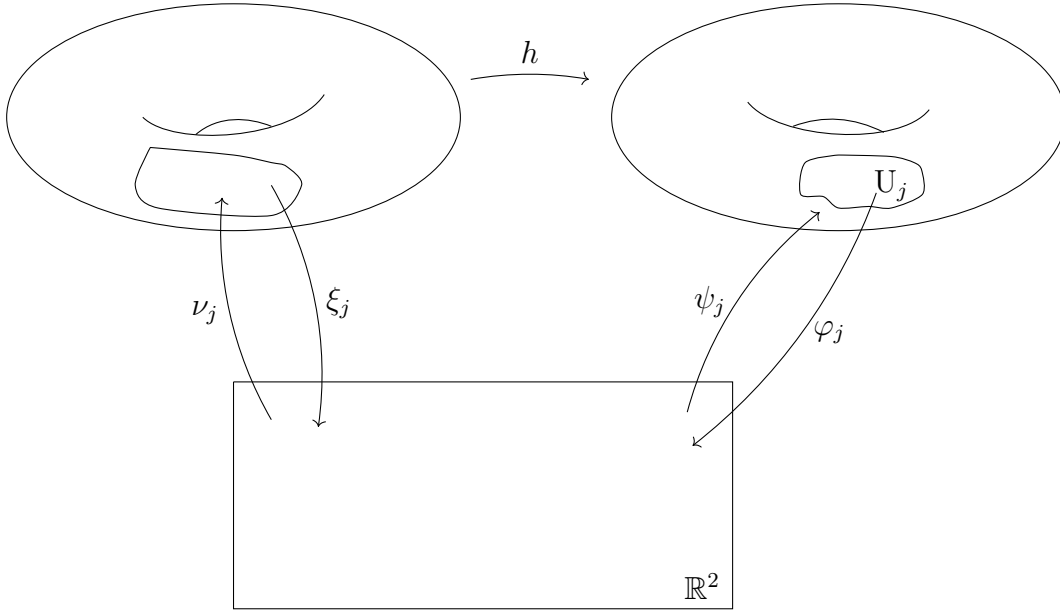
since both $\det(C^{-1})$ and $\det B$ equal to ± 1 because B and C are orthogonal. That is for any linear map $\varphi: V \rightarrow W$ between Euclidean spaces $|\det \varphi| := |\det A_\varphi|$ is well-defined.

Since for any $p \in S_1$ both $T_p S_1$ and $T_{h(p)} S_2$ are Euclidean, $|\det dh|$ is a well-defined function on S_1 .

Proof of Theorem 1.116. Let $\mathcal{U}_2 = \{(U_\alpha, \varphi_\alpha) \mid \alpha \in A\}$ be an atlas on S_2 . Pick a partition of unity $\{\rho_j \mid j = 1, \dots, n\}$ on S_2 subordinate to \mathcal{U}_2 . Then $\mathcal{U}_1 = \{(h^{-1}(U_\alpha), \xi_\alpha := \varphi_\alpha \circ h) \mid \alpha \in A\}$ is an atlas on S_1 and $\{\rho_j \circ h \mid j = 1, \dots, n\}$ is a partition of unity subordinate to \mathcal{U}_1 . If $\text{supp } \rho_j \subset U_{\alpha_j} =: U_j$, denote $\psi_j = \varphi_j^{-1}$, $\xi_j = \varphi_{\alpha_j} \circ h$ and $\nu_j = \xi_j^{-1} = h^{-1} \circ \psi_j$. Hence,

$$\begin{aligned} \psi_j = h \circ \nu_j &\implies \partial_u \psi_j = dh(\partial_u \nu_j) \quad \text{and} \quad \partial_v \psi_j = dh(\partial_v \nu_j) \\ &\implies |\partial_u \psi_j \times \partial_v \psi_j| = |\det dh| |\partial_u \nu_j \times \partial_v \nu_j|. \end{aligned} \quad (1.118)$$

The last equality follows from the following fact: If $E \subset \mathbb{R}^3$ is a plane spanned by two vectors v and w , for any $A \in \text{End}(E)$ we have $(Av) \times (Aw) = (\det A) \cdot v \times w$.



Thus, we have

$$\begin{aligned} \int_{S_1} (\rho_j \circ h) \cdot (f \circ h) \cdot |\det dh| &= \int_{\mathbb{R}^2} (\rho_j \circ h \circ \xi_j^{-1}) \cdot (f \circ h \circ \xi_j^{-1}) \cdot |\det dh| \cdot |\partial_u \nu_j \times \partial_v \nu_j| \\ &= \int_{\mathbb{R}^2} (\rho_j \circ \psi_j) \cdot (f \circ \psi_j) |\partial_u \psi_j \times \partial_v \psi_j| \\ &= \int_{S_2} \rho_j \cdot f, \end{aligned}$$

where the second equality follows from (1.118). Summing up by j , we obtain (1.117). \square

Remark 1.119. Notice that (1.117) is nothing else but a fancy restatement of the theorem about the change of coordinates for the integration, which is well-known from the analysis course.

1.9 Quadratic forms on surfaces

Definition 1.120. A Riemannian metric on a smooth surface S is a family of scalar products $\{\langle \cdot, \cdot \rangle_p \mid p \in S\}$, where $\langle \cdot, \cdot \rangle_p$ is a scalar product on $T_p S$, such that $\langle \cdot, \cdot \rangle_p$ depends smoothly on p .

To explain, let $\psi: V \rightarrow U$ be a parametrization. If $q \in V$ and $p = \psi(q)$, then $T_p S$ has a basis $(\partial_u \psi, \partial_v \psi)$. Hence, the scalar product $\langle \cdot, \cdot \rangle_p$ is represented by its Gram matrix

$$M = \begin{pmatrix} E & F \\ F & G \end{pmatrix}, \quad \text{where} \quad \begin{aligned} E &= \langle \partial_u \psi, \partial_u \psi \rangle_p, \\ F &= \langle \partial_u \psi, \partial_v \psi \rangle_p, \\ G &= \langle \partial_v \psi, \partial_v \psi \rangle_p. \end{aligned}$$

We say, that $\langle \cdot, \cdot \rangle_p$ depends smoothly on p , if all 3 functions E, F, G are smooth on U (where they are defined).

Example 1.121. For any $p \in S$ we have $T_p S \subset \mathbb{R}^3$. Since \mathbb{R}^3 is equipped with the standard scalar product.

$$\langle x, y \rangle_{st} := x_1 y_1 + x_2 y_2 + x_3 y_3$$

we can restrict $\langle \cdot, \cdot \rangle_{st}$ to $T_p S$ to obtain a scalar product on $T_p S$. This is a Riemannian metric on S , since

$$E(u, v) = \langle \partial_u \psi, \partial_u \psi \rangle_S = \langle \partial_u \psi, \partial_u \psi \rangle_{st}$$

is a smooth function of (u, v) (and similarly for F and G).

This particular Riemannian metric on S is called *the first fundamental form* of S in the classical theory of surfaces.

Exercise 1.122. Let $\langle \cdot, \cdot \rangle$ be the first fundamental form of S and $f: S \rightarrow S$ be a diffeomorphism. For $v, w \in T_p S$ define a new scalar product

$$\langle v, w \rangle_f := \langle d_p f(v), d_p f(w) \rangle_{f(p)}$$

where $d_p f(v) \in T_{f(p)} S$ and $d_p f(w) \in T_{f(p)} S$. Show that $\langle \cdot, \cdot \rangle_f$ is a Riemannian metric on S .

For the sake of simplicity of exposition, assume S is oriented and let n be the unit normal field. We can regard n as a smooth map

$$n: S \longrightarrow S^2,$$

which is called *the Gauss map*. Then for all $p \in S$ we have

$$d_p n: T_p S \longrightarrow T_{n(p)} S^2 = n(p)^\perp = T_p S.$$

This linear map is called *the shape operator* of S at p .

As a linear map in a 2-dimensional vector space, the shape operator has two invariants:

$$K(p) := \det(d_p n) \quad \text{and} \quad H(p) := -\frac{1}{2} \operatorname{tr}(d_p n).$$

Definition 1.123. $K(p)$ is called *the Gauss curvature* and $H(p)$ is called *the mean curvature* of S at p .

Notice that both K and H are smooth functions on S .

Example 1.124. For the plane $S = \mathbb{R}^2 \equiv \mathbb{R}^2 \times \{0\} \subset \mathbb{R}^3$ the Gauss map is constant. Hence, the shape operator vanishes and therefore both K and H vanish too.

Example 1.125. For the sphere of radius r

$$S_r^2 := \{x \in \mathbb{R}^3 \mid |x|^2 = r^2\}$$

the Gauss map is given by $n(p) = \frac{1}{r}p$. Hence, for the shape operator we obtain: $d_p n(v) = \frac{1}{r}v$. Thus, $d_p n = \frac{1}{r}\text{id} \Rightarrow K(p) = \frac{1}{r^2}$ is constant on S^2 .

Notice that for $r \rightarrow \infty$, we have $K(p) \rightarrow 0$ and the sphere looks more and more flat in a neighbourhood of each point (that is why our Earth is "flat"). Thus, we can view the Gauss curvature as a measure of flatness of S .

Lemma 1.126. *The shape operator is symmetric, that is for any $p \in S$ and any $v, w \in T_p S$ we have*

$$\langle d_p n(v), w \rangle = \langle v, d_p n(w) \rangle.$$

Proof. Let $\psi: V \rightarrow S$ be a parametrization such that $\psi(0) = p$. Then $(\partial_u \psi, \partial_v \psi) \Big|_{(u,v)=0}$ is a basis of $T_p S$. Hence, it suffices to show the equality

$$\langle d_p n(\partial_u \psi), \partial_v \psi \rangle = \langle \partial_u \psi, d_p n(\partial_v \psi) \rangle, \quad (1.127)$$

where the derivatives are evaluated at the origin. To this end, notice that by the definition of n we have

$$\langle n(\psi(u, v)), \partial_u \psi(u, v) \rangle = 0 \quad \forall (u, v) \in V.$$

Differentiating this equality with respect to v and setting $(u, v) = 0$, we obtain

$$\langle d_p n(\partial_u \psi), \partial_v \psi \rangle + \langle n(p), \partial_{uv} \psi \rangle = 0.$$

Similarly, we obtain

$$\langle \partial_u \psi, d_p n(\partial_v \psi) \rangle + \langle \partial_{uv} \psi, n(p) \rangle = 0.$$

Subtracting these two equalities, we arrive at (1.127). □

Definition 1.128. The bilinear symmetric map

$$\text{II}: T_p S \times T_p S \longrightarrow \mathbb{R}, \quad (v, w) \longmapsto \langle v, d_p n(w) \rangle_p$$

is called *the second fundamental form* of S at p .

Notice that II is smooth, that is for any parametrization ψ the functions

$$\text{II}(\partial_u \psi(u, v), \partial_u \psi(u, v)), \quad \text{II}(\partial_u \psi, \partial_v \psi), \quad \text{II}(\partial_v \psi, \partial_v \psi)$$

are smooth in (u, v) .

Remark 1.129. One can recover the shape operator from the second fundamental form, that is these two objects contain the same amount of information.

Remark 1.130. Observe that the shape operator and the second fundamental form depend on the choice of orientation. If one changes the orientation to the opposite one, the sign of the fundamental form changes too. However, this does not affect the Gauss curvature. In particular, the Gauss curvature is well-defined for non-orientable surfaces too, since any surface is *locally* orientable.

1.10 The geometric meaning of the sign of the Gauss curvature

Let $p \in S$ be a critical point of $f \in C^\infty(S)$. Given $v \in T_p S$, pick a smooth curve $\gamma: (-\varepsilon, \varepsilon) \rightarrow S$ such that $\gamma(0) = p$ and $\dot{\gamma}(0) = v$.

Definition 1.131. The map

$$\text{Hess}_p f: T_p S \longrightarrow \mathbb{R}, \quad \text{Hess}_p f(v) = \left. \frac{d^2}{dt^2} \right|_{t=0} (f \circ \gamma(t))$$

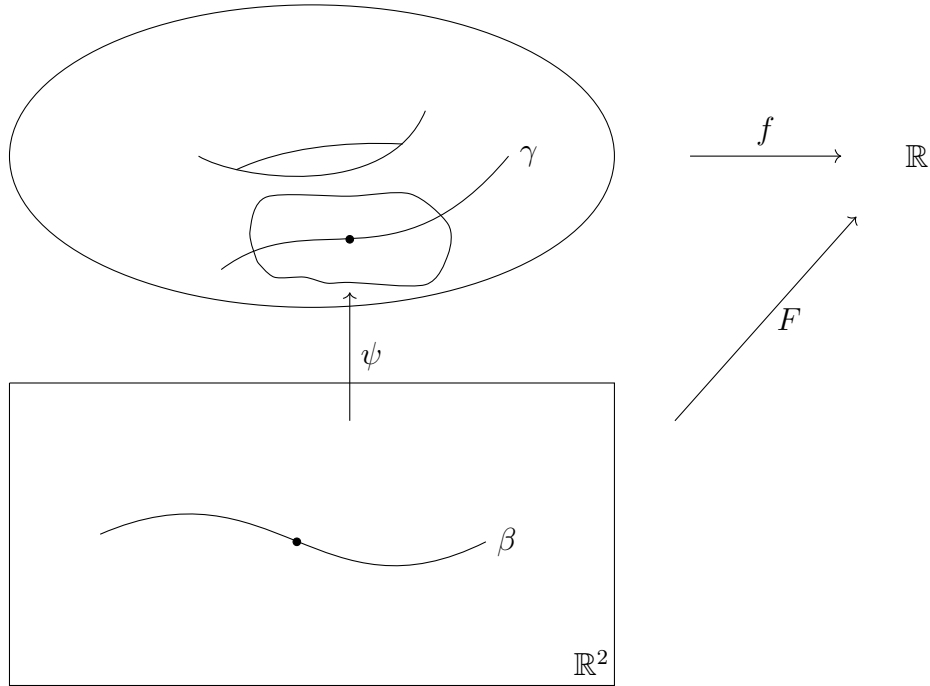
is called the Hessian of f at p .

Proposition 1.132.

- (i) $\text{Hess}_p f$ is a well-defined quadratic map.
- (ii) If p is a point of local minimum, then $\text{Hess}_p(f)(v) \geq 0$ for all $v \in T_p S$. If p is a point of local maximum, then $\text{Hess}_p f(v) \leq 0$.
- (iii) If $\text{Hess}_p f(v) > 0$ for all $v \neq 0$, then p is a point of local minimum. If $\text{Hess}_p f(v) < 0$ for all $v \neq 0$, then p is a point of local maximum.

Proof. Choose a parametrization ψ such that $\psi(0) = p$ and denote

$$F := f \circ \psi \quad \text{and} \quad \beta := \varphi \circ \gamma = \psi \circ \gamma.$$



Then if $\beta(t) = (\beta_1(t), \beta_2(t))$, we have

$$\begin{aligned} f \circ \gamma(t) &= F \circ \beta(t) = F(\beta_1(t), \beta_2(t)) \implies \\ \frac{d}{dt} f \circ \gamma(t) &= \partial_u F(\beta(t)) \beta'_1(t) + \partial_v F(\beta(t)) \beta'_2(t). \end{aligned}$$

Notice that $\beta(0) = 0$ and $\partial_u F(0) = 0 = \partial_v F(0)$.

Furthermore we have

$$\frac{d^2}{dt^2} \Big|_{t=0} f \circ \gamma(t) = \partial_{uu}^2 F(0) \beta_1'(0)^2 + 2\partial_{uv}^2 F(0) \beta_1'(0) \beta_2'(0) + \partial_{vv}^2 F(0) \beta_2'(0)^2. \quad (1.133)$$

Recalling that $\beta'(0) = d_p \varphi(v)$, we see that the right-hand-side of (1.133) depends only on $\beta'(0)$ and not on the choice of γ . Moreover, (1.133) also shows that $\text{Hess}_p f(v)$ is a quadratic form in v .

In fact the above computation shows that $\text{Hess}_p f$ corresponds to the Hessian of the local representation F of f in the following sense: The diagram

$$\begin{array}{ccc} T_p S & \xrightarrow{\text{Hess}_p f} & \mathbb{R} \\ \downarrow d_p \varphi & & \uparrow \text{Hess}_{\varphi(p)} F \\ \mathbb{R}^2 & \xrightarrow{\text{Hess}_{\varphi(p)} F} & \mathbb{R} \end{array}$$

commutes. That is we can identify $\text{Hess}_p f$ with $\text{Hess}_{\varphi(p)} F$ by means of the isomorphism $d_p \varphi: T_p S \rightarrow \mathbb{R}^2$. This immediately implies (ii) and (iii). \square

Let $H_a: \mathbb{R}^3 \rightarrow \mathbb{R}$, $H_a(x) = \langle x, a \rangle$, be the height function in the direction of $a \in \mathbb{R}^3$, $a \neq 0$. Denote by h_a the restriction of H_a to S , see Example 1.26. Recall that p is a critical point of h_a if and only if $T_p S \perp a$. For example, for $a = (0, 0, 1)$ we have the standard height function, which has 4 critical points on the torus as shown on Figure 1.21 below.

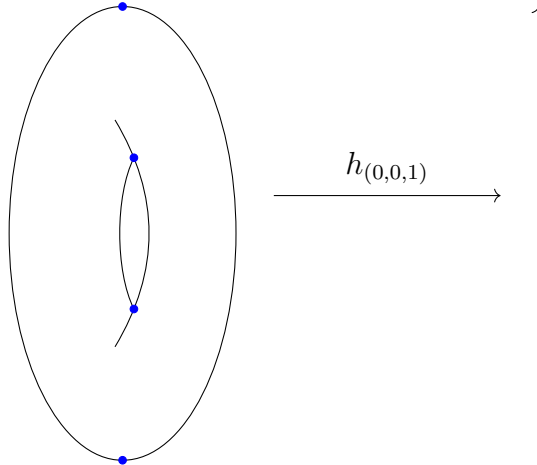


Figure 1.21: Critical points of the standard height function in the torus

Proposition 1.134. *Let n be an orientation of S . Then for any $p \in S$ we have*

$$\Pi_p = -\text{Hess}_p(h_{n(p)}).$$

Proof. Observe first that $T_p S \perp n(p)$ implies that p is a critical point of $h_{n(p)}$.

Given $v \in T_p S$, choose a curve $\gamma: (-\varepsilon, \varepsilon) \rightarrow S$ such that $\gamma(0) = p$ and $\dot{\gamma}(0) = v$. Then

$$\text{Hess}_p(h_{n(p)}) = \frac{d^2}{dt^2} \Big|_{t=0} \langle \gamma(t), n(p) \rangle = \langle \ddot{\gamma}(0), n(p) \rangle.$$

However,

$$\gamma(t) \in S \implies \dot{\gamma}(t) \in T_{\gamma(t)} S \quad \forall t \implies \langle \dot{\gamma}(t), n(\gamma(t)) \rangle = 0 \quad \forall t.$$

Differentiating the last equality in t , we obtain

$$\langle \ddot{\gamma}(0), n(p) \rangle + \langle \dot{\gamma}(0), d_p n(\dot{\gamma}(0)) \rangle = 0.$$

where the second summand equals $\Pi_p(v)$. This yields

$$\Pi_p(v) = -\langle \ddot{\gamma}(0), n(p) \rangle = -\text{Hess}_p(h_{n(p)}).$$

□

Fix $p \in S$. Without loss of generality assume that

$$p = 0 \in \mathbb{R}^3 \quad \text{and} \quad n(0) = (0, 0, 1).$$

This can be always achieved by applying a translation and a rotation in \mathbb{R}^3 .

Since the shape operator $d_0 n: T_0 S \rightarrow T_0 S$, where $T_0 S = \mathbb{R}^2$, is symmetric, $d_0 n$ has two real eigenvalues, say k_1 and k_2 . Consider the following cases:

- A) If $K(p) > 0$, then $\det(d_p n) = k_1 \cdot k_2 > 0$ so that k_1 and k_2 are either both positive or both negative. Hence, $\text{Hess}_0(h_{n(0)})$ is either positive-definite or negative definite, that is the height function in the direction $(0, 0, 1)$, which is simply $z|_S$, has a local minimum or local maximum at $p = 0$. Hence, there exists a neighbourhood U of p in S such that U lies either above or below $T_p S$ as shown on Figure 1.22 below.

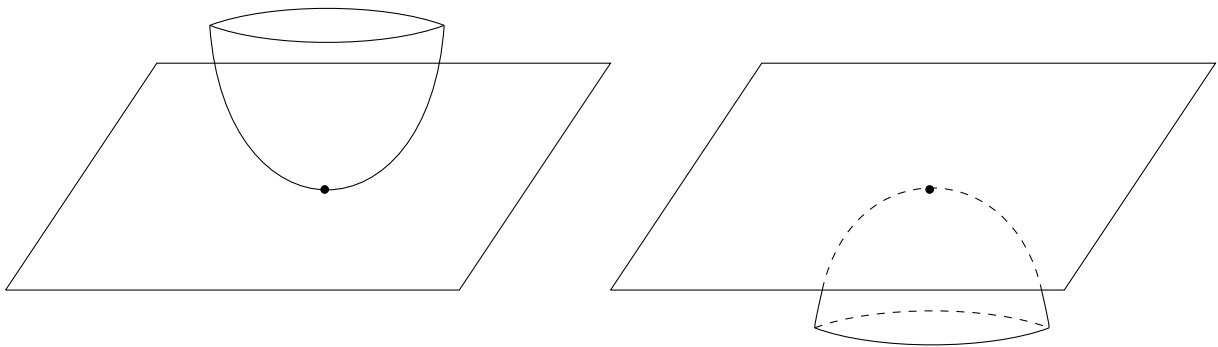


Figure 1.22: Local shape of a surface with positive Gauss curvature

- B) If $K(p) < 0$, then $z|_S$ attains both positive and negative values on each neighbourhood of p . In other words, in any neighbourhood of p there are points in S above and below $T_p S$ as shown on Figure 1.23 below.

Remark 1.135. If $K(p) = 0$, in general one cannot say anything about the position of S relative to $T_p S$.

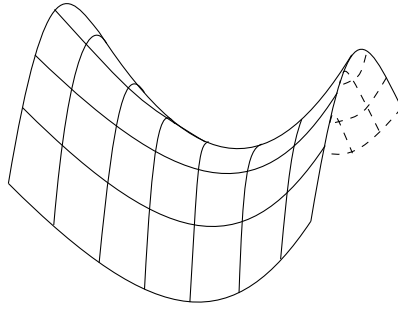


Figure 1.23: A local shape of a surface with negative curvature: the saddle surface

1.11 Surfaces of positive curvature and the Gauss–Bonnet theorem

Throughout this section, assume that S is a smooth connected surface.

Theorem 1.136 (Jordan separation theorem). *If S is closed as a subset of \mathbb{R}^3 , then $\mathbb{R}^3 \setminus S$ has exactly two connected components, whose common boundary is S .* \square

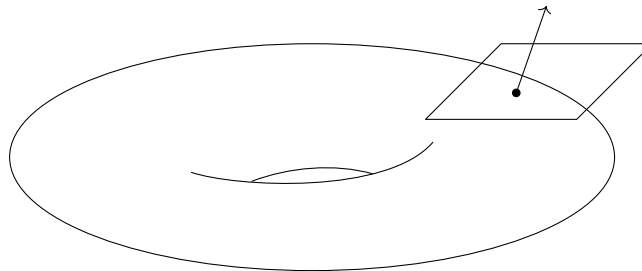
Remark 1.137. The Jordan separation theorem is a well-known result from topology. However its proof relies on certain results, which are typically not proved in a standard course in topology. Hence, we take the Jordan separation theorem as granted. An interested reader may find a proof in [MR09, Thm. 4.16].

If S is compact, then one and only one component of $\mathbb{R}^3 \setminus S$ is bounded. This bounded open domain is called *the inner domain of S* . The unbounded domain is called *the outer domain of S* .

Corollary 1.138. *Any compact surface in \mathbb{R}^3 is orientable.*

Proof. Let $S \subset \mathbb{R}^3$ be a compact surface. Without loss of generality we can assume that S is connected (otherwise, pick a connected component of S).

Pick a point $p \in S$. A unit vector n , which is normal at p , is said to be *pointing outwards*, if there exists $\varepsilon > 0$ such that $p + tn \in \Omega_{out}$ for all $t \in (0, \varepsilon)$, where Ω_{out} is the outer domain of S .



Pick a neighbourhood W of p in \mathbb{R}^3 and a smooth function $\varphi: W \rightarrow \mathbb{R}$ such that $S \cap W = \varphi^{-1}(0)$ and $\nabla\varphi(x) \neq 0$ for all $x \in W$.

Exercise 1.139. Show that $\varphi|_{\Omega_{in} \cap W} < 0$ and $\varphi|_{\Omega_{out} \cap W} > 0$ (or the other way around). In other words,

$$\Omega_{in} \cap W = \{\varphi < 0\} \quad \text{and} \quad \Omega_{out} \cap W = \{\varphi > 0\},$$

which we assume for the sake of definiteness.

Since

$$\varphi(p + t\nabla\varphi(p)) = \varphi(p) + |\nabla\varphi(p)|^2 \cdot t + O(t^2) = 0 + |\nabla\varphi(p)|^2 \cdot t + O(t^2) > 0$$

provided $t > 0$ is sufficiently small, we obtain that $\frac{\nabla\varphi(p)}{|\nabla\varphi(p)|}$ is pointing outwards for any $p \in S \cap W$. A similar argument shows that $-\frac{\nabla\varphi(p)}{|\nabla\varphi(p)|}$ is pointing inwards.

Let \widehat{W} be any other open subset of \mathbb{R}^3 and $\widehat{\varphi} \in C^\infty(\widehat{W})$ such that

$$\begin{aligned} S \cap \widehat{W} &= \widehat{\varphi}^{-1}(0), & \nabla\widehat{\varphi}(x) &\neq 0 & \forall x \in \widehat{W}, \\ \Omega_{in} \cap \widehat{W} &= \{\widehat{\varphi} < 0\} & \text{and} & & \Omega_{out} \cap \widehat{W} = \{\widehat{\varphi} > 0\}. \end{aligned}$$

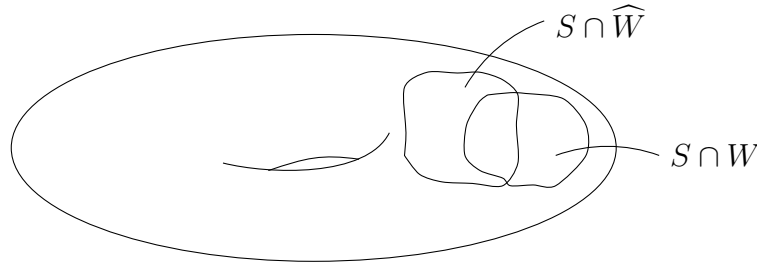
Then $\frac{\nabla\widehat{\varphi}(p)}{|\nabla\widehat{\varphi}(p)|}$ is necessarily pointing outwards. In particular,

$$\frac{\nabla\widehat{\varphi}(p)}{|\nabla\widehat{\varphi}(p)|} = \frac{\nabla\varphi(p)}{|\nabla\varphi(p)|} \quad \forall p \in W \cap \widehat{W} \cap S.$$

That is

$$n(p) := \begin{cases} \frac{\nabla\varphi(p)}{|\nabla\varphi(p)|} & \text{if } p \in S \cap W, \\ \frac{\nabla\widehat{\varphi}(p)}{|\nabla\widehat{\varphi}(p)|} & \text{if } p \in S \cap \widehat{W}, \end{cases}$$

is well-defined and smooth on $S \cap (W \cup \widehat{W})$.



Since we can cover all of S by such subsets, n is a well-defined unit normal field pointing outwards. \square

Corollary 1.140. Let S be a compact surface with positive Gauss curvature. If n is the unit normal field pointing outwards, then the second fundamental form of S with respect to n is positive-definite.

Proof. Notice first that the second fundamental form of S with respect to the outwards pointing normal field is either positive-definite or negative-definite everywhere on S , because S is connected. Thus, it suffices to find a single point p on S such that Π_p is positive-definite.

Since S is compact, there exists some $R > 0$ such that the closed ball $\bar{B}_R(0)$ of radius R centered at the origin contains S . Decreasing R if necessary, we can find a new number $R > 0$, still denoted by the same letter, such that $S \subset \bar{B}_R(0)$ and $S \cap \partial\bar{B}_R(0) \neq \emptyset$.

Let p be a point in $S \cap \partial \bar{B}_R(0)$ and γ any curve on S through p . Clearly, the function $t \mapsto \|\gamma(t)\|^2$ has a maximum at $t = 0$ which yields

$$0 = d \frac{d}{dt} \Big|_{t=0} \|\gamma(t)\|^2 = 2 \langle \dot{\gamma}(0), p \rangle.$$

Hence, $T_p S = p^\perp$. Moreover, the vector p is pointing outwards, hence $n(p) = p/|p|$. Now it is clear that the height function $h_{n(p)}$ has a maximum at p and therefore

$$\text{Hess}(h_{n(p)}) = -\Pi_p < 0 \quad \Longleftrightarrow \quad \Pi_p > 0.$$

□

Proposition 1.141. *Let $S \subset \mathbb{R}^3$ be a compact connected surface. If $K(p) > 0$ for all $p \in S$, then Ω_{in} is convex, that is*

$$x, y \in \Omega_{in} \quad \Longrightarrow \quad [x, y] \subset \Omega_{in},$$

where $[x, y]$ is the segment in \mathbb{R}^3 connecting x and y . In particular, $\bar{\Omega}_{in}$ is also convex and, moreover, if $x, y \in S$, then $]x, y[\subset \Omega_{in}$.

Proof. Assume $\Omega = \Omega_{in}$ is not convex. Consider $A := \{(x, y) \in \Omega \times \Omega \mid [x, y] \subset \Omega\}$.

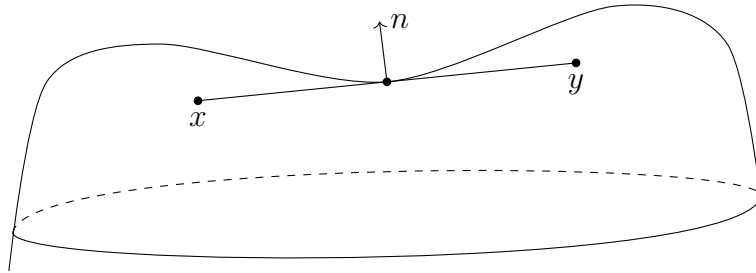
Notice that

- $A \neq \emptyset$, since $(x, x) \in A$ for all $x \in \Omega$;
- $A \neq \Omega \times \Omega$, since otherwise Ω were convex.

Then the topological boundary ∂A of $A \subset \Omega \times \Omega$ is non-empty. This means the following: there exist sequences $x_n, y_n, x'_n, y'_n \in \Omega$ such that

$$\begin{aligned} x_n, x'_n &\longrightarrow x \in \Omega, \quad \text{and} \quad y_n, y'_n \longrightarrow y \in \Omega \quad \text{such that} \\ [x_n, y_n] &\subset \Omega \quad \text{and} \quad [x'_n, y'_n] \not\subset \Omega. \end{aligned}$$

Exercise 1.142. Show that there exists $z \in [x, y] \cap \partial \Omega$, where $\partial \Omega = S$, such that $v := y - x \in T_z S$. In particular, $[x, y] \subset T_z S$.



Assuming Exercise 1.142, we proceed as follows. Let n be a unit normal vector at z pointing outwards (locally, so that a neighbourhood of z in S is located below the tangent plane). Then $\text{Hess}_z h_n < 0$ so that h_n has a strict local maximum at z . Furthermore, we can assume that

$$z = 0, \quad n = (0, 0, 1), \quad v = (1, 0, 0), \quad \text{and} \quad S = \{(u, v, f(u, v))\}$$

in a neighbourhood of the origin.

Consider the curve $\gamma: (-\varepsilon, \varepsilon) \rightarrow S$ given by $\gamma(t) = (t, 0, f(t, 0))$. Since $\gamma(t)$ lies above $(t, 0, 0)$, we must have $f(t, 0) \geq 0$ and $f(0, 0) = 0$. Hence, $t = 0$ must be a point of local minimum for the function $t \mapsto f(t, 0)$. However, this is impossible, because $h_n \circ \gamma: t \mapsto f(t, 0)$ must have a strict local maximum at $t = 0$. □

Proposition 1.143. *Let S be a surface with positive Gauss curvature. The affine tangent plane*

$$T_p^a S = \{p + v \mid v \in T_p S\}$$

intersects S at p only.

Proof. Assume $q \in T_p^a S \cap S$ and $q \neq p$. Then $]p, q[\in \Omega_{in}$ by **Proposition 1.141**. However, the positivity of the Gauss curvature implies that all points in a neighbourhood of p in $T_p^a S$ lie in Ω_{out} . This is a contradiction. \square

Theorem 1.144. *Let S be a compact connected surface. If $K(p) > 0$ for all $p \in S$, then the Gauss map $n: S \rightarrow S^2$ of S is a diffeomorphism.*

Proof. The proof of this theorem consists of the following steps.

Step 1. *The Gauss map is a local diffeomorphism.*

Since $K(p) := \det(d_p n) \neq 0$, $d_p n$ is an isomorphism. Hence, n is a local diffeomorphism by **Theorem 1.70**.

Step 2. *The Gauss map is surjective.*

Since S is compact and n is continuous, $n(S) \subset S^2$ is a compact subset. Therefore, $n(S)$ is closed, because S^2 is Hausdorff. Also, $n(S)$ is clearly non-empty.

Furthermore, **Step 1** implies that $n(S)$ is open. Since S^2 is connected, we must have $n(S) = S^2$.

Step 3. *The Gauss map is injective.*

Given $n \in S^2$ consider the height function

$$H_n: \overline{\Omega}_{in} \longrightarrow \mathbb{R}, \quad x \longmapsto \langle n, x \rangle$$

so that $H_n|_{\partial \overline{\Omega}_{in} = S} = h_n$. Notice that any point of local maximum of H_n must be on $\partial \overline{\Omega}_{in} = S$, since $\nabla H_n \neq 0$ at any interior point of $\overline{\Omega}_{in}$.

Assume H_n has two distinct points of local maxima. Denote these points by p and q . Without loss of generality we can assume $H_n(p) \geq H_n(q)$. It is convenient to consider the following two cases separately.

Case 1. $H_n(p) > H_n(q)$.

In this case for any $t > 0$ we have

$$\begin{aligned} H_n(tp + (1-t)q) &= tH_n(p) + (1-t)H_n(q) \\ &> tH_n(q) + (1-t)H_n(q) = H_n(q). \end{aligned}$$

For $t > 0$ and $t \rightarrow 0$, we have $p_t := tp + (1-t)q \rightarrow q$ and $H_n(p_t) > H_n(q)$. Thus, q cannot be a point of local maximum for H_n .

Case 2. $H_n(p) = H_n(q)$.

We have

$$\begin{aligned}
 H_n(p) = H_n(q) &\iff \langle n, p - q \rangle = 0 \\
 &\implies p - q \in T_p S \\
 &\implies p + t(p - q) \in T_p^a S \quad \forall t \in \mathbb{R} \\
 &\stackrel{t=-1}{\implies} q \in T_p^a S \\
 &\implies q = p.
 \end{aligned}$$

However, this contradicts the assumption that p and q are distinct.

Thus, H_n has at most one local maximum on $\bar{\Omega}_{in}$. Since $\bar{\Omega}_{in}$ is compact, such point must exist, so that H_n has a unique point of local maximum p , which lies on S . Then p is also a unique point of local maximum for h_n , that is a unique solution of $n(q) = n$. This finishes the proof of [Step 3](#).

The proof of this theorem now follows easily from the preceding steps. Indeed, [Steps 2](#) and [3](#) yield that the inverse of the Gauss map exists and [Step 1](#) immediately implies that n^{-1} is smooth. \square

Corollary 1.145. *Let S be any compact surface with positive Gauss curvature K . Then*

$$\int_S K = 4\pi. \quad (1.146)$$

Proof. The claim of this corollary follows from the following computation

$$\int_S K = \int_S |K| = \int_S |\det(dn)| = \int_{S^2} 1 = \text{Area}(S^2) = 4\pi,$$

where the first equality follows from $K > 0$, the second one from the definition of K , and the third one from [Theorem 1.116](#). \square

Remark 1.147. It turns out that albeit we did use the hypothesis $K > 0$ in the proof, [\(1.146\)](#) still holds for any S diffeomorphic to S^2 .

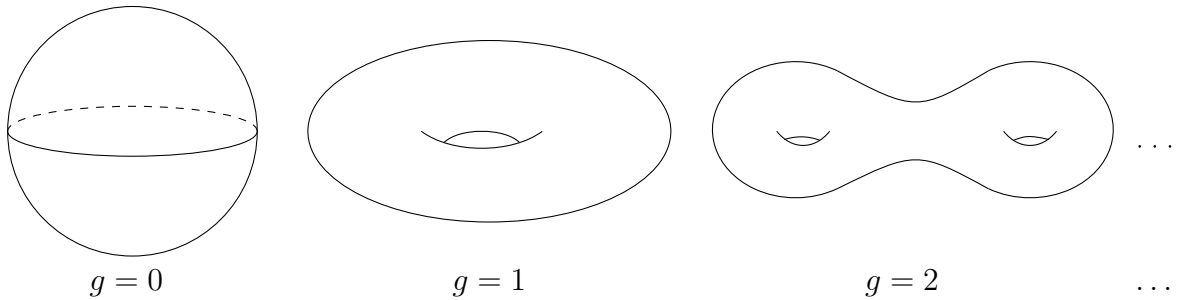


Figure 1.24: Surfaces with 0 holes (the sphere), 1 hole (the torus), and 2 holes

Even more generally, let g denote the number of "holes" of S as shown on [Fig. 1.24](#). Then we have

$$\int_S K = 4\pi(1 - g)$$

provided S is compact and orientable. This is the celebrated Gauss-Bonnet theorem.

1.11.1 A solution of Exercise 1.142

Since $[x'_n, y'_n] \not\subset \Omega$, there exists some $t_n \in [0, 1]$ such that $z'_n = t_n x'_n + (1 - t_n) y'_n \notin \Omega$. By the compactness of $[0, 1]$, there exists a subsequence t_{n_m} converging to some $t \in [0, 1]$. In fact, $t \in (0, 1)$ since the endpoint of $[x, y]$ belong to Ω by construction.

Furthermore, any neighbourhood of $z := tx + (1 - t)y$ contains points from the complement of Ω , for example z'_{n_m} for m sufficiently large. However, any neighbourhood of z contains also points from Ω , for example $z_{n_m} := t_{n_m} x_{n_m} + (1 - t_{n_m}) y_{n_m}$ provided m is sufficiently large. Hence, $z \in \partial\Omega = S$.

Assume $v \notin T_z S$. Then any neighbourhood of z in $[x, y]$ would contain points both from Ω and $\mathbb{R}^3 \setminus \Omega$. Indeed, if S is given by the equation $\varphi(p) = 0$ in a neighbourhood of z , then

$$v \notin T_z S \iff \langle \nabla \varphi(z), v \rangle \neq 0 \implies \varphi(z + tv) = 0 + t \langle \nabla \varphi(z), v \rangle + O(t^2).$$

Hence, since $\nabla \varphi(z) \neq 0$, φ takes both positive and negative values on $[z - \varepsilon v, z + \varepsilon v]$. This is impossible, since otherwise $[x_{n_m}, y_{n_m}]$ cannot be contained in Ω .

Chapter 2

Manifolds

There is a number of ways we could generalize our discussion of surfaces.

Hypersurfaces. These are subsets $S \subset \mathbb{R}^{k+1}$ admitting (smooth) parametrizations $\psi: V \rightarrow U \subset S, V \subset \mathbb{R}^k$ in a neighbourhood of each point just as in the definition of the surface. Virtually all notions and theorems about surfaces we have seen above generalize immediately to this case (together with proofs), since the condition $k = 2$ was never used in an essential way.

Embedded submanifolds. Roughly speaking these are "k-dimensional surfaces in \mathbb{R}^{k+l} ". More formally, we could call $S \subset \mathbb{R}^{k+l}$ a k-dimensional submanifold, if S admits parametrizations $\psi: V \rightarrow U \subset S$, where $V \subset \mathbb{R}^k$ is open and $D\psi$ is injective at each point. Most of the statements about surfaces we have seen above generalize to this case too (and rather trivially) except the very last section involving the Gauss map. It generalizes too, however, this requires some extra work and, more importantly, not all statements made for surfaces hold true in this case.

An interested reader may find further details for example in [Tho79] or [GP10]. However, even higher degree of abstraction is required for applications. Therefore, we consider below what is known as *abstract manifolds* skipping the above intermediate steps. Abstract manifolds are basically "surfaces", which are not necessarily contained in any ambient Euclidean space.

2.1 Abstract manifolds

Definition 2.1. A Hausdorff topological space M is said to be a topological manifold of dimension $k \in \mathbb{N}_0$, if M is locally homeomorphic to \mathbb{R}^k .

To explain: for all $m \in M$ there exists a neighbourhood $U \subset M$ and a homeomorphism $\varphi: U \rightarrow V \subset \mathbb{R}^k$, where V is open. A pair (U, φ) is called a *chart* on M .

Example 2.2. Any surface is a topological manifold of dimension $k = 2$.

Example 2.3. S^k is a topological manifold of dimension k . This can be seen by covering S^k by two charts just in the case $k = 2$.

Example 2.4 (A non-example). The union of two intersecting lines, which can be described more explicitly as $\{(x, y) \in \mathbb{R}^2 \mid x^2 = y^2\}$, is not a topological manifold. This should be compared with Examples 1.12 and 1.18.

Definition 2.5 (Smooth manifold).

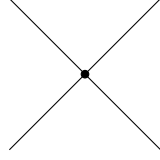


Figure 2.1: The union of two intersecting lines is not a manifold

- A collection $\mathcal{U} = \{(U_\alpha, \varphi_\alpha) \mid \alpha \in A\}$ of charts on M is called a C^0 -atlas, if

$$\bigcup_{\alpha \in A} U_\alpha = M.$$

- A C^0 -atlas is called smooth, if each coordinate transformation

$$\theta_{\alpha\beta} := \varphi_\alpha \circ \varphi_\beta^{-1} : \varphi_\beta(U_\alpha \cap U_\beta) \longrightarrow \varphi_\alpha(U_\alpha \cap U_\beta)$$

is smooth, where $\varphi_\beta(U_\alpha \cap U_\beta) \subset \mathbb{R}^k$ and $\varphi_\alpha(U_\alpha \cap U_\beta) \subset \mathbb{R}^k$.

- A smooth manifold is a topological manifold equipped with a smooth atlas.

Example 2.6.

- 1) \mathbb{R}^k with a single chart $(\mathbb{R}^k, \text{id})$ is a smooth manifold. More generally, any open subset of \mathbb{R}^k is a smooth manifold.
- 2) Any smooth surface is a smooth manifold of dimension $n = 2$.
- 3) S^k is a smooth manifold of dimension k .
- 4) The real projective space is defined as follows:

$$\begin{aligned} \mathbb{RP}^k &= \text{the set of all lines in } \mathbb{R}^{k+1} \text{ through the origin;} \\ &= \mathbb{R}^{k+1} \setminus \{0\} / \sim, \quad (x_0, \dots, x_k) \sim (\lambda x_0, \dots, \lambda x_k) \text{ for some } \lambda \in \mathbb{R} \setminus \{0\}; \\ &= S^k / \sim, \quad x \sim -x. \end{aligned}$$

Define the topology on \mathbb{RP}^k as the quotient topology of $\mathbb{R}^{k+1} \setminus \{0\}$, that is $U \subset \mathbb{RP}^k$ is declared to be open if and only if $\pi^{-1}(U) \subset \mathbb{R}^{k+1} \setminus \{0\}$ is open, where $\pi : \mathbb{R}^{k+1} \setminus \{0\} \rightarrow \mathbb{RP}^k$ is the quotient map.

For example, the reader should be able to show following Fig. 2.2 that \mathbb{RP}^1 is homeomorphic to S^1 .

Define

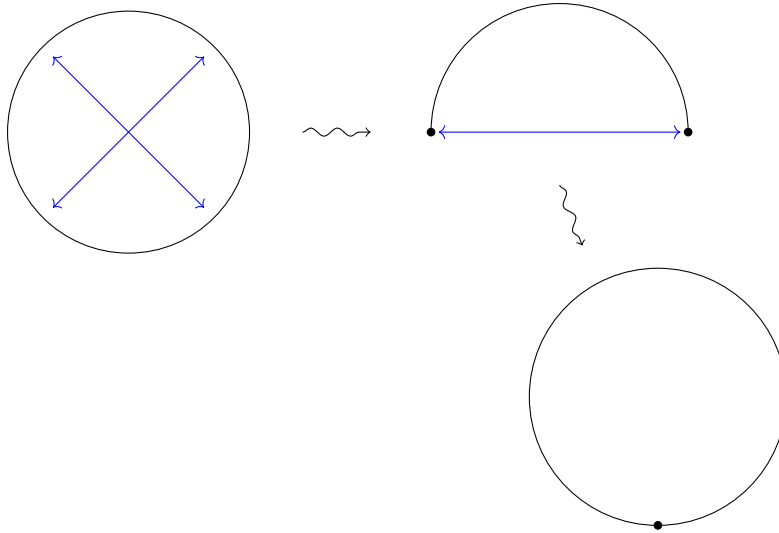
$$U_j := \{[x_0 : \dots : x_k] \in \mathbb{RP}^k \mid x_j \neq 0\} \quad j = 0, \dots, k.$$

U_j is open, since

$$\pi^{-1}(U_j) = \{(x_0, \dots, x_k) \in \mathbb{R}^{k+1} \setminus \{0\} \mid x_j \neq 0\}$$

is open. Furthermore, consider the map $\varphi_j : U_j \rightarrow \mathbb{R}^k$

$$\varphi_j([x]) = \left(\frac{x_0}{x_j}, \dots, \frac{x_{j-1}}{x_j}, \frac{x_{j+1}}{x_j}, \dots, \frac{x_k}{x_j} \right).$$


 Figure 2.2: A homeomorphism between \mathbb{RP}^1 and S^1

Exercise 2.7. Show that φ_j is continuous. (Hint: If X is any topological space, a map $f: \mathbb{RP}^k \rightarrow X$ is continuous if and only if $f \circ \pi$ is continuous.)

Then

$$\psi_j: \mathbb{R}^n \rightarrow U_j, \quad \psi_j(y_0, \dots, y_{k-1}) = [y_0: \dots: y_{j-1}: 1: y_j: \dots: y_{k-1}]$$

is the inverse of φ_j . In particular, φ_j is a homeomorphism. Thus,

$$\mathcal{U} = \{(U_j, \varphi_j) \mid j = 0, \dots, k\}$$

is a C^0 -atlas on \mathbb{RP}^k .

Consider the coordinate transformation $\theta_{01} = \varphi_0 \circ \varphi_1^{-1} = \varphi_0 \circ \psi_1$, which is given by

$$\theta_{01}(y_0, \dots, y_{k-1}) = \varphi_0([y_0: 1: y_1: \dots: y_{k-1}]) = \left(\frac{1}{y_0}, \frac{y_1}{y_0}, \frac{y_2}{y_0}, \dots, \frac{y_{k-1}}{y_0} \right)$$

and is smooth on $\{y \in \mathbb{R}^k \mid y_0 \neq 0\} = \varphi_0(U_0 \cap U_1)$. A similar argument yields that each $\theta_{ij} = \varphi_i \circ \varphi_j^{-1}$ is smooth. Thus, \mathcal{U} is in fact a smooth atlas.

Remark 2.8. For $k = 2$ we obtain a smooth manifold of dimension 2, however it turns out that \mathbb{RP}^2 cannot be represented as a surface in \mathbb{R}^3 . We would have discovered this manifold if we would consider non-orientable surfaces more carefully. Indeed, the Gauss map of a non-orientable surface $S \subset \mathbb{R}^3$ is naturally defined as a map

$$S \ni p \mapsto (T_p S)^\perp \in \mathbb{RP}^2.$$

- 5) **Products:** If M and N are smooth manifolds of dimensions k and l respectively, then $M \times N$ is a smooth manifold of dimension $k + l$. Indeed, if $\mathcal{U} = \{(U_\alpha, \varphi_\alpha) \mid \alpha \in A\}$ is a smooth atlas on M and $\mathcal{V} = \{(V_\beta, \xi_\beta) \mid \beta \in B\}$ is a smooth atlas on N , that

$$\mathcal{W} := \{(U_\alpha \times V_\beta, \varphi_\alpha \times \xi_\beta) \mid \alpha \in A, \beta \in B\}$$

is a smooth atlas on $M \times N$.

Exercise 2.9. Find the coordinate transformations for the atlas \mathcal{W} and show that these are smooth indeed.

In particular,

- (i) $\mathbb{T}^k = S^1 \times \dots \times S^1$ is a smooth manifold of dimension k ;
- (ii) the cylinder $\mathbb{R} \times S^1$ is a smooth manifold of dimension 2.

A smooth atlas does not need to be unique. For example, on S^2 we can choose

$$\mathcal{U} = \{ (S^2 \setminus \{N\}, \varphi_N), (S^2 \setminus \{S\}, \varphi_S) \}$$

or the atlas consisting of 6 hemispheres. However, we have seen that the resulting notions (e.g. the space of smooth functions on S^2) do not depend on this choice. The crucial point is that the charts of these two atlases are smoothly compatible, that is the corresponding coordinate transformations are smooth. This motivates the following definition.

Definition 2.10. Two atlases $\mathcal{U} = \{(U_\alpha, \varphi_\alpha) \mid \alpha \in A\}$ and $\mathcal{V} = \{(V_\beta, \xi_\beta) \mid \beta \in B\}$ on the same topological space M are said to be equivalent if $\mathcal{U} \cup \mathcal{V}$ is also a smooth atlas, that is if

$$\xi_\beta \circ \varphi_\alpha^{-1} \quad \text{and} \quad \varphi_\alpha \circ \xi_\beta^{-1}$$

are smooth for all $\alpha \in A$ and for all $\beta \in B$.

Definition 2.11. A *smooth structure* is an equivalence class of atlases.

In the sequel we shall feel free to replace an atlas by an equivalent one.

2.2 Smooth maps

Let (M, \mathcal{U}) be a smooth manifold.

Definition 2.12. A function $f: M \rightarrow \mathbb{R}$ is called smooth, if for all $\alpha \in A$ the coordinate representation

$$F_\alpha := f \circ \varphi_\alpha^{-1}: \mathbb{R}^k \longrightarrow \mathbb{R}$$

with respect to $(U_\alpha, \varphi_\alpha)$ is smooth.

Just as in the case of surfaces each F_α is defined on an open subset of \mathbb{R}^k , namely $\varphi_\alpha(U_\alpha)$. This should be clear by now and will not be mentioned explicitly below unless really necessary.

Exercise 2.13. Let $f: M \rightarrow \mathbb{R}$ be a function. If $\mathcal{U} \sim \mathcal{V}$, show that f is smooth with respect to \mathcal{U} if and only if f is smooth with respect to \mathcal{V} .

Proposition 2.14. The set $C^\infty(M)$ of all smooth functions on a smooth manifold is an algebra, that is

$$\left. \begin{array}{l} f, g \in C^\infty(M) \\ \lambda, \mu \in \mathbb{R} \end{array} \right\} \implies \lambda f + \mu g \in C^\infty(M);$$

$$f, g \in C^\infty(M) \implies f \cdot g \in C^\infty(M).$$

The proof of this proposition is similar to the proof of [Proposition 1.28](#) and is left as an exercise to the reader.

More generally, let (M, \mathcal{U}) and (N, \mathcal{V}) be two smooth manifolds of dimensions k and l respectively.

Definition 2.15. A map $f: M \rightarrow N$ is said to be smooth, if each coordinate representation

$$\xi_\beta \circ f \circ \varphi_\alpha^{-1}: \mathbb{R}^k \longrightarrow \mathbb{R}^l$$

is smooth.

Proposition 2.16.

$$\left. \begin{array}{l} f \in C^\infty(M; N) \\ g \in C^\infty(N; L) \end{array} \right\} \implies g \circ f \in C^\infty(M; L).$$

Again, the proof of this proposition is a verbatim repetition of the proof of [Theorem 1.39](#).

Also, just in the case of surfaces, we have the notions of a diffeomorphism and a local diffeomorphism.

2.3 The tangent space

If M is an abstract manifold and $\gamma: (-\varepsilon, \varepsilon) \rightarrow M$ is a smooth curve, then $\dot{\gamma}(0)$ does not make sense in any obvious way. Hence, our definition of the tangent space does not immediately generalize to the present setting.

To come up with a suitable generalization, observe the following: $v \in \mathbb{R}^k$ is the tangent vector of a curve $\gamma: (-\varepsilon, \varepsilon) \rightarrow \mathbb{R}^k, \gamma(0) = p$, if and only if

$$\gamma(t) = p + v \cdot t + o(t) \quad \text{as } t \longrightarrow 0.$$

Hence we may consider the following equivalence relation: two smooth curves $\gamma_1, \gamma_2: (-\varepsilon, \varepsilon) \rightarrow \mathbb{R}^k$ such that $\gamma_1(0) = p = \gamma_2(0)$, are said to be *equivalent* if $\gamma_1(t) - \gamma_2(t) = o(t)$.

Our observation above yields immediately the following.

Proposition 2.17. $\gamma_1 \sim \gamma_2 \iff \dot{\gamma}_1(0) = \dot{\gamma}_2(0)$. □

Hence, we may identify \mathbb{R}^n , which is thought of as a tangent space of \mathbb{R}^n at p , with the set of equivalence classes of curves through p . Explicitly, the map $\gamma \mapsto \dot{\gamma}(0)$ induces a bijection

$$\{\gamma \mid \gamma(0) = p\} / \sim \longrightarrow \mathbb{R}^n.$$

Thus, we may think of tangent vectors at a given point p as classes of curves through p . This approach generalized to manifolds as follows.

Definition 2.18. Let M be a smooth manifold of dimension k . Pick a point $m \in M$. Two smooth curves $\gamma_1, \gamma_2: (-\varepsilon, \varepsilon) \rightarrow M$ such that $\gamma_1(0) = m = \gamma_2(0)$ are said to be equivalent, if for any chart (U, φ) such that $m \in U$ we have

$$\varphi \circ \gamma_1 \sim_{\mathbb{R}^k} \varphi \circ \gamma_2 \iff \varphi \circ \gamma_1(t) - \varphi \circ \gamma_2(t) = o(t). \quad (2.19)$$

An equivalence class of curves is called a tangent vector at the point m .

Lemma 2.20. If (2.19) holds for some chart (U, φ) containing m , then (2.19) holds for any chart containing m .

Proof. Let $(\widehat{U}, \widehat{\varphi})$ be any other chart such that $m \in \widehat{U}$. Denote $p := \varphi(m)$. Then

$$\begin{aligned} \widehat{\varphi} \circ \gamma_1(t) - \widehat{\varphi} \circ \gamma_2(t) &= \underbrace{\widehat{\varphi} \circ \varphi^{-1}}_{\theta} \circ \underbrace{\varphi \circ \gamma_1}_{\beta_1}(t) - \underbrace{\widehat{\varphi} \circ \varphi^{-1}}_{\theta} \circ \underbrace{\varphi \circ \gamma_2}_{\beta_2}(t) \\ &= \theta \circ \beta_1(t) - \theta \circ \beta_2(t) \end{aligned}$$

Since θ is smooth, θ is Lipschitz, that is there exists $L > 0$ such that

$$|\theta(x) - \theta(y)| \leq L|x - y| \quad \forall x, y \in B_\delta(p),$$

where $\delta > 0$. Hence,

$$|\theta \circ \beta_1(t) - \theta \circ \beta_2(t)| \leq L|\beta_1(t) - \beta_2(t)| = o(t),$$

because $\beta_1(t) - \beta_2(t) = o(t)$. □

Definition 2.21. The set $T_m M := \{[\gamma] \mid \gamma \text{ is a smooth curve through } m\}$ is called the tangent space of M at m .

Exercise 2.22. Let V be a vector space and $\Phi: X \rightarrow V$ a bijective map, where X is an arbitrary set. Then there is a unique structure of a vector space on X such that Φ is an isomorphism. In fact, we have

$$\lambda \cdot x = \Phi^{-1}(\lambda \cdot \Phi(x)) \quad \text{and} \quad x_1 + x_2 = \Phi^{-1}(\Phi(x_1) + \Phi(x_2)).$$

Proposition 2.23. $T_m M$ is a vector space of dimension k .

Proof. Pick a chart (U, φ) containing m and suppose $\varphi(m) = 0 \in \mathbb{R}^k$. Consider the map

$$\{\gamma \mid \gamma(0) = m\} \longrightarrow \mathbb{R}^k, \quad \gamma \longmapsto \left. \frac{d}{dt} \right|_{t=0} \varphi \circ \gamma(t), \quad (2.24)$$

where γ is the smooth curve in M and, hence, $\varphi \circ \gamma(t)$ is the curve in \mathbb{R}^k .

Exercise 2.25. Show that this map is surjective.

If $\gamma_1 \sim \gamma_2$, then $\beta_1 := \varphi \circ \gamma_1 \sim \beta_2 := \varphi \circ \gamma_2$ so that $\dot{\beta}_1(0) = \dot{\beta}_2(0)$. Therefore, (2.24) induces a surjective map $\varphi_*: T_m M \rightarrow \mathbb{R}^k$, which is in fact bijective, since

$$\varphi_*[\gamma_1] = \varphi_*[\gamma_2] \iff \beta_1 \sim \beta_2 \iff \dot{\beta}_1(0) = \dot{\beta}_2(0).$$

Thus, we define the structure of a vector space on $T_m M$ so that φ_* is a linear isomorphism.

Exercise 2.26. Show that the following holds:

- (i) If $\gamma \in T_m M$ and $\lambda \in \mathbb{R}$, then $\lambda[\gamma] = [\gamma(\lambda \cdot)]$;
- (ii) For two curves γ_1, γ_2 through m define

$$\gamma(t) := \varphi^{-1}(\beta_1(t) + \beta_2(t)),$$

where $\beta_j := \varphi \circ \gamma_j$. Show that γ is a smooth curve through m and

$$[\gamma_1] + [\gamma_2] = [\gamma].$$

We still need to show that the structure of the vector space on $T_m M$ does not depend on the choice of the chart (U, φ) . To this end, let $(\hat{U}, \hat{\varphi})$ be another chart such that $m \in \hat{U}$. Let

$$\hat{\varphi}_*: T_m M \longrightarrow \mathbb{R}^k, \quad [\gamma] \longmapsto \left. \frac{d}{dt} \right|_{t=0} \hat{\varphi} \circ \gamma(t)$$

be the corresponding map. Denoting temporarily by $+_{\varphi}$ the addition obtained via φ_* , we obtain

$$[\gamma] = [\gamma_1] +_{\varphi} [\gamma_2] \iff \dot{\beta}(0) = \dot{\beta}_1(0) + \dot{\beta}_2(0),$$

where $\beta(t) = \varphi \circ \gamma(t)$ and $\beta_j(t) = \varphi \circ \gamma_j(t)$. Denote $\hat{\beta}(t) = \hat{\varphi} \circ \gamma(t)$ and $\hat{\beta}_j(t) = \hat{\varphi} \circ \gamma_j(t)$.

Then

$$\hat{\beta} = \hat{\varphi} \circ \gamma = \hat{\varphi} \circ \varphi^{-1} \circ \varphi \circ \gamma = \theta \circ \beta \implies \dot{\hat{\beta}}(0) = D_p \theta(\dot{\beta}(0)).$$

Similarly, we have $\dot{\hat{\beta}}_j(0) = D_p \theta(\dot{\beta}_j(0))$.

Since $D_p \theta$ is a linear map, we have

$$\dot{\hat{\beta}}(0) = D_p \theta(\dot{\beta}_1(0) + \dot{\beta}_2(0)) = D_p \theta(\dot{\beta}_1(0)) + D_p \theta(\dot{\beta}_2(0)) = \dot{\hat{\beta}}_1(0) + \dot{\hat{\beta}}_2(0).$$

Hence, if $[\gamma] = [\gamma_1] +_{\varphi} [\gamma_2]$, then also $[\gamma] = [\gamma_1] +_{\hat{\varphi}} [\gamma_2]$.

The fact that the multiplication with scalars is independent of the choice of a chart follows immediately from Exercise 2.26, (i). \square

Notice that the origin in $T_m M$ is represented by the constant curve $\gamma(t) = m$ (or any other curve equivalent to this one).

Remark 2.27. The proof of Proposition 2.23 implies the following. Let (U, φ) be a chart on M and $m \in U$. Denote $\varphi(m) = p \in \mathbb{R}^k$ and define $\gamma_j: (-\varepsilon, \varepsilon) \rightarrow U$, $\gamma_j(0) = m$ by

$$\varphi \circ \gamma_j(t) = p + (0, \dots, 0, t, 0, \dots, 0).$$

where the non-trivial component is at the j^{th} place. Then

$$e_{\varphi} := ([\gamma_1], \dots, [\gamma_k]) \quad (2.28)$$

is a basis of $T_m M$.

At this point for a surface $S \subset \mathbb{R}^3$ we have two definitions of the tangent space. The following proposition shows that these are equivalent.

Proposition 2.29. *If $S \subset \mathbb{R}^3$ is a smooth surface, then $T_p S$ in the sense of Definition 2.21 is naturally isomorphic to the tangent plane of S .*

Proof. Denote temporarily the tangent plane of S at p in the sense of Definition 2.21 by E_p . Consider the map

$$T_p S \longrightarrow E_p, \quad [\gamma] \longmapsto \dot{\gamma}(0). \quad (2.30)$$

Exercise 2.31. Check that this map is well-defined, that is independent of the choice of the representative.

This map is linear. Indeed, if ψ is a parametrization at p such that $\psi(0) = p$ and

$$\gamma_1 := \psi \circ \beta_1, \quad \gamma_2 := \psi \circ \beta_2$$

then $[\gamma_1] + [\gamma_2]$ is represented by the curve $t \mapsto \psi(\beta_1(t) + \beta_2(t)) = \gamma(t)$. Hence

$$\dot{\gamma}(0) = D_0 \psi(\dot{\beta}_1(0) + \dot{\beta}_2(0)) = D_0 \psi(\dot{\beta}_1(0)) + D_0 \psi(\dot{\beta}_2(0)) = \dot{\gamma}_1(0) + \dot{\gamma}_2(0).$$

That is $[\gamma_1] + [\gamma_2] \in T_p S$ is mapped onto $\dot{\gamma}_1(0) + \dot{\gamma}_2(0)$.

Since $\lambda[\gamma] = [\gamma(\lambda \cdot)] \mapsto \left. \frac{d}{dt} \right|_{t=0} \gamma(\lambda t) = \lambda \dot{\gamma}(0)$, we see that (2.30) is linear. Since this map is clearly surjective and $T_p S$ and E_p have equal dimension, (2.30) is an isomorphism. \square

2.4 The differential of a smooth map

Let $f: M^k \rightarrow N^l$ be a smooth map.

Definition 2.32. For $m \in M$ the map

$$d_m f: T_m M \longrightarrow T_{f(m)} N, \quad [\gamma] \longmapsto [f \circ \gamma]$$

is called the differential of f at m .

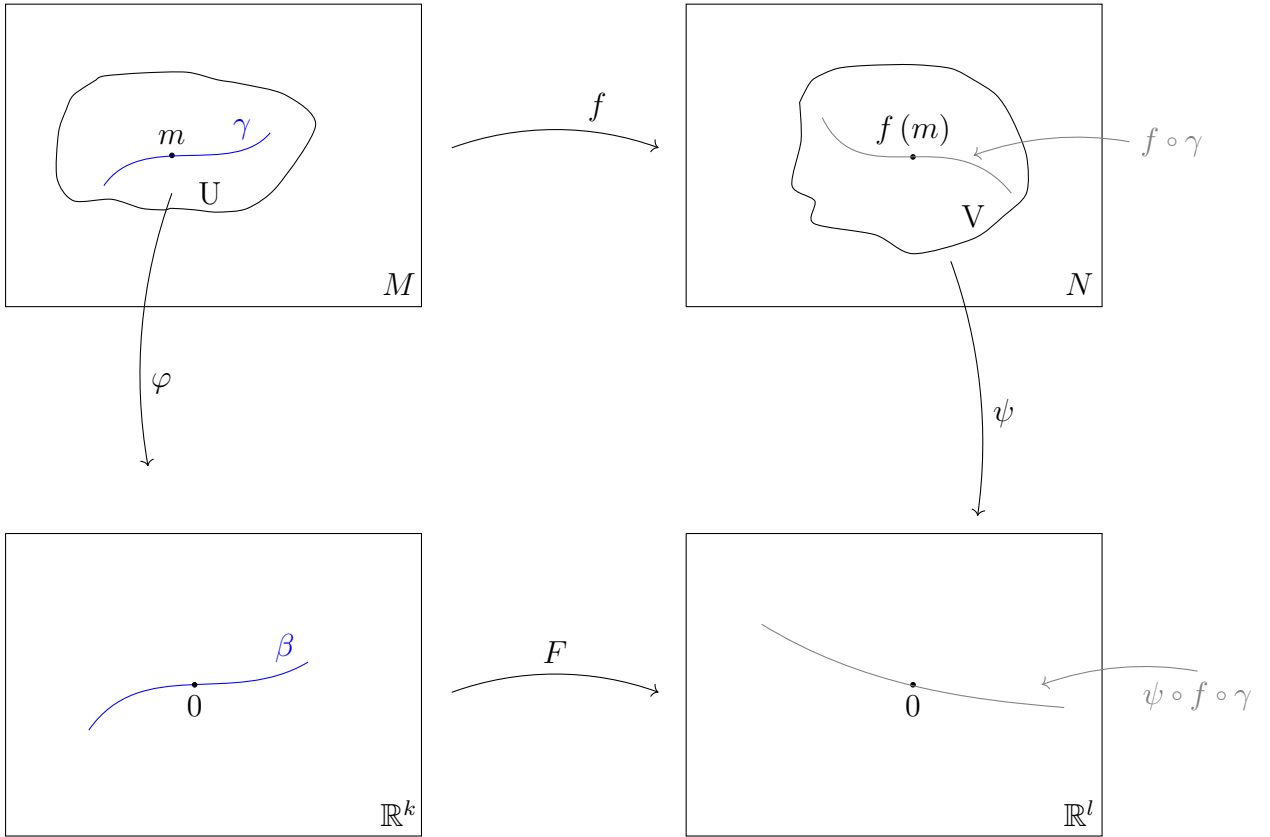
Proposition 2.33. *The differential is a linear map. If (U, φ) is a chart on M such that $m \in U$ and (V, ψ) is a chart on N such that $f(m) \in V$, then $d_m f$ is represented by the Jacobi matrix of $F := \psi \circ f \circ \varphi^{-1}$ with respect to the bases e_φ and e_ψ , that is*

$$d_m f(e_\varphi) = e_\psi \cdot D_{\varphi(m)} F.$$

Proof. Assume for simplicity

$$\varphi(m) = 0 \in \mathbb{R}^k \quad \text{and} \quad \psi(f(m)) = 0 \in \mathbb{R}^l$$

For $\gamma: (-\varepsilon, \varepsilon) \rightarrow M$ such that $\gamma(0) = m$, denote $\beta := \varphi \circ \gamma: (-\varepsilon, \varepsilon) \rightarrow \mathbb{R}^k$.



We have

$$f \circ \gamma = f \circ \varphi^{-1} \circ \varphi \circ \gamma = f \circ \varphi^{-1} \circ \beta.$$

This yields

$$\psi_* [f \circ \gamma] = \frac{d}{dt} \Big|_{t=0} \left(\underbrace{\psi \circ f \circ \varphi^{-1}}_F \circ \beta(t) \right) = \frac{d}{dt} \Big|_{t=0} (F \circ \beta(t)) = D_0 F(\dot{\beta}(0)).$$

By noticing the following $\dot{\beta}(0) = \frac{d}{dt}\Big|_{t=0} \varphi \circ \gamma(t) = \varphi_*[\gamma]$, we obtain

$$\psi_* d_m f([\gamma]) = D_0 F \circ \varphi_*[\gamma] \quad \forall \gamma \quad \Longleftrightarrow \quad d_m f = \psi_*^{-1} \circ D_0 F \circ \varphi_*.$$

Since ψ_*^{-1} , $D_0 F$, and φ_* are linear, we obtain that $d_m f$ is linear too.

Furthermore, by the definition of e_φ , see (2.28), we have $\dot{\beta}_j(0) = (0, \dots, 0, 1, 0, \dots, 0) = e_j$. Hence,

$$\psi_* d_m f([\gamma_j]) = D_0 F(e_j) = \sum_{i=1}^l \frac{\partial F_i}{\partial x_j} \hat{e}_i,$$

where $(\hat{e}_1, \dots, \hat{e}_l)$ is a standard basis of \mathbb{R}^l . Hence,

$$\begin{aligned} d_m f[\gamma_j] &= \psi_*^{-1} \left(\sum_{i=1}^l \frac{\partial F_i}{\partial x_j} \hat{e}_i \right) = \sum_{i=1}^l \frac{\partial F_i}{\partial x_j} \underbrace{\psi_*^{-1}(\hat{e}_i)}_{[\hat{\gamma}_i]} \implies \\ (d_m f[\gamma_1], \dots, d_m f[\gamma_k]) &= ([\hat{\gamma}_1], \dots, [\hat{\gamma}_l]) \begin{pmatrix} \frac{\partial F_1}{\partial x_1} & \dots & \frac{\partial F_1}{\partial x_k} \\ \dots & \dots & \dots \\ \frac{\partial F_l}{\partial x_1} & \dots & \frac{\partial F_l}{\partial x_k} \end{pmatrix}, \end{aligned}$$

where $[\hat{\gamma}_i]$ is the i^{th} element of e_ψ . This finishes the proof of this proposition. \square

Proposition 2.34. *For any smooth manifolds M, N, K and any $f \in C^\infty(M; N)$ and $g \in C^\infty(N; K)$ we have*

$$d_m(g \circ f) = d_{f(m)}g \circ d_m f.$$

Proof. For any $[\gamma] \in T_m M$ we have

$$d_m(g \circ f)[\gamma] = [g \circ f \circ \gamma] = [g \circ (f \circ \gamma)] = d_{f(m)}g([f \circ \gamma]) = d_{f(m)}g(d_m f[\gamma]),$$

where the third and fourth equalities follow from the definitions of $d_{f(m)}g$ and $d_m f$ respectively. \square

Corollary 2.35. *If $f: M \rightarrow N$ is a diffeomorphism, then $d_m f: T_m M \rightarrow T_{f(m)} N$ is an isomorphism. Conversely, if $d_m f$ is an isomorphism, then f is a local diffeomorphism at m . \square*

2.5 Submanifolds

Think of \mathbb{R}^{k+l} as $\mathbb{R}^k \times \mathbb{R}^l$, where $k \geq 1, l \geq 1$. We have the maps

$$\begin{aligned} \iota_2: \mathbb{R}^l &\longrightarrow \mathbb{R}^{k+l}, & \iota_2(y) &= (0, y) \\ \pi_2: \mathbb{R}^{k+l} &\longrightarrow \mathbb{R}^l, & \pi_2(x, y) &= y \end{aligned}$$

where $x \in \mathbb{R}^k$ and $y \in \mathbb{R}^l$.

Let $f: \mathbb{R}^{k+l} \rightarrow \mathbb{R}^\ell$ be a smooth map, which is defined on some neighbourhood U of the origin. For any point $p_0 = (x_0, y_0) \in U$ we have the following linear map

$$D_y f(p_0): \mathbb{R}^\ell \xrightarrow{\iota_2} \mathbb{R}^{k+l} \xrightarrow{D_{p_0} f} \mathbb{R}^\ell. \quad (2.36)$$

For example, if $k = \ell = 1$, we have $D_y f(p_0) = \frac{\partial f}{\partial y}(p_0)$. For this reason, we call (2.36) the *partial derivative* of f with respect to y (at the point p_0).

To simplify the notations it is convenient to assume that p_0 is the origin and $f(0) = 0$, although this is immaterial.

Theorem 2.37. *If $D_y f(0)$ is an isomorphism, then there exists a smooth map $\theta: \mathbb{R}^{k+\ell} \rightarrow \mathbb{R}^{k+\ell}$, which is a local diffeomorphism at 0, such that $\theta(0) = 0$ and*

$$f \circ \theta = \pi_2$$

holds in a neighbourhood of the origin.

Proof. Define

$$g: \mathbb{R}^{k+\ell} \rightarrow \mathbb{R}^{k+\ell} \quad \text{by} \quad g(x, y) := (x, f(x, y)). \quad (2.38)$$

Then for the differential of g we have

$$Dg(0) = \begin{pmatrix} id_{\mathbb{R}^k} & 0 \\ D_x f(0) & D_y f(0) \end{pmatrix} \iff Dg(0) \begin{pmatrix} u \\ v \end{pmatrix} = \begin{pmatrix} u \\ D_x f(0)u + D_y f(0)v \end{pmatrix},$$

where $u \in \mathbb{R}^k$ and $v \in \mathbb{R}^\ell$.

If $(u, v) \in \ker Dg(0)$, then $u = 0$ and $D_y f(0)v = 0$. However, $D_y f$ is an isomorphism by assumption of this theorem, so that $v = 0$. Therefore, $Dg(0)$ is injective and, hence, an isomorphism.

By the inverse map theorem, there is a local inverse $\theta: \mathbb{R}^{k+\ell} \rightarrow \mathbb{R}^{k+\ell}$ to g , that is in a neighbourhood of the origin we have

$$g \circ \theta = id_{\mathbb{R}^{k+\ell}} \implies \pi_2 = \pi_2 \circ id_{\mathbb{R}^{k+\ell}} = \pi_2 \circ g \circ \theta = f \circ \theta.$$

Thus, the theorem is proved. \square

Corollary 2.39 (The implicit function theorem). *Suppose that the assumptions of [Theorem 2.37](#) hold. Then there exists a neighbourhood V_1 of $0 \in \mathbb{R}^k$, a neighbourhood V_2 of $0 \in \mathbb{R}^\ell$, and a unique smooth map $h: V_1 \rightarrow V_2$ such that*

$$f(x, y) = 0 \iff y = h(x) \quad (2.40)$$

whenever $(x, y) \in V_1 \times V_2$.

Furthermore, denoting $W := f^{-1}(0) \cap V_1 \times V_2$, the map

$$\psi := \pi_1|_W: W \rightarrow V_1, \quad (x, y) \mapsto x$$

is a homeomorphism, that is (W, ψ) is a chart on $f^{-1}(0) \cap U$.

Proof. Let $\theta: U \rightarrow \theta(U)$ be the local diffeomorphism provided by [Theorem 2.37](#). Pick any open subsets V_1 and V_2 as in the formulation of the theorem such that $V_1 \times V_2 \subset U$. For $x \in V_1$ define $h(x) := \pi_2 \circ \theta(x, 0)$. Furthermore, for $(x, y) \in V_1 \times V_2$, denote

$$(z, w) := \theta^{-1}(x, y) = g(x, y) = (x, f(x, y)).$$

Here we used the fact, that g , which is given by (2.38), is the inverse of θ . Then

$$\begin{aligned} f(x, y) = 0 &\implies 0 = f \circ \theta \circ \theta^{-1}(x, y) = f \circ \theta(z, w) = w \\ &\implies (z, 0) = (x, f(x, y)). \end{aligned}$$

Hence, $z = x$ and $(x, y) = \theta(x, 0)$, which yields in turn $y = h(x)$.

Furthermore, for any $x \in V_1$ we have

$$(x, 0) = g \circ \theta(x, 0) = g(\pi_1 \circ \theta(x, 0), \pi_2 \circ \theta(x, 0))$$

From the definition of g we obtain $x = \pi_1 \circ \theta(x, 0)$ and, hence, $0 = f(x, h(x))$.

To show the uniqueness, notice that

$$\begin{aligned} f(x, h(x)) = 0 &\implies g(x, h(x)) = (x, f(x, h(x))) = (x, 0) \\ f(x, \hat{h}(x)) = 0 &\implies g(x, \hat{h}(x)) = (x, 0). \end{aligned}$$

Since g is a local diffeomorphism, we obtain $h(x) = \hat{h}(x)$ provided x is sufficiently close to the origin.

Furthermore, notice that the map

$$V_1 \rightarrow W, \quad x \mapsto (x, h(x))$$

is a continuous inverse of ψ . Hence, ψ is a homeomorphism. \square

The hypothesis of **Corollary 2.39** implies that the differential of f at the origin is *surjective*. In fact, the surjectivity of the differential is decisive in **Theorem 2.37** and **Corollary 2.39**, whereas the hypothesis that $D_y f(0)$ is an isomorphism can be achieved by a linear change of coordinates, see the proof of ?? below for some details.

Definition 2.41. Let N be a smooth manifold with an atlas \mathcal{U} . A chart (U, φ) is said to be smoothly compatible with \mathcal{U} if $\mathcal{U} \cup \{(U, \varphi)\}$ is again a smooth atlas.

The above definition simply means that both $\varphi \circ \varphi_\alpha^{-1}$ and $\varphi_\alpha \circ \varphi^{-1}$ are smooth for any chart $(U_\alpha, \varphi_\alpha) \in \mathcal{U}$. Equivalently, this means that $\varphi: U \rightarrow \varphi(U) \subset \mathbb{R}^k$ is a diffeomorphism.

The proofs of **Theorem 2.37** and **Corollary 2.39** show that in the setting of these theorems there is a chart (U, φ) on $\mathbb{R}^{k+\ell}$ smoothly compatible with $\mathcal{U} = \{(\mathbb{R}^{k+\ell}, id)\}$ such that $\varphi(U \cap N) \subset \mathbb{R}^k \times \{0\}$. This motivates the following.

Definition 2.42. Let N be a manifold of dimension $k + \ell$. A subset $M \subset N$ is said to be a *submanifold* of dimension k (or *k-submanifold*), if for each point $m \in M$ there exists a smoothly compatible chart (U, φ) on N centered at m such that

$$\varphi(U \cap N) = \varphi(U) \cap (\mathbb{R}^k \times \{0\}) \quad (2.43)$$

holds. Under these circumstances, the chart (U, φ) is said to be *adapted to M*.

Below we consider only charts smoothly compatible with a given atlas and therefore this will not be mentioned explicitly each time. Alternatively, given a smooth atlas \mathcal{U} one can always replace \mathcal{U} by the unique maximal atlas containing \mathcal{U} . Thus we can assume that \mathcal{U} is maximal from the very beginning and in this case any chart smoothly compatible with \mathcal{U} is contained in \mathcal{U} so that one can simply talk about charts (from a maximal atlas).

Bibliography

- [GP10] V. Guillemin and A. Pollack, *Differential topology*, AMS Chelsea Publishing, Providence, RI, 2010. Reprint of the 1974 original. MR2680546 ↑47
- [MR09] S. Montiel and A. Ros, *Curves and surfaces*, Second (Donald Babbitt, ed.), Graduate Studies in Mathematics, vol. 69, American Mathematical Society, Providence, RI; Real Sociedad Matemática Española, Madrid, 2009. MR2522595 ↑41
- [Tho79] J. Thorpe, *Elementary topics in differential geometry*, Undergraduate Texts in Mathematics, Springer-Verlag, New York-Heidelberg, 1979. MR528129 ↑47