

# Differential Geometry I

Lecture notes

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

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# 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.

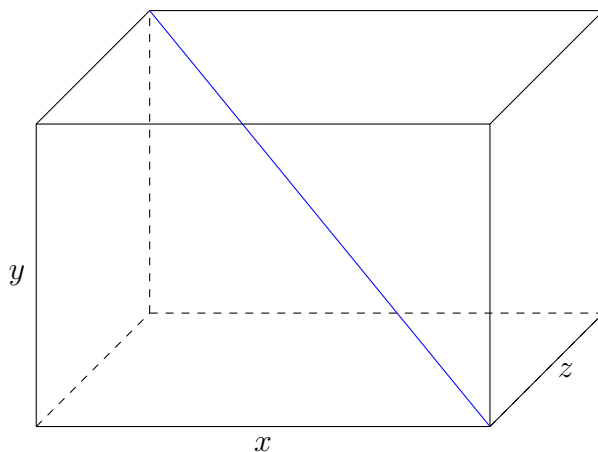


Figure 1.1: A parallelepiped

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 recipe known from the analysis course is not readily applicable.

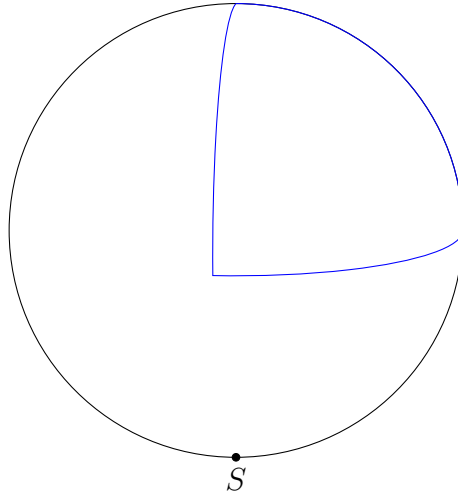


Figure 1.2: The spherical triangle  $x, y, z > 0$

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

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

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  $(\frac{1}{\sqrt{3}}, \frac{1}{\sqrt{3}}, \frac{1}{\sqrt{3}})$  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  $\lambda$ . □

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  $\varphi$  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  $\psi$  be as in **Proposition 1.29**. Define  $\Psi(x, y) := (x, y, \psi(x, y))$ . If  $U$  and  $V$  are also as in **Proposition 1.29**, 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.

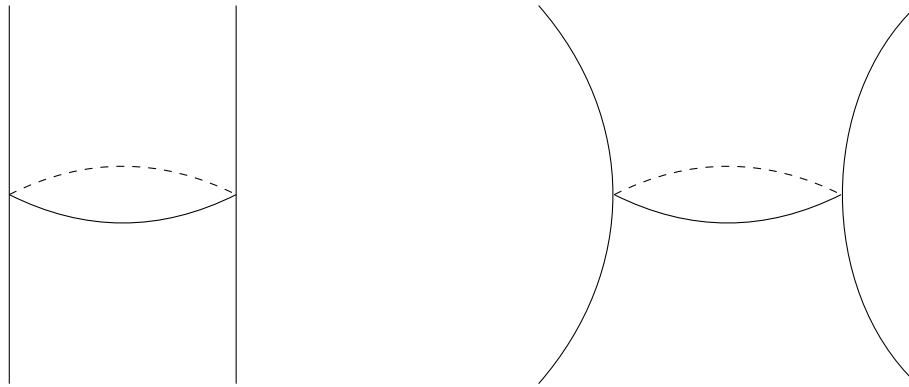


Figure 1.3: The cylinder and hyperboloid

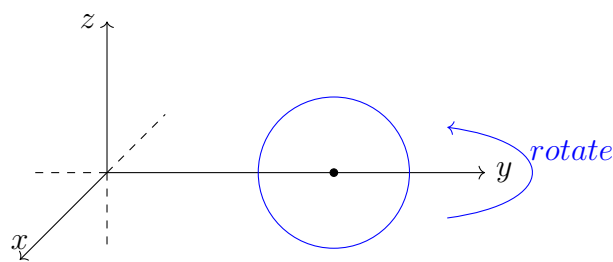


Figure 1.4: The torus as a circle rotated with respect to an axis

**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  $\psi$  in the definition of a surface is called a (local) *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  $(u, v) \in V$ .

Let  $W$  and  $X$  be open subsets of  $\mathbb{R}^n$ . Recall that a smooth map  $\Phi: W \rightarrow X$  is called a *diffeomorphism*, if there exists a smooth map  $\Psi: X \rightarrow W$  such that

$$\Phi \circ \Psi = id_X \quad \text{and} \quad \Psi \circ \Phi = id_W.$$

In other words,  $\Phi$  is a diffeomorphism if and only if  $\Phi^{-1}$  exists and is smooth.

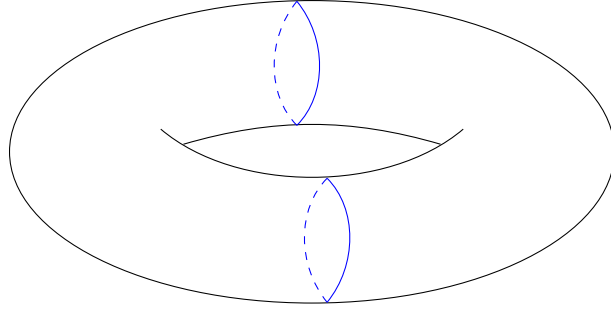


Figure 1.5: The torus

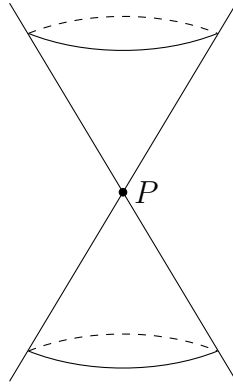


Figure 1.6: The double cone

**Proposition 1.15.** *Let  $S$  be a smooth surface. For any  $p \in S$  there exists a neighbourhood  $W$  of  $p$  in  $\mathbb{R}^3$  and a diffeomorphism  $\Phi: W \rightarrow X$ , where  $X \subset \mathbb{R}^3$  is open, such that*

$$\Phi(S \cap W) = (\mathbb{R}^2 \times \{0\}) \cap X.$$

*If  $\psi$  is a parametrization of  $S$  near  $p$ , one can choose  $\Phi$  such that  $\Phi \circ \psi = id$ .*

*Moreover, there exists a function  $\varphi \in C^\infty(W)$  such that*

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

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

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

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

are linearly independent and 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  $\Psi$  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  $\varphi$  defined in a neighbourhood  $W$  of the origin such that  $\varphi$  vanishes on  $S$  and  $\nabla\varphi(0) \neq 0$  by **Proposition 1.15**. Notice that  $\varphi$  vanishes identically along  $S$ , hence  $\varphi$  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  $\psi_1$  and  $\psi_2$  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  $\psi_{21}$  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.

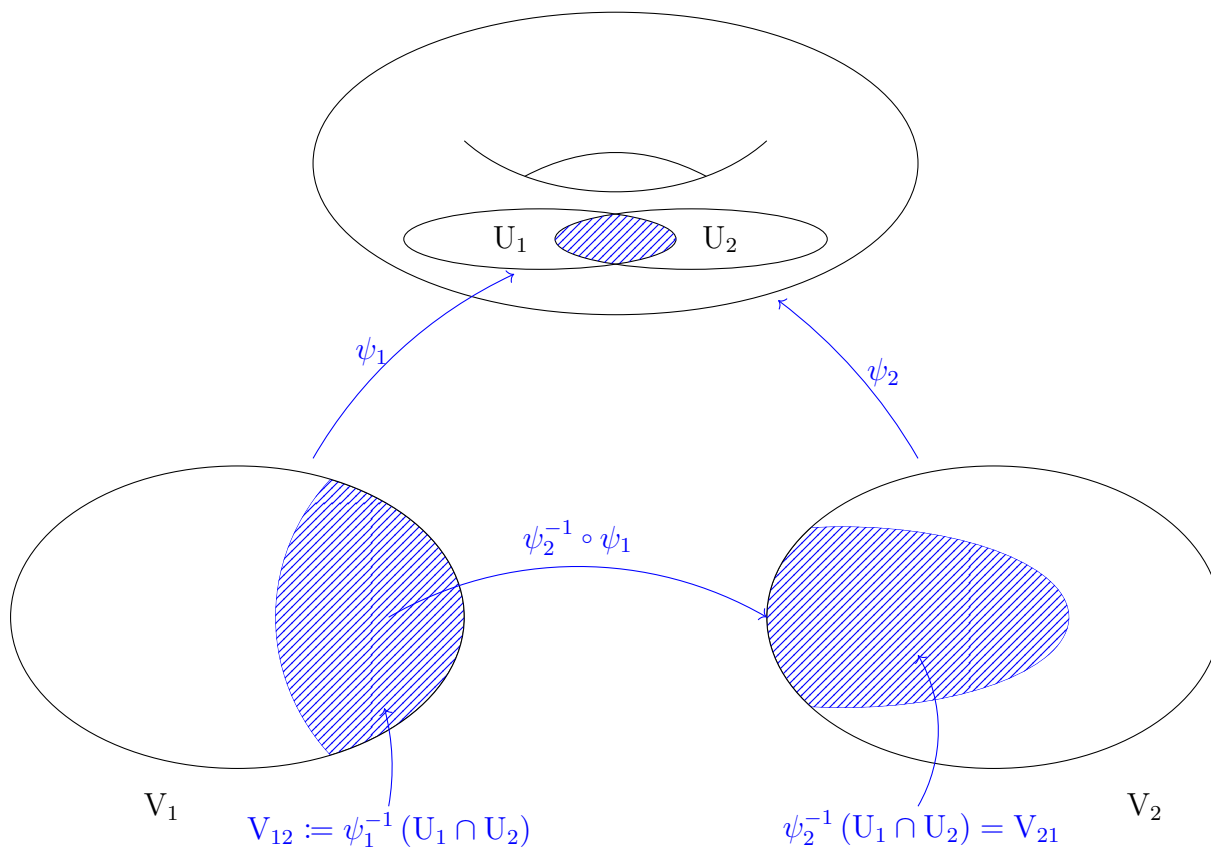


Figure 1.7: The transition map

**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

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

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

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

Thus,  $\psi_N$  is a parametrization (at each point  $p \in S^2 \setminus \{N\}$ ). Of course, we have also the inverse  $\psi_S$  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  $\psi_{SN} := \psi_S^{-1} \circ \psi_N: \mathbb{R}^2 \setminus \{0\} \rightarrow \mathbb{R}^2 \setminus \{0\}$  is given by

$$\psi_{SN}(u, v) = \frac{1}{u^2 + v^2} (u, v) \tag{1.22}$$

**Exercise 1.23.** Show that the sphere can not be covered by the image of a single parametrization.

**Theorem 1.24.** Let  $S$  be a surface. For any two parametrizations  $\psi_1$  and  $\psi_2$  as above, the change of coordinates map  $\psi_{12}$  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.

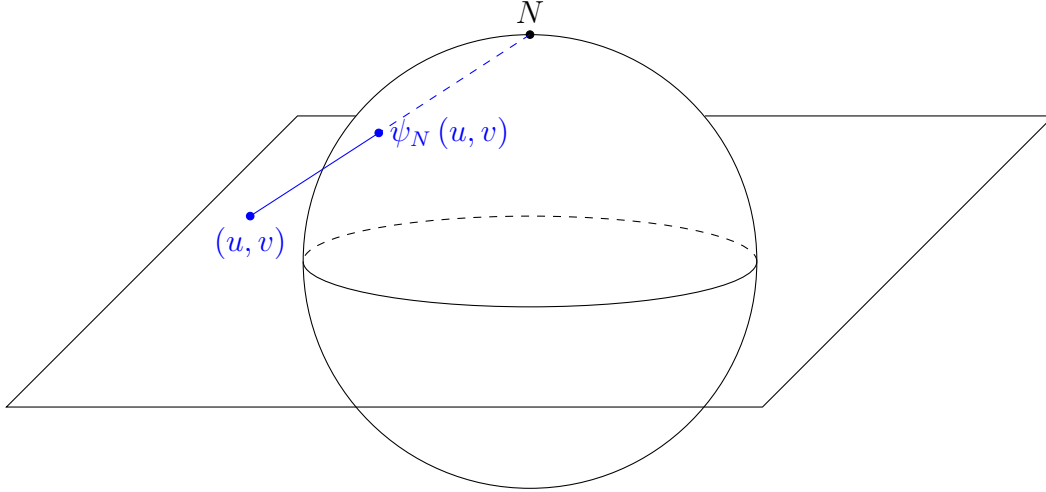


Figure 1.8: The inverse of the stereographic projection

Thus, set  $p_0 := \psi_1(u_0, v_0)$ . For this  $p_0$  and  $\psi_2$  construct a smooth map  $\Phi_2: W \rightarrow V_2 \times \mathbb{R}$  as in [Proposition 1.15](#). Recall that

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

equals  $\psi_2^{-1}$ .

The map  $\Phi_2 \circ \psi_1: \psi_1^{-1}(S \cap W) \rightarrow V_2$  is clearly smooth as the composition of smooth maps. Set  $V_0 := V_{12} \cap \psi_1^{-1}(S \cap W)$ . Since the image of  $\psi_1$  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 1.25.** 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

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

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

*Remark 1.26.* [Theorem 1.24](#) 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  $\psi_{12}$  are smooth. Hence, if  $(V_i, \psi_i)$  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 1.27.** 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  $\psi$  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  $\psi_N$  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 1.28.** Let  $\psi: V \rightarrow U$  be a parametrization of a surface  $S$ . Since  $\psi$  is a homeomorphism, we have the inverse map

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

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

**Proposition 1.29.** Let  $S$  be a surface. Then the set  $C^\infty(S)$  of all smooth functions on  $S$  is a vector space, that is

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

In fact, we also have

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

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 1.30.** 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  $\varphi \circ f$ .

**Proposition 1.31.**  $f: W \rightarrow S$  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

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

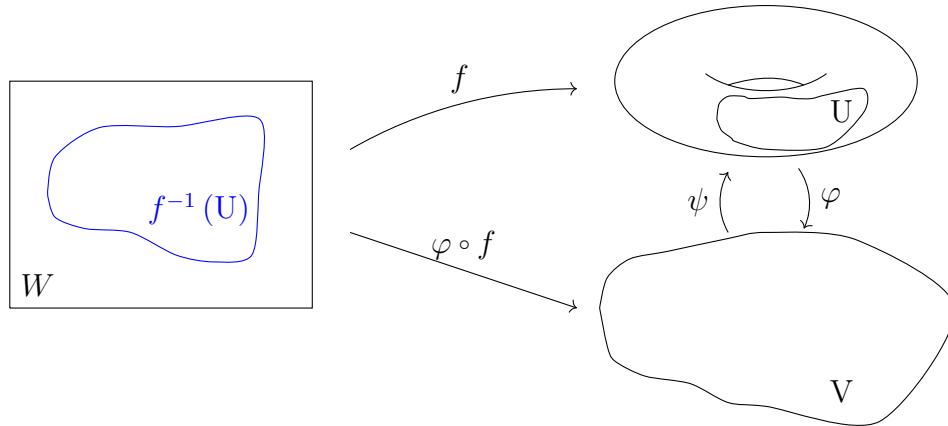


Figure 1.9: A map into a surface and its coordinate representation

*Proof.* Pick a parametrization  $\psi$  of  $S$  and construct a smooth map  $\Phi: X \rightarrow \mathbb{R}^3$  just as in **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  $\varphi \circ f = \Phi \circ f: W \rightarrow \mathbb{R}^2$  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. □

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

**Definition 1.32.** 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  $\gamma$  is a smooth curve through  $p := \gamma(0) \in S$ .

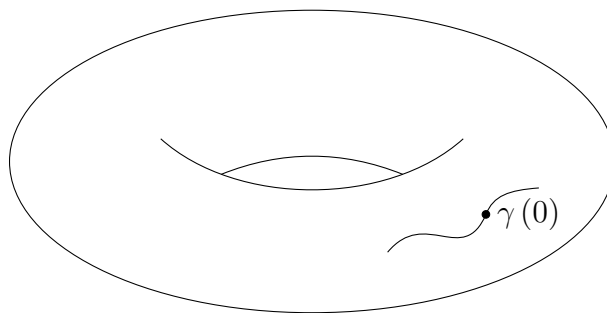
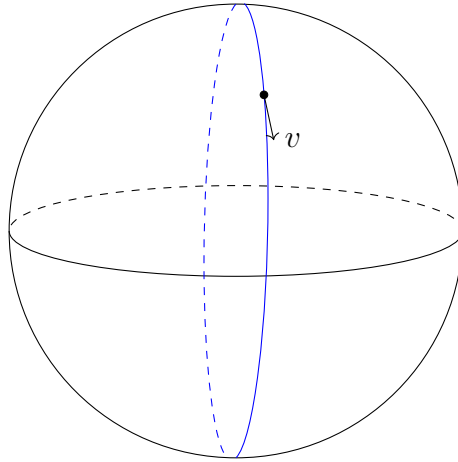


Figure 1.10: A smooth curve on a surface

**Example 1.33.** 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  $\gamma_v$  is a great circle on  $S^2$ .

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

**Definition 1.34.** 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

$$\chi^{-1} \circ f \circ \psi: \psi^{-1}(f^{-1}(X)) \rightarrow W \tag{1.35}$$

is smooth. Just like in the case of functions, (1.35) is called the coordinate (or local) representation of  $f$ .

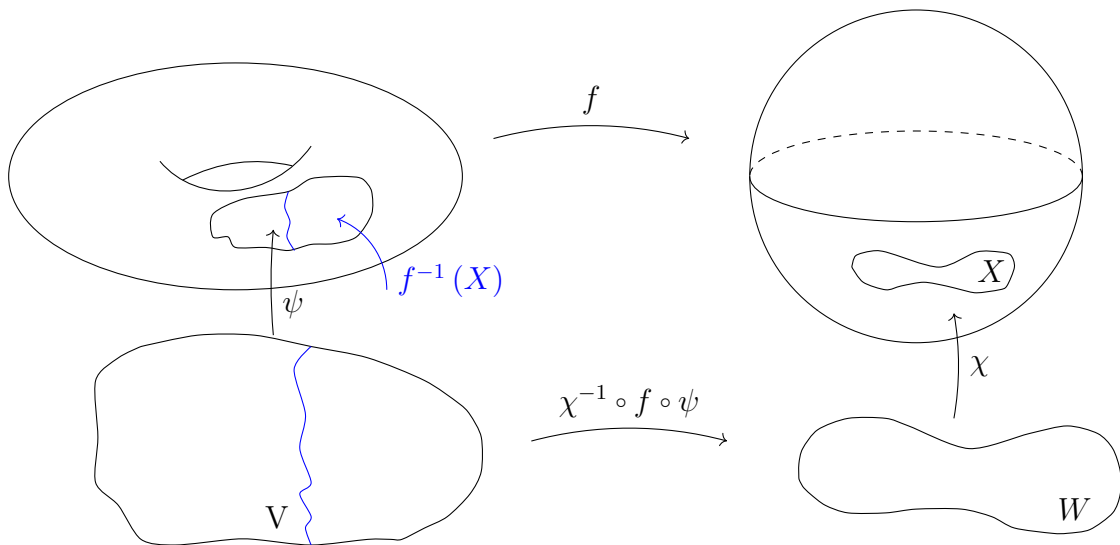


Figure 1.11: A smooth map between surfaces and its coordinate representation

*Remark 1.36.* 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  $(U, \varphi)$  on  $S_1$  and any chart  $(X, \xi)$  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  $(U, \varphi)$  and  $(X, \xi)$ ).

*Remark 1.37.* 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 1.38.** 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 1.31](#) and is left as an exercise to the reader.

To construct a more interesting example, pick a polynomial

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

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

$$f(p) = \begin{cases} \psi_N \circ p \circ \psi_N^{-1}(p) & \text{if } p \neq N, \\ N & \text{if } p = N. \end{cases} \quad (1.39)$$

I claim that  $f$  is smooth. Indeed, since by the construction of  $f$ , the coordinate representation of  $f$  with respect to the pair  $(\mathbb{R}^2, \psi_N)$  and  $(\mathbb{R}^2, \psi_N)$  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

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

By (1.22), we have

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

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 1.40.** *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

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

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 1.41.* The proof of the above theorem shows that the coordinate representation of the composition is the composition of coordinate representations.

Notice that **Theorem 1.40** 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.

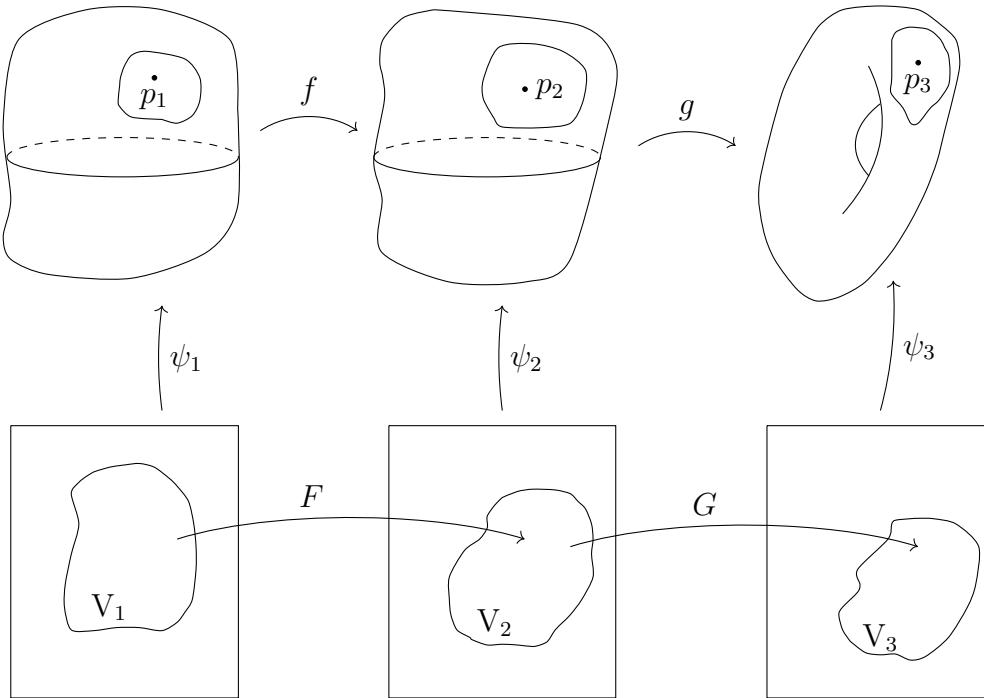
**Definition 1.42.** A smooth map  $f: S_1 \rightarrow S_2$  is called a diffeomorphism, if there exists a smooth map  $g: S_2 \rightarrow S_1$  such that

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

Two surfaces  $S_1$  and  $S_2$  are said to be diffeomorphic, if there exists a diffeomorphism between  $S_1$  and  $S_2$ .

For example, 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

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

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  $\psi$ . Then  $\varphi = \psi^{-1}$  exists and is smooth as we have seen in Example 1.28. 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  $\gamma$  we think of  $\gamma$  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 1.33. 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  $\dot{\gamma}(0) = \lambda \dot{\gamma}_{v_1}(0) = v$ . In other words, we have shown that  $T_p S^2 \subset p^\perp$ .

Furthermore, it is easy to see that  $T_p S^2$  in fact equals to  $p^\perp$ : if  $\gamma: (-\varepsilon, \varepsilon) \rightarrow S^2$  is any curve through  $p$ , we have

$$\langle \gamma(t), \gamma(t) \rangle \equiv 1 \quad \implies \quad 2 \langle \gamma(0), \dot{\gamma}(0) \rangle = 2 \langle p, \dot{\gamma}(0) \rangle = 0.$$

**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  $\varepsilon$  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  $\gamma$  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. □

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

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

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  $\gamma$  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  $\gamma_1$  and  $\gamma_2$  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  $f: \mathbb{R}^2 \rightarrow \mathbb{R}$  be any smooth function. 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

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

where  $v \in T_p S$ .

**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  $\gamma$  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,

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

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.

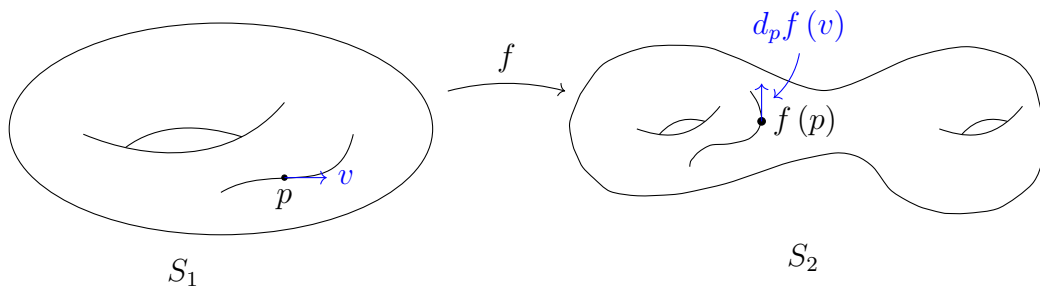


Figure 1.12: The differential of a smooth map

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

*Proof.* Let  $\gamma_1$  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  $\psi_2(0) = f(p)$ .

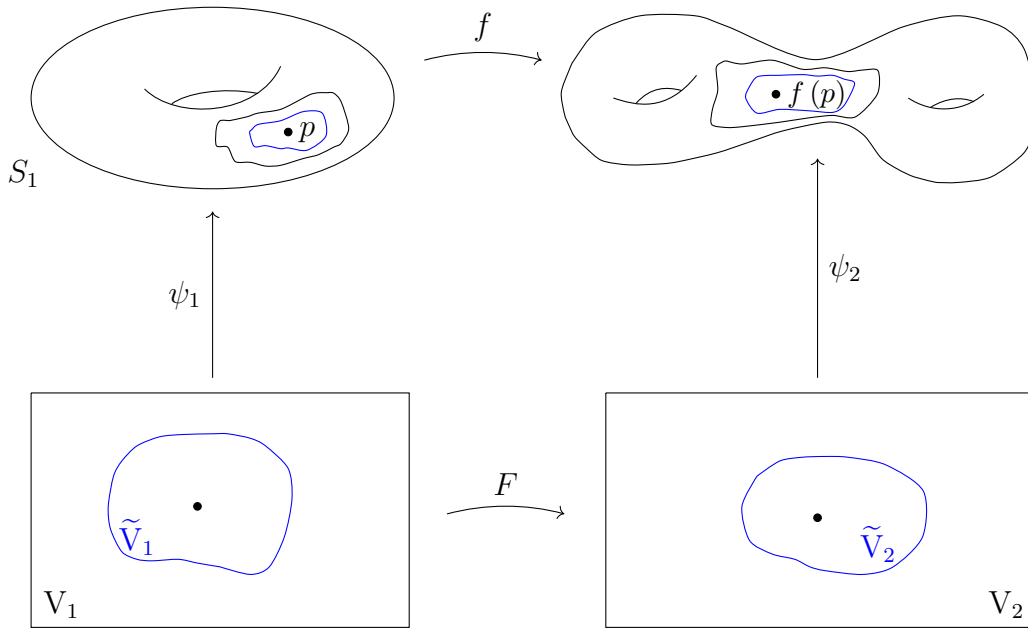


Figure 1.13: Illustration for the proof of **Theorem 1.70**

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

$$d_0 \psi_1: \mathbb{R}^2 \longrightarrow T_p S_1, \quad d_{f(p)} \psi_2^{-1}: T_{f(p)} S_2 \longrightarrow \mathbb{R}^2, \quad \text{and} \quad d_p f: T_p S_1 \rightarrow T_p S_2$$

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. □

*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  $f'(z) = 0 \iff n z^{n-1} = 0 \iff z = 0$ . 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,  $\#f^{-1}(r') \geq \#f^{-1}(r)$  for all  $r' \in W$ .

Furthermore, I claim that in fact  $\#f^{-1}(r') = \#f^{-1}(r)$  for all  $r'$  contained in some neighbourhood of  $r$ . Indeed, arguing by contradiction, assume that there is a sequence  $r'_i$  converging to  $r$  with the following property: for each  $i$  there is some  $p'_i \in f^{-1}(r'_i)$  such that  $p'_i$  is not contained in any of  $\tilde{U}_1, \dots, \tilde{U}_m$ . By the compactness of  $S^2$ , a subsequence of  $p'_i$  converges to some  $p$ . Then, by the continuity of  $f$  we must have  $f(p) = r$  so that  $p = p_j$  for some  $j \in \{1, \dots, m\}$ . But then a subsequence of  $p'_i$  must be contained in  $\tilde{U}_j$ . This is a contradiction.

Thus, the function

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

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  $\psi$  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  $(\partial_u \psi, \partial_v \psi) \big|_q$  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  $\partial_u \psi \times \partial_v \psi \neq 0$ . □

**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

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

□

**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  $\varphi$  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  $v \in \mathbb{R}^3$ .

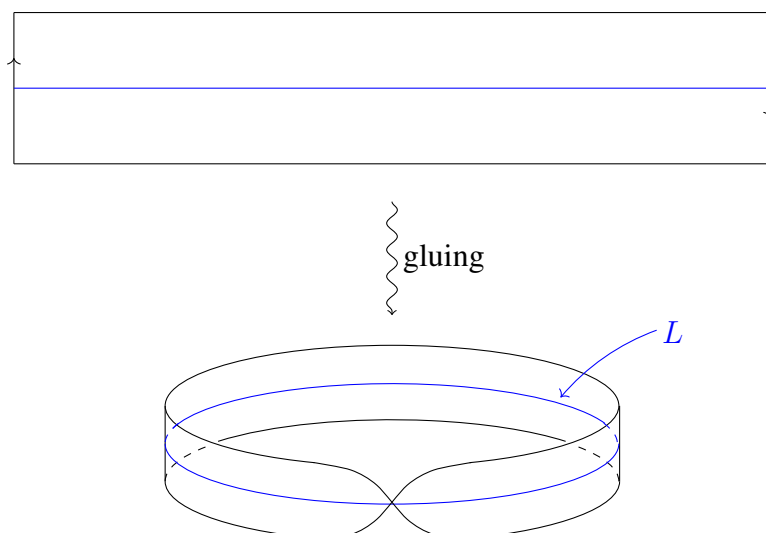


Figure 1.14: The Möbius band from the strip

*Proof.* Since  $T_p S = \nabla \varphi(p)^\perp$ , we see that  $\nabla \varphi$  is a normal field. Since 0 is a regular value of  $\varphi$ ,  $\nabla \varphi$  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.

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  $\Psi$  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  $S = S^2$ ,  $\mathcal{A} = \left\{ (\psi_N, \mathbb{R}^2, S^2 \setminus \{N\}), (\psi_S, \mathbb{R}^2; S^2 \setminus \{S\}) \right\}$  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

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

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

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

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

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

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  $(\psi_a, V_a, U_a)$  belongs to  $\mathcal{B}$ . If  $\det(\partial_u \psi_a, \partial_v \psi_a, n(\psi_a(u, v))) < 0$ , then  $(\psi_a \circ \sigma, \sigma(V_a), U_a) = (\widehat{\psi}_a, \widehat{V}_a, U_a)$  belongs to  $\mathcal{B}$ , where  $\sigma : \mathbb{R}^2 \rightarrow \mathbb{R}^2$ ,  $\sigma(u, v) = (-u, v)$ . This yields

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

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,

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

which yields in turn

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

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

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

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

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

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

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

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

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

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

Assume  $\psi_b$  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.

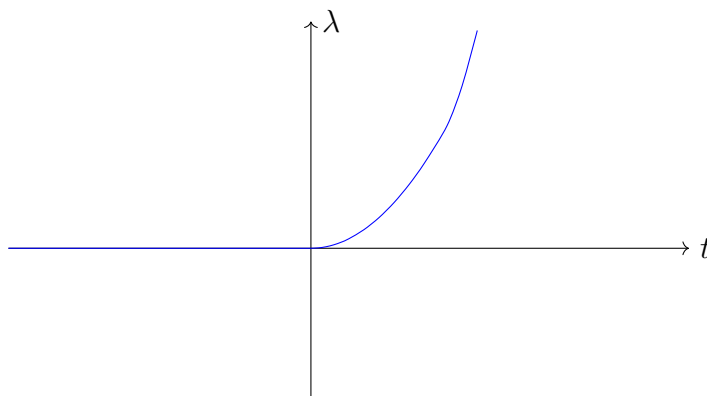


Figure 1.15: The graph of  $\lambda$

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  $\mathbb{R}$  and takes values in  $[0, 1]$ . Denote also

$$\chi_r(t) := \hat{\chi}_r(t - 1)$$

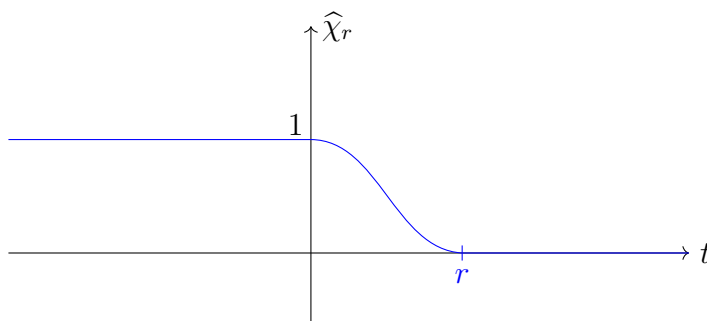


Figure 1.16: The graph of  $\hat{\chi}_r$

**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:*

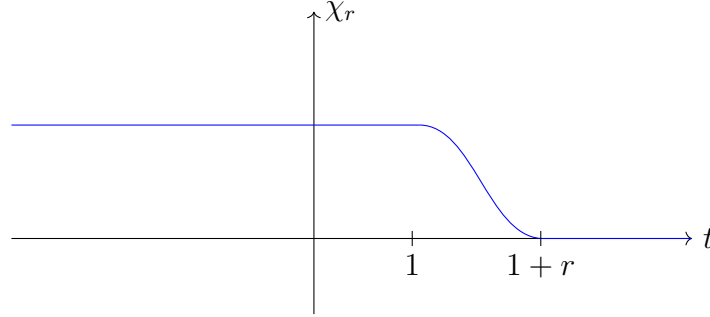


Figure 1.17: The graph of  $\chi_r$

- $0 \leq \rho(x) \leq 1$  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

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

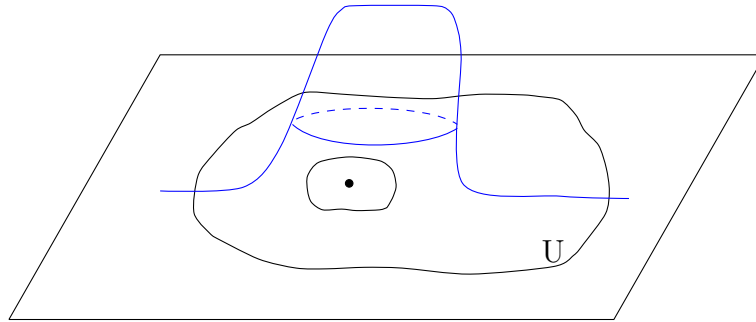


Figure 1.18: Schematic graph of  $\rho$

If  $B_{2R}(p) \subset U$ , then  $\rho$  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  $\rho$  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  $\{\widehat{\rho}_j(x) \mid j \in \mathbb{Z}\}$ , where  $\widehat{\rho}_j(x) = \chi_1(|x - j|)$ . Notice that  $\text{supp } \widehat{\rho}_j \subset [j - 2, j + 2]$  so that the function  $\widehat{\rho}(x) := \sum_{j \in \mathbb{Z}} \widehat{\rho}_j(x)$  is well-defined, smooth and positive everywhere on  $\mathbb{R}$ . Hence,

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

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

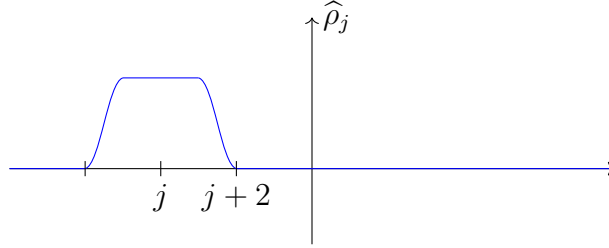


Figure 1.19: A schematic graph of  $\rho_j$

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

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

Then  $\rho$  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  $\rho$  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  $U_\alpha$  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  $\rho$  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  $(U, \varphi)$  is a chart.

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

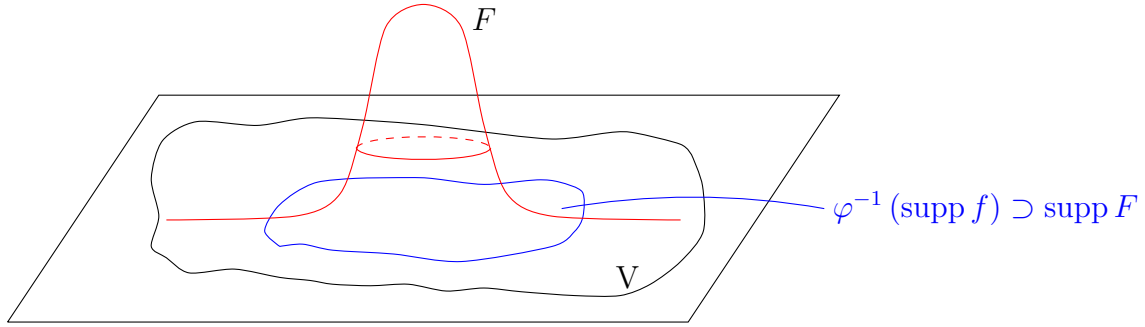
$$F := f \circ \varphi^{-1} = f \circ \psi : V \longrightarrow \mathbb{R}.$$

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.

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

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

where  $\text{supp } \rho_j \subset U_j = U_{\alpha(j)}$  and  $\psi_j = \varphi_{\alpha(j)}^{-1}$ .

**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  $\{\lambda_{jk} := \rho_j \mu_k \mid j = 1, \dots, J, k = 1, \dots, K\}$  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  $\rho$  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  $\varepsilon$ .

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

- $|\rho(\varepsilon u, \varepsilon v) F_N(u, v)| \leq \sup_{S^2} |f|$ ;

$$\bullet \int_{B_{2\varepsilon^{-1}}(0) \setminus B_{\varepsilon^{-1}}(0)} |\partial_u \psi \times \partial_v \psi| du dv \leq \text{Area}(S^2 \setminus \psi_N(B_{\varepsilon^{-1}}(0))) \rightarrow 0.$$

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  $f \in C^\infty(S_2)$  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  $A'_\varphi$  be the matrix of  $\varphi$  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,

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

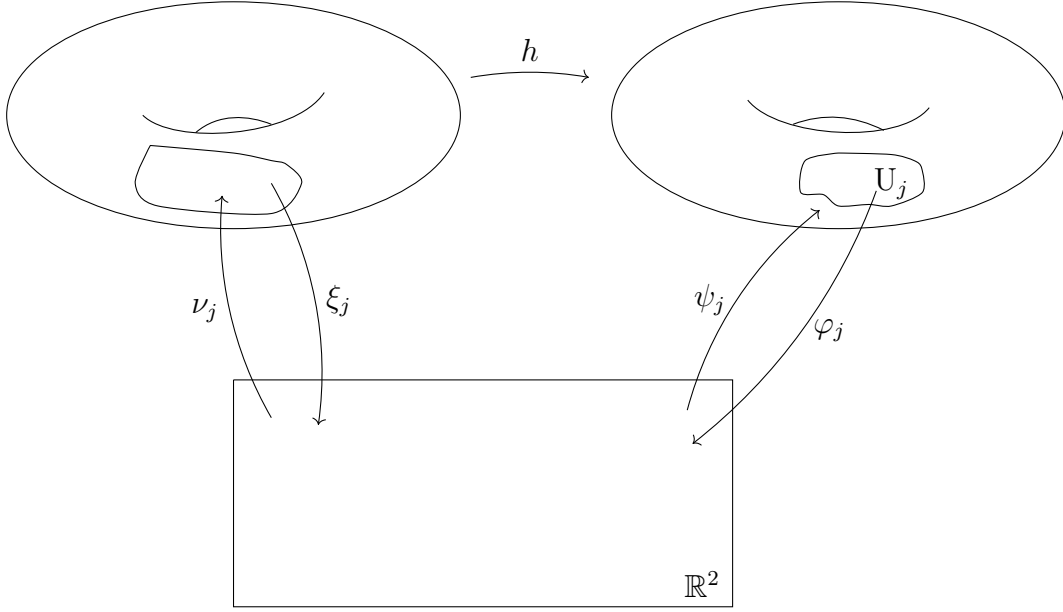
since both  $\det(C^{-1})$  and  $\det B$  equal to  $\pm 1$  because  $B$  and  $C$  are orthogonal. That is for any linear map  $\varphi: V \rightarrow W$  between Euclidean spaces  $|\det \varphi| := |\det A_\varphi|$  is well-defined.

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  $\psi$  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  $\dot{\gamma}(p) = v$ .

**Definition 1.131.** The map

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

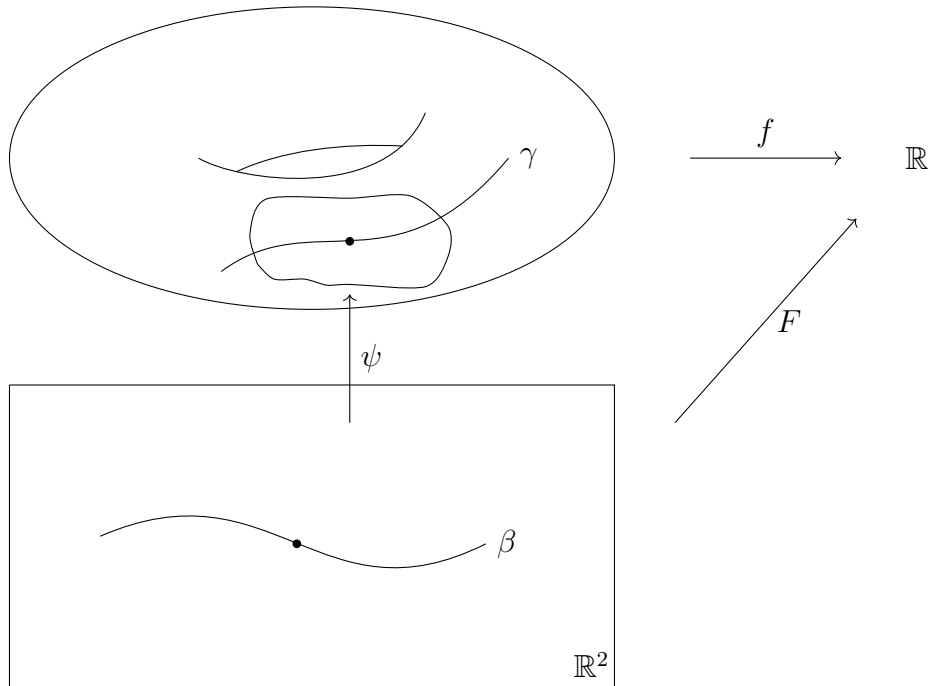
is called the Hessian of  $f$  at  $p$ .

**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  $\psi$  such that  $\psi(0) = p$  and denote

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



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  $\gamma$ . 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

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

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 1.27. 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.

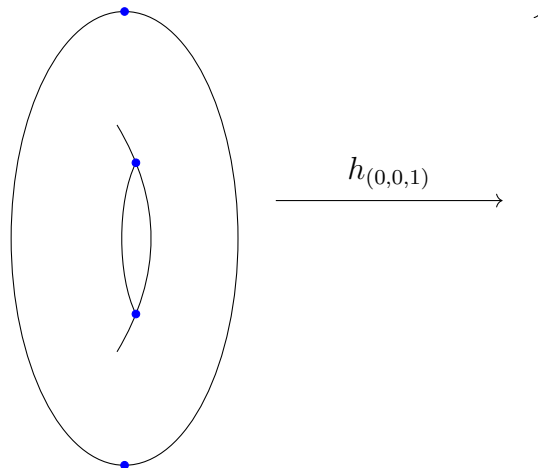


Figure 1.21: Critical points of the standard height function in the torus

**Proposition 1.134.** *Let  $n$  be an orientation of  $S$ . Then  $p$  is a critical point of  $h_{n(p)}$  and*

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

*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

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

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  $\text{II}_p(v)$ . This yields

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

□

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.

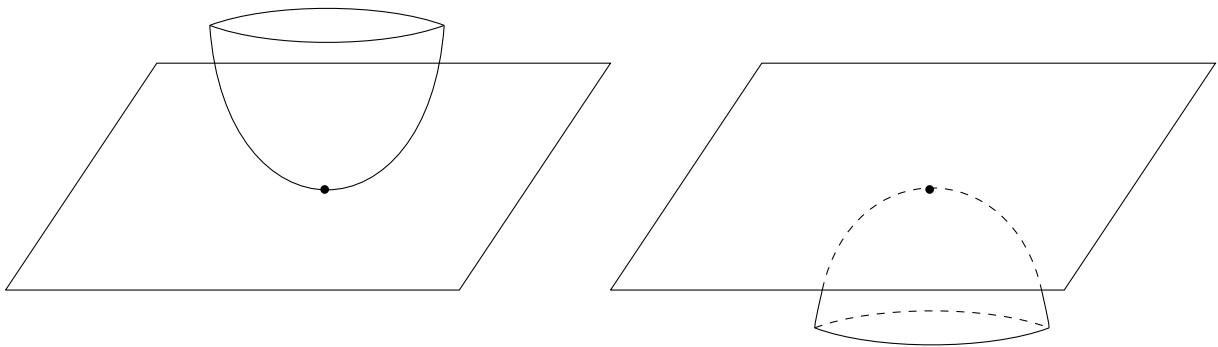


Figure 1.22: Local shape of a surface with positive Gauss curvature

- 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  $T_p S$ .

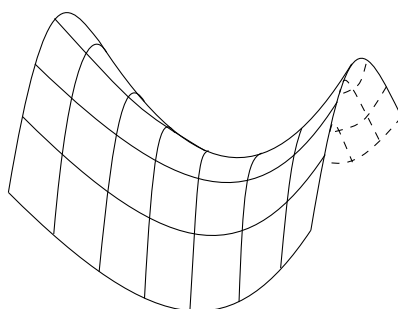


Figure 1.23: A local shape of a surface with negative curvature: the saddle surface

## 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  $S$ .*  $\square$

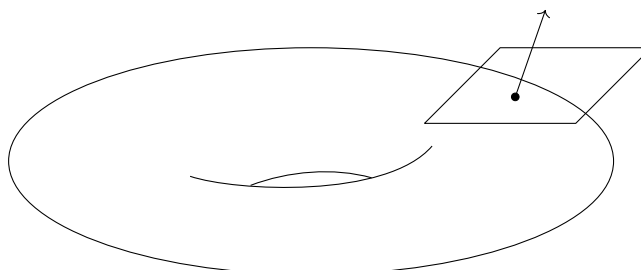
*Remark 1.137.* The Jordan separation theorem is a well-known result from topology. However its proof relies on certain results, which are typically not proved in a standard course in topology. Hence, we take the Jordan separation theorem as granted. An interested reader may find a proof in [MR09, Thm.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

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

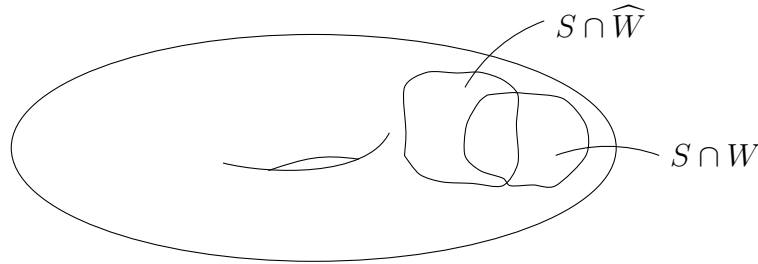
Then  $\frac{\nabla\widehat{\varphi}(p)}{|\nabla\widehat{\varphi}(p)|}$  is necessarily pointing outwards. In particular,

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

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. □

**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  $\text{II}_p$  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  $\gamma$  any curve on  $S$  through  $p$ . Clearly, the function  $t \mapsto \|\gamma(t)\|^2$  has a maximum at  $t = 0$  which yields

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

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

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

□

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

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

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  $A := \{(x, y) \in \Omega \times \Omega \mid [x, y] \subset \Omega\}$ .

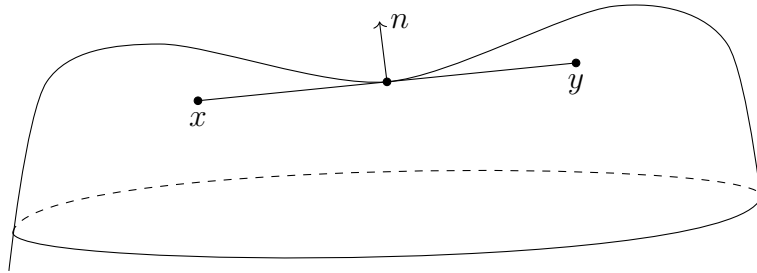
Notice that

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

Then the topological boundary  $\partial A$  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

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

**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

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

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  $\Omega_{out}$ . 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. □

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

$$\int_S K = 4\pi. \tag{1.146}$$

*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](#). □

*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  $S^2$ .

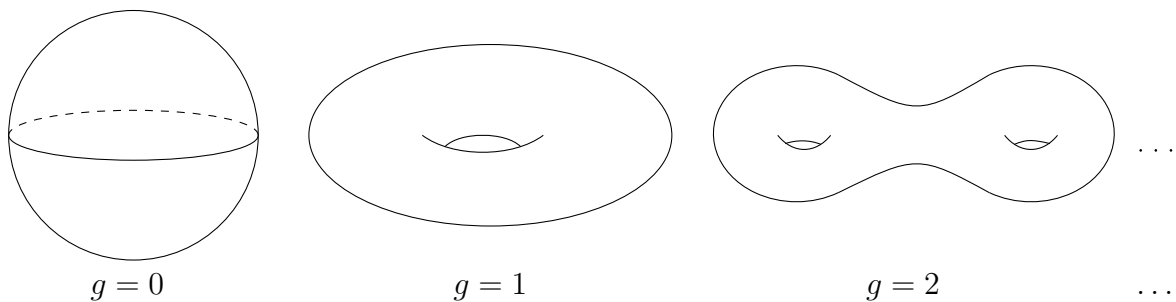


Figure 1.24: Surfaces with 0 holes (the sphere), 1 hole (the torus), and 2 holes

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  $\Omega$  by construction.

Furthermore, any neighbourhood of  $z := tx + (1 - t)y$  contains points from the complement of  $\Omega$ , for example  $z'_{n_m}$  for  $m$  sufficiently large. However, any neighbourhood of  $z$  contains also points from  $\Omega$ , 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  $\Omega$  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  $\nabla \varphi(z) \neq 0$ ,  $\varphi$  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  $\Omega$ .



# 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  $(U, \varphi)$  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).

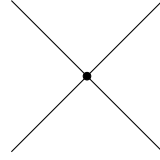


Figure 2.1: The union of two intersecting lines is not a manifold

- 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

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

$U_j$  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  $\varphi_j : U_j \rightarrow \mathbb{R}^k$

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

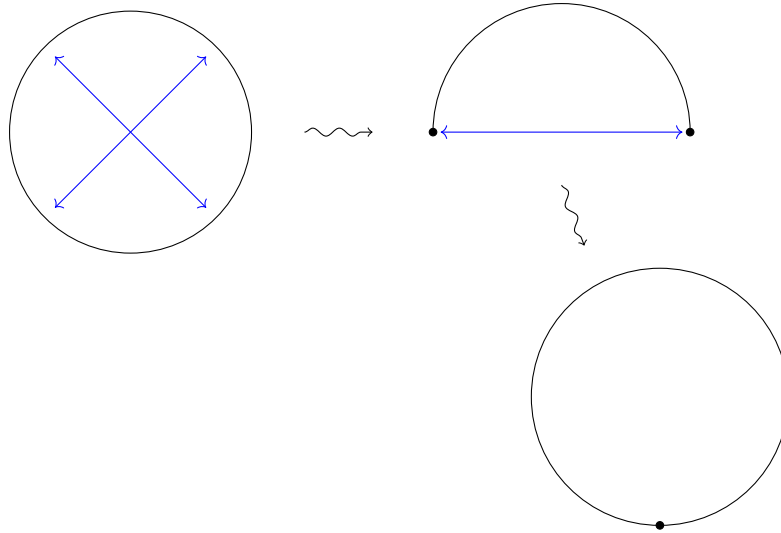


Figure 2.2: A homeomorphism between  $\mathbb{RP}^1$  and  $S^1$

**Exercise 2.7.** Show that  $\varphi_j$  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  $\varphi_j$ . In particular,  $\varphi_j$  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 to 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  $F_\alpha$  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 1.29](#) 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 continuous 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 1.40](#).

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  $(U, \varphi)$  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  $(U, \varphi)$  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  $\theta$  is smooth,  $\theta$  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  $\Phi$  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  $(U, \varphi)$  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  $\gamma$  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  $\varphi_*$  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  $\gamma_1, \gamma_2$  through  $m$  define

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

where  $\beta_j := \varphi \circ \gamma_j$ . Show that  $\gamma$  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  $(U, \varphi)$ . To this end, let  $(\widehat{U}, \widehat{\varphi})$  be another chart such that  $m \in \widehat{U}$ . Let

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

be the corresponding map. Denoting temporarily by  $+_\varphi$  the addition obtained via  $\varphi_*$ , 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  $\widehat{\beta}(t) = \widehat{\varphi} \circ \gamma(t)$  and  $\widehat{\beta}_j(t) = \widehat{\varphi} \circ \gamma_j(t)$ .

Then

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

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

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

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

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

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  $(U, \varphi)$  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  $j^{\text{th}}$  place. Then

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

is a basis of  $T_m M$ .

At his 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

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

**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  $\psi$  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  $[\gamma_1] + [\gamma_2] \in T_pS$  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  $T_pS$  and  $E_p$  have equal dimension, (2.30) is an isomorphism.  $\square$

**Exercise 2.32** (The tangent space of a vector space). Let  $V$  be a finite dimensional vector space. Show that for any  $v \in V$  the map  $\gamma \mapsto \dot{\gamma}(0)$ , where  $\gamma$  is a smooth curve through  $v$ , induces a natural isomorphism  $T_vV \rightarrow V$ . Thus, in the sequel we identify  $T_vV$  with  $V$  without further comments.

## 2.4 The differential of a smooth map

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

**Definition 2.33.** 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 2.34.** *The differential is a linear map. If  $(U, \varphi)$  is a chart on  $M$  such that  $m \in U$  and  $(V, \psi)$  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  $e_\varphi$  and  $e_\psi$ , 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

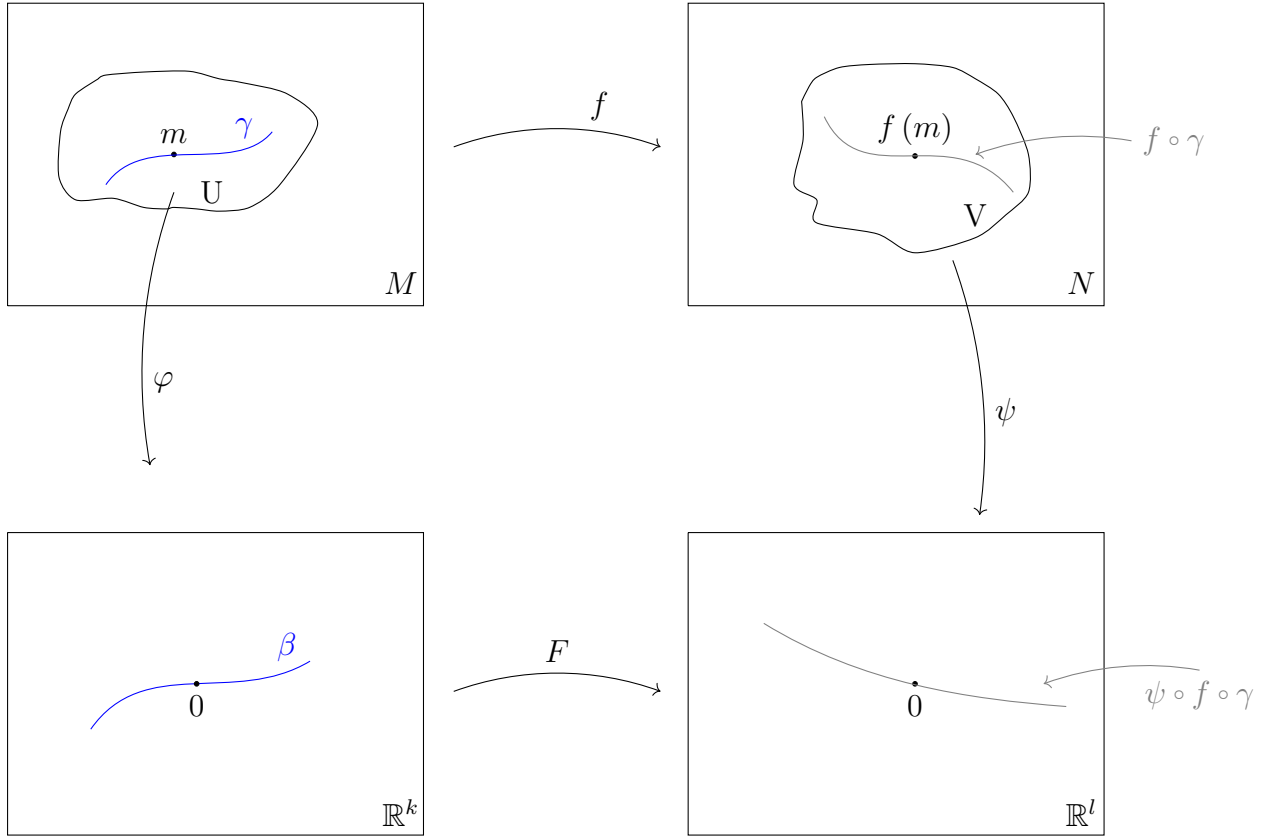
$$\psi_* [f \circ \gamma] = \left. \frac{d}{dt} \right|_{t=0} \left( \underbrace{\psi \circ f \circ \varphi^{-1}}_F \circ \beta(t) \right) = \left. \frac{d}{dt} \right|_{t=0} (F \circ \beta(t)) = D_0 F(\dot{\beta}(0)).$$

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

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

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





Furthermore, by the definition of  $e_\varphi$ , 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,

$$d_m f[\gamma_j] = \psi_*^{-1} \left( \sum_{i=1}^l \frac{\partial F_i}{\partial x_j} \hat{e}_i \right) = \sum_{i=1}^l \frac{\partial F_i}{\partial x_j} \underbrace{\psi_*^{-1}(\hat{e}_i)}_{[\hat{\gamma}_i]} \implies$$

$$(d_m f[\gamma_1], \dots, d_m f[\gamma_k]) = ([\hat{\gamma}_1], \dots, [\hat{\gamma}_l]) \begin{pmatrix} \frac{\partial F_1}{\partial x_1} & \cdots & \frac{\partial F_1}{\partial x_k} \\ \vdots & \cdots & \vdots \\ \frac{\partial F_l}{\partial x_1} & \cdots & \frac{\partial F_l}{\partial x_k} \end{pmatrix},$$

where  $[\hat{\gamma}_i]$  is the  $i^{\text{th}}$  element of  $e_\psi$ . This finishes the proof of this proposition. □

**Exercise 2.35.** Just as in Exercise 2.32, for a finite dimensional vector space  $V$  identify  $T_v V$  with  $V$ . Show that if  $A: V \rightarrow W$  is a linear map, where  $W$  is another vector space, then  $d_v A = A$ .

**Proposition 2.36.** 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 2.37.** *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

$$D_y f(p_0): \mathbb{R}^\ell \xrightarrow{\iota_2} \mathbb{R}^{k+l} \xrightarrow{D_{p_0} f} \mathbb{R}^\ell. \quad (2.38)$$

For example, if  $k = l = 1$ , we have  $D_y f(p_0) = \frac{\partial f}{\partial y}(p_0)$ . For this reason, we call (2.38) *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 2.39.** *If  $D_y f(0)$  is an isomorphism, then there exists a smooth map  $\theta: \mathbb{R}^{k+l} \rightarrow \mathbb{R}^{k+l}$ , 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

$$g: \mathbb{R}^{k+l} \rightarrow \mathbb{R}^{k+l} \quad \text{by} \quad g(x, y) := (x, f(x, y)). \quad (2.40)$$

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  $v \in \mathbb{R}^l$ .

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  $\theta: \mathbb{R}^{k+l} \rightarrow \mathbb{R}^{k+l}$  to  $g$ , that is in a neighbourhood of the origin we have

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

Thus, the theorem is proved.  $\square$

**Corollary 2.41** (The implicit function theorem). *Suppose that the assumptions of [Theorem 2.39](#) 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*

$$f(x, y) = 0 \iff y = h(x) \tag{2.42}$$

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  $(W, \psi)$  is a chart on  $f^{-1}(0)$  near the origin.

*Proof.* Let  $\theta: U \rightarrow \theta(U)$  be the local diffeomorphism provided by [Theorem 2.39](#). 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 [\(2.40\)](#), is the inverse of  $\theta$ . 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  $\psi$ . Hence,  $\psi$  is a homeomorphism. □

The hypothesis of [Corollary 2.41](#) implies that the differential of  $f$  at the origin is *surjective*. In fact, the surjectivity of the differential is decisive in [Theorem 2.39](#) and [Corollary 2.41](#), whereas the hypothesis that  $D_y f(0)$  is an isomorphism can be achieved by a linear change of coordinates, see the proof of [Theorem 2.47](#) below for some details.

**Definition 2.43.** Let  $N$  be a smooth manifold with an atlas  $\mathcal{U}$ . A chart  $(U, \varphi)$  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 2.39** and **Corollary 2.41** show that in the setting of these theorems there is a chart  $(U, \varphi)$  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 2.44.** 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  $(U, \varphi)$  on  $N$  centered at  $m$  such that

$$\varphi(U \cap N) = \varphi(U) \cap (\mathbb{R}^k \times \{0\}) \quad (2.45)$$

holds. Under these circumstances, the chart  $(U, \varphi)$  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).

Notice that if  $(U, \varphi)$  is an adapted chart, then  $(M \cap U, \psi)$  is a chart on  $M$ , where

$$\psi := \pi_1 \circ \varphi|_{U \cap M}: U \cap M \rightarrow \mathbb{R}^k.$$

**Proposition 2.46.** A *k-submanifold is a smooth k-manifold*.

*Proof.* By its very definition, a *k-submanifold* is equipped with a  $C^0$ -atlas  $\mathcal{U}$ , consisting of restrictions of all adapted charts.

I claim that this atlas is in fact smooth. Indeed, let  $(U_1, \varphi_1)$  and  $(U_2, \varphi_2)$  be two charts adapted to  $M$ . Denoting by  $\iota_1: \mathbb{R}^k \rightarrow \mathbb{R}^{k+\ell}$  the inclusion  $\iota_1(x) = (x, 0)$ , we have

$$\psi_1 \circ \psi_2^{-1}(x) = \psi_1(\varphi_2^{-1}(x, 0)) = \pi_1 \circ \varphi_1 \circ \varphi_2^{-1} \circ \iota_1(x) = \pi_1 \circ \theta_{12} \circ \iota_1(x).$$

Thus,  $\mathcal{U}$  is smooth. □

We are now in the position to state one of the central theorems of this chapter.

**Theorem 2.47.** *Let  $M$  and  $N$  be smooth manifolds. If  $n$  is a regular value of a smooth map  $f: M \rightarrow N$  and  $\dim M \geq \dim N$ , then  $f^{-1}(n)$  is a submanifold of  $M$  of dimension  $k := \dim M - \dim N$ .*

*Proof.* Denote

$$\ell = \dim N \quad \implies \quad \dim M = k + \ell.$$

Pick any  $m \in f^{-1}(n)$  and any charts  $(U, \varphi)$  and  $(V, \psi)$  centered at  $m$  and  $n$  respectively. Let  $F = \psi \circ f \circ \varphi^{-1}$  be the coordinate representation of  $f$  with respect to the charts  $(U, \varphi)$  and  $(V, \psi)$ . Since  $\varphi$  and  $\psi$  are diffeomorphisms, we obtain that the differential  $D_0F$  of  $F$  at the origin is surjective (in fact,  $D_pF$  is surjective at any point  $p \in F^{-1}(0)$ ). In particular,  $\dim \ker D_0F = k$ .

Choose a basis  $(v_1, \dots, v_{k+\ell})$  of  $\mathbb{R}^{k+\ell}$  such that  $(v_1, \dots, v_k)$  is a basis of  $\ker D_0F$ . Set

$$A: \mathbb{R}^{k+\ell} \rightarrow \mathbb{R}^{k+\ell}, \quad z \mapsto \sum_{j=1}^{k+\ell} z_j v_j.$$

Notice that by the definition of  $A$  and elementary facts from linear algebra, the following holds:

- $A$  is an isomorphism;
- $A \circ \iota_1 : \mathbb{R}^k \rightarrow \ker D_0F$  is an isomorphism;
- $D_0F \circ A \circ \iota_2 : \mathbb{R}^\ell \rightarrow \mathbb{R}^\ell$  is an isomorphism.

Furthermore, consider the map  $G := F \circ A : \mathbb{R}^{k+\ell} \rightarrow \mathbb{R}^\ell$ . By Exercise 2.35, we have

$$D_0G = D_0F \circ A \quad \implies \quad D_yG = D_0F \circ A \circ \iota_2.$$

Since the latter map is an isomorphism, by the proofs of Theorem 2.39 and Corollary 2.41 we obtain a chart  $(W, \xi)$  on  $\mathbb{R}^{k+\ell}$  adapted to  $G^{-1}(0)$ , that is

$$\xi(W \cap G^{-1}(0)) = \xi(W) \cap (\mathbb{R}^k \times \{0\}).$$

Without loss of generality we can assume that  $W$  is contained in  $A^{-1}(\varphi(U))$ .

Various charts involved in the proof are shown schematically on Figure 2.3.

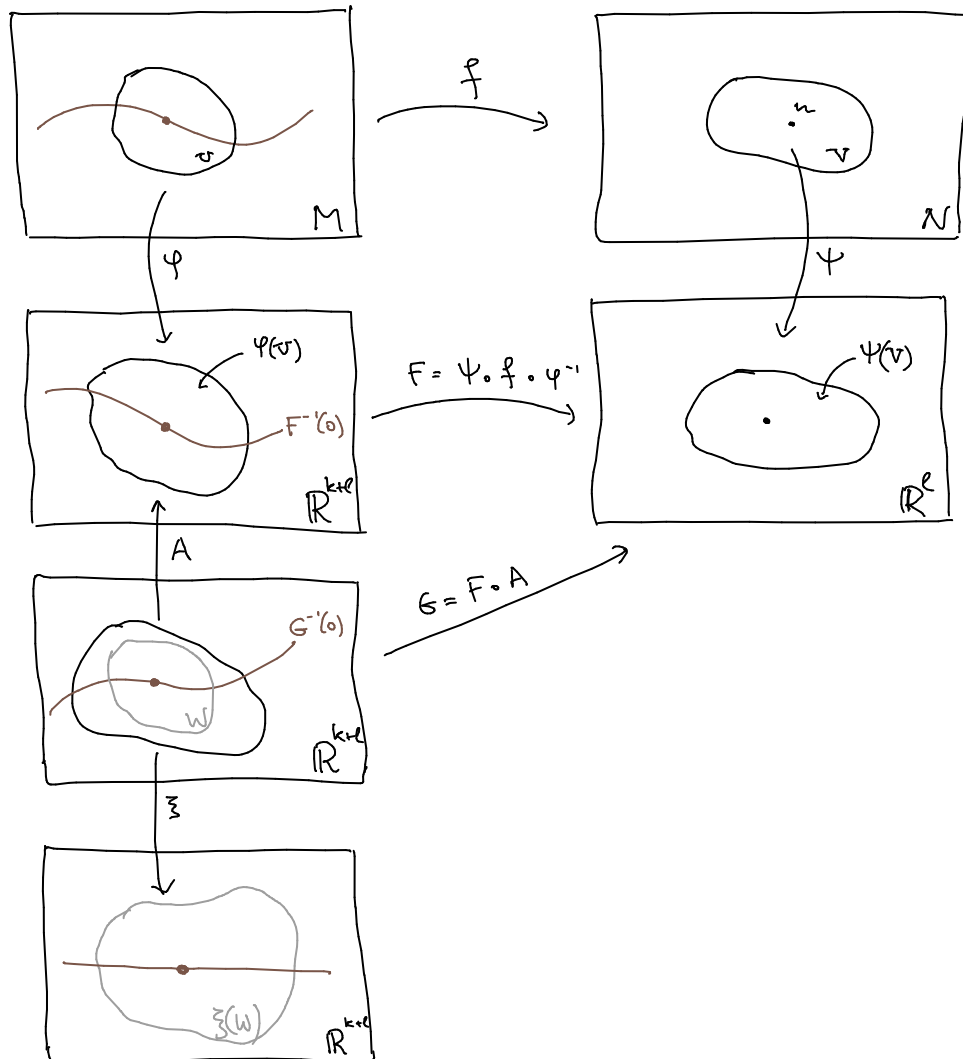


Figure 2.3: Scheme of the proof of Theorem 2.47.

Define a chart  $(\hat{W}, \hat{\xi})$  on  $\mathbb{R}^{k+\ell}$  by

$$(\hat{W}, \hat{\xi}) = (A^{-1}(W), \xi \circ A^{-1}).$$

Since  $z \in G^{-1}(0) \Leftrightarrow Az \in F^{-1}(0)$ , we obtain

$$\hat{\xi}(\hat{W} \cap F^{-1}(0)) = \xi(W \cap G^{-1}(0)) = \xi(W) \cap (\mathbb{R}^k \times \{0\}).$$

Finally, setting

$$\varphi_1 := \hat{\xi} \circ \varphi \quad \text{and} \quad U_1 = \varphi_1^{-1}(\hat{\xi}(\hat{W})) = \varphi^{-1}(\hat{W})$$

we obtain

$$\varphi_1(U_1 \cap f^{-1}(n)) = \hat{\xi}(\hat{W} \cap F^{-1}(0)) = \xi(W) \cap (\mathbb{R}^k \times \{0\}) = \varphi_1(U_1) \cap (\mathbb{R}^k \times \{0\}).$$

Thus,  $(U_1, \varphi_1)$  is a chart adapted to  $f^{-1}(n)$  at  $m$ . □

Notice the following: If  $\dim M < \dim N$ , then  $n$  is a regular value of smooth map  $f: M \rightarrow N$  if and only if  $n \notin \text{Im } f$ , see the paragraph following Definition 1.74. In this case  $f^{-1}(n) = \emptyset$  is also (by definition) a smooth manifold. Thus, the condition  $\dim M \geq \dim N$  can be dropped in the formulation of Theorem 2.47.

**Proposition 2.48.** *In the setting of Theorem 2.47, for any  $m \in f^{-1}(n)$  we have*

$$T_m f^{-1}(n) = \ker d_m f. \tag{2.49}$$

*Proof.* Pick any curve  $\gamma$  in  $f^{-1}(n)$  through  $m$ . Since  $\gamma$  lies in the level set of  $f$ , we have

$$f \circ \gamma(t) = n \quad \text{for all } t \in (-\varepsilon, \varepsilon). \tag{2.50}$$

Since the constant curve  $t \mapsto n$  represents the zero vector in  $T_n N$ , by the definition of the differential of  $f$  and (2.50) we obtain  $d_m f([\gamma]) = 0$ . In other words any vector  $[\gamma]$  tangent to  $f^{-1}(n)$  lies in the kernel of  $d_m f$ . Since  $\dim T_m f^{-1}(n) = k = \dim \text{Ker } d_m f = k$ , we obtain (2.49). □

**Example 2.51.**

- (i) Consider the map  $f: \mathbb{R}^{n+1} \rightarrow \mathbb{R}$ ,  $f(x) = |x|^2$ . Then 1 is a regular value of  $f$ . In particular,  $S^n = f^{-1}(1)$  is a manifold of dimension  $n$ . Of course, the reader knows this fact by now very well.
- (ii) Let  $M_n(\mathbb{R})$  be the space of all  $n \times n$  matrices with real entries. One can show that 1 is a regular value of the function  $\det: M_n(\mathbb{R}) \rightarrow \mathbb{R}$ ,  $A \mapsto \det A$ . Consequently,

$$\text{SL}_n(\mathbb{R}) := \{A \in M_n(\mathbb{R}) \mid \det A = 1\}$$

is a manifold of dimension  $\dim M_n(\mathbb{R}) - 1 = n^2 - 1$ .

Let us compute the tangent space to  $\text{SL}_n(\mathbb{R})$  at the point  $\mathbf{1}$ . To this end, it is convenient to identify  $M_n(\mathbb{R})$  with  $\mathbb{R}^{n^2}$ . Recalling that

$$\det A = \sum_{\sigma} \text{sign } \sigma a_{1\sigma(1)} \cdots a_{n\sigma(n)},$$

where  $\sigma$  runs through all permutations of the set  $\{1, \dots, n\}$ , for any  $B \in M_n(\mathbb{R})$  we obtain

$$\det(\mathbb{1} + tB) = (1 + tb_{11})(1 + tb_{22}) \dots (1 + tb_{nn}) + \sum_{\sigma \neq id} \text{sign } \sigma (\delta_{1\sigma(1)} + tb_{1\sigma(1)})(\delta_{2\sigma(2)} + tb_{2\sigma(2)}) \dots (\delta_{n\sigma(n)} + tb_{n\sigma(n)}).$$

Notice that for any  $\sigma \neq id$ ,  $\sigma(i) \neq i$  at least for two values of  $i$ . Hence, the last term in the above expression is  $o(t)$ . This yields

$$\det(\mathbb{1} + tB) = (\mathbb{1} + t \text{tr } B + o(t)) + o(t).$$

Consequently,  $(d_{\mathbb{1}} \det) B = \text{tr } B$  and therefore

$$T_{\mathbb{1}}\text{SL}_n(\mathbb{R}) = \{B \in M_n(\mathbb{R}) \mid \text{tr } B = 0\}.$$

(iii) Let  $\text{Sym}^n(\mathbb{R}) \subset M_n(\mathbb{R})$  denote the subspace of all symmetric matrices. One can show that the identity matrix  $\mathbb{1} \in \text{Sym}^n(\mathbb{R})$  is a regular value of the map

$$f: M_n(\mathbb{R}) \rightarrow \text{Sym}^n(\mathbb{R}), \quad f(A) = A \cdot A^t. \quad (2.52)$$

Consequently,

$$O(n) := \{A \in M_n(\mathbb{R}) \mid A \cdot A^t = \mathbb{1}\}$$

is a manifold and

$$\dim O(n) = \dim M_n(\mathbb{R}) - \dim \text{Sym}^n(\mathbb{R}) = n^2 - \frac{n(n+1)}{2} = \frac{n(n-1)}{2}.$$

Notice that if we would consider (2.52) as a map  $M_n(\mathbb{R}) \rightarrow M_n(\mathbb{R})$ , then  $\mathbb{1}$  would not be a regular value.

Just like in the case of  $\text{SL}_n(\mathbb{R})$ , let us compute the tangent space to  $O(n)$  at the point  $\mathbb{1}$ . We have

$$f(\mathbb{1} + sB) = (\mathbb{1} + sB) \cdot (\mathbb{1} + sB)^t = \mathbb{1} + s(B + B^t) + o(s).$$

Hence,  $d_{\mathbb{1}}f(B) = B + B^t$  and

$$T_{\mathbb{1}}O(n) = \{B \in M_n(\mathbb{R}) \mid B^t = -B\}.$$

We finish this section by Sard's theorem, which, loosely speaking, says that for any smooth map almost any point is a regular value. More precisely, we say that a subset  $A$  of a smooth  $k$ -manifold  $M$  is of measure zero, if for any chart  $(U, \varphi)$  on  $M$  the set  $\varphi(A \cap U) \subset \mathbb{R}^k$  is of measure zero.

**Theorem 2.53** (Sard). *Let  $f: M \rightarrow N$  be a smooth map between smooth manifolds. Then almost any point  $n \in N$  is a regular value of  $f$ , that is the set of critical values for  $f$  is of measure zero.*  $\square$

A proof of Sard's theorem can be found for example in [BT03, 9.4] or [Mil65, §3].

## 2.6 Immersions and embeddings

Just like maps with surjective differentials can be conveniently described as projections after applying a diffeomorphism, the maps with injective differentials admit an analogous description. We begin, however, with the following auxiliary result.

**Theorem 2.54.** *Let  $U$  be an open subset of  $\mathbb{R}^k$  containing the origin and  $f: U \rightarrow \mathbb{R}^k \times \mathbb{R}^\ell$  be a smooth map such that  $f(0) = 0$  and*

$$D_0 f_1: \mathbb{R}^k \rightarrow \mathbb{R}^k, \quad \text{where } f_1 := \pi_1 \circ f,$$

*is an isomorphism. Then there exists a neighbourhood  $V \subset \mathbb{R}^{k+\ell}$  of the origin and a diffeomorphism  $\theta: V \rightarrow \theta(V) \subset \mathbb{R}^{k+\ell}$  such that  $\theta \circ f = \iota_1$  and  $\theta(V \cap f(U)) = \theta(V) \cap (\mathbb{R}^k \times \{0\})$ .*

*Proof.* The proof of this theorem is similar to the proof of [Theorem 2.39](#).

Thus, consider the map

$$F: U \times \mathbb{R}^\ell \rightarrow \mathbb{R}^{k+\ell} = \mathbb{R}^k \times \mathbb{R}^\ell, \quad F(x, y) := f(x) + (0, y) = (f_1(x), f_2(x) + y).$$

The differential of this map

$$D_0 F = \begin{pmatrix} D_0 f_1(0) & 0 \\ D_0 f_2(0) & \text{id}_{\mathbb{R}^\ell} \end{pmatrix}$$

is an isomorphism. Hence, there exists a neighbourhood  $V$  of the origin and a diffeomorphism  $\theta: V \rightarrow \theta(V)$  such that

$$\theta \circ F = \text{id}_{\theta(V)}.$$

In particular, for any  $(x, 0) \in \theta(V)$  the above equality yields:

$$\theta \circ F(x, 0) = \theta \circ f(x) = \iota_1(x) \quad \implies \quad \theta \circ f = \iota_1.$$

Hence,  $\theta(V) \cap (\mathbb{R}^k \times \{0\}) \subset \theta(V \cap f(U))$ .

To show the converse inclusion, let  $(x, y) \in \theta(V \cap f(U))$ . Hence, there exists some  $(z, w) \in V \cap f(U)$  such that  $(x, y) = \theta(z, w)$ . In this case we must have  $(z, w) = f(x)$  for some  $x \in U$  and therefore

$$(x, y) = \theta(z, w) = \theta \circ f(x) = (x, 0).$$

Thus,  $y = 0$  and  $(x, 0) \in V$ , which yields  $\theta(V \cap f(U)) \subset \theta(V) \cap (\mathbb{R}^k \times \{0\})$ .  $\square$

**Definition 2.55.** A smooth map  $f: M^k \rightarrow N^\ell$  such that  $d_m f$  is injective at each point  $m \in M$  is called an *immersion*. An immersion, which is a diffeomorphism onto a  $k$ -submanifold of  $N$ , is called an *embedding*.

Clearly, an immersion  $f: M \rightarrow N$  can exist only if  $\dim M \leq \dim N$ . Notice also, that by [Theorem 2.54](#) each immersion is locally injective, however an immersion does not need to be globally injective. Even if an immersion is injective, this may fail to be an embedding. This is shown schematically on [Figures 2.4](#) and [2.5](#) below. In particular, the image of an immersion does not need to be a submanifold.

**Proposition 2.56.** *An immersion which is a homeomorphism onto its image is an embedding.*

*Proof.* Denote  $k := \dim M$  and  $\ell := \dim N$ . The proof consists of the following 3 steps.

**Step 1.** *For any  $m \in M$  there exists a chart  $(V, \psi)$  on  $N$  centered at  $n := f(m)$  with the following properties:*



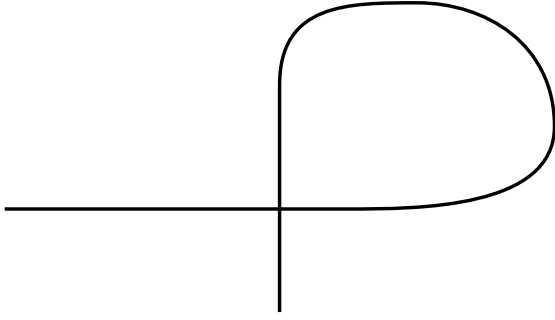


Figure 2.4: The image of a non-injective immersion  $\mathbb{R} \rightarrow \mathbb{R}^2$ .

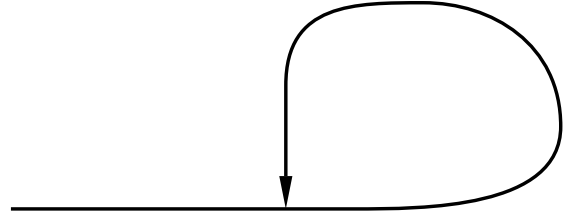


Figure 2.5: The image of an injective immersion  $\mathbb{R} \rightarrow \mathbb{R}^2$ , which is not an embedding.

- $d_n \psi_1|_{\text{Im } d_m f}: \text{Im } d_m f \rightarrow \mathbb{R}^k$  is an isomorphism, where  $\psi_1 = \pi_1 \circ \psi$  and  $\pi_1: \mathbb{R}^\ell = \mathbb{R}^k \oplus \mathbb{R}^{\ell-k} \rightarrow \mathbb{R}^k$  is the projection.
- There exists a neighbourhood  $U$  of  $m$  such that  $f(U) = V \cap f(M)$ .

Since  $f$  is a homeomorphism onto its image,  $f: M \rightarrow f(M)$  is an open map. In particular, for any open  $\hat{U} \subset M$  there exists an open subset  $\hat{V} \subset N$  such that  $f(\hat{U}) = \hat{V} \cap f(M)$ . If  $\hat{U}$  is a neighbourhood of  $m$ , we can choose a chart  $(V, \xi)$  centered at  $n$  such that  $V \subset \hat{V}$ .

Furthermore, since  $d_n \xi: T_n N \rightarrow \mathbb{R}^\ell$  is an isomorphism and  $\text{Im } d_m f$  is a  $k$ -dimensional subspace of  $T_n N$ , we can find a linear isomorphism  $A: \mathbb{R}^\ell \rightarrow \mathbb{R}^\ell$  such that

$$A(d_n \xi(\text{Im } d_m f)) = \mathbb{R}^k \times \{0\}.$$

Then  $(V, \psi) = (V, A \circ \xi)$  is the required chart. Also, setting  $U := f^{-1}(V)$  we obtain  $f(U) = V \cap f(M)$ .

**Step 2.**  $f(M)$  is a submanifold of  $N$ .

Pick any  $m \in M$  and a chart  $(U, \varphi)$  centered at  $m$ . Pick also a chart  $(V, \psi)$  as in the previous step. Denote also  $W := \psi(V) \subset \mathbb{R}^\ell$ .

Let  $F = \psi \circ f \circ \varphi^{-1}$  be the coordinate representation of  $f$ . Denoting  $F_1 := \pi_1 \circ F: \mathbb{R}^k \rightarrow \mathbb{R}^k$ , we have

$$D_0 F_1(0) = D_0 \pi_1 \circ D_0 F = D_0 \pi_1 \circ d_n \psi \circ d_m f \circ d_0 \varphi^{-1} = d_n \psi_1 \circ d_m f \circ d_0 \varphi^{-1}$$

Since  $d_0 \varphi^{-1}$  is an isomorphism, by Step 1 we obtain that  $D_0 F_1$  is injective. Hence,  $D_0 F_1$  is an isomorphism. Hence, by Theorem 2.54 we can find a diffeomorphism<sup>1</sup>  $\theta: W \rightarrow \theta(W) \subset \mathbb{R}^\ell$  such that

$$\theta \circ F = \iota_1 \iff (\theta \circ \psi) \circ f \circ \varphi^{-1} = \iota_1$$

Denote  $\hat{\psi} := \theta \circ \psi$ . Then  $(W, \hat{\psi})$  is a chart on  $N$  adapted to  $f(M)$ .

**Step 3.**  $f$  is a diffeomorphism between  $M$  and  $f(M)$ .

<sup>1</sup>Without loss of generality we may assume that  $V$  was chosen so that  $\theta$  is defined everywhere on  $W$ .

Let  $(U, \varphi)$  and  $(W, \hat{\psi})$  be as in the preceding step. By the construction of  $\hat{\psi}$ , the coordinate representation of  $f$  is  $\hat{\psi} \circ f \circ \varphi^{-1} = \nu_1: \mathbb{R}^k \rightarrow \mathbb{R}^\ell$ . Since the restriction of  $\pi_1 \circ \psi$  to  $f(M) \cap W$  is a chart on  $f(M)$ , the coordinate representation of  $f$  viewed as a map  $f: M \rightarrow f(M)$  is given by

$$\pi_1 \circ \hat{\psi} \circ f \circ \varphi^{-1} = \pi_1 \circ \nu_1 = \text{id}.$$

Hence,  $f$  is a local diffeomorphism. Since  $f: M \rightarrow f(M)$  is bijective, this is a diffeomorphism.  $\square$

**Corollary 2.57.** *If  $M$  is compact, then any injective immersion  $f: M \rightarrow N$  is an embedding.*

*Proof.* Pick a closed subset  $A \subset M$ . Since  $A$  is closed in  $M$ ,  $A$  is compact and therefore  $f(A)$  is compact in  $N$ . Since  $N$  is Hausdorff,  $f(A)$  is closed. Hence,  $f$  is a closed map, i.e., the image of any closed subset is closed. This means that  $f^{-1}: f(M) \rightarrow M$  is continuous, that is,  $f: M \rightarrow f(M)$  is a homeomorphism. The statement of this corollary now follows immediately from [Proposition 2.56](#).  $\square$

[Theorem 2.47](#) combined with Sard's theorem allows us to construct many smooth manifolds, which are in fact submanifolds of Euclidean spaces. It turns out that any smooth manifold can be embedded into some Euclidean space, see, however, the discussion in the following section. Here we prove a version of this result in the case when the manifold under consideration is compact.

**Theorem 2.58.** *Any smooth compact manifold admits an embedding into some Euclidean space.*

*Proof.* For any  $m \in M$  choose a chart  $(U_m, \varphi_m)$ . Pick also open neighbourhoods  $W_m \subset V_m$  and a bump function  $\rho_m$  such that the following holds:

- $\overline{W}_m \subset U_m$ ;
- $\rho_m|_{\overline{W}_m} \equiv 1$  and  $\rho_m < 1$  outside of  $\overline{W}_m$ ;
- $\rho_m$  vanishes outside of  $V_m$ .

Since  $M$  is compact, there is a finite subset  $\{m_1, \dots, m_p\}$  of  $M$  such that  $\{W_i\}$  cover all of  $M$ , where  $W_i := W_{m_i}$ . Consider each  $\psi_i := \rho_i \cdot \varphi_i := \rho_{m_i} \cdot \varphi_{m_i}$  as a smooth map  $M \rightarrow \mathbb{R}^k$  (extended by zero outside of  $V_m$ ), where  $k = \dim M$ . Finally, define

$$f: M \rightarrow \mathbb{R}^{pk+p} \quad \text{by} \quad f(m) = (\psi_1(m), \dots, \psi_p(m), \rho_1(m), \dots, \rho_p(m)).$$

Clearly,  $f$  is smooth. I claim that this map is also injective. Indeed, pick any two distinct points  $m$  and  $\hat{m}$ . Without loss of generality, we can assume  $m \in W_1$ . If  $\hat{m} \in \overline{W}_1$ , then  $\psi_1(m) = \varphi_1(m) \neq \varphi_1(\hat{m}) = \psi_1(\hat{m})$ . If  $\hat{m} \notin \overline{W}_1$ , then  $1 = \rho_1(m) \neq \rho_1(\hat{m})$ , so that  $f$  is injective indeed.

Furthermore, assuming  $m \in W_1$  again,  $d_m \psi_1: T_m M \rightarrow \mathbb{R}^k$  is an isomorphism, in particular,  $d_m \psi_1$  is injective. Hence,  $d_m f: T_m M \rightarrow \mathbb{R}^{kp+p}$  is injective at any  $m \in M$ . By [Corollary 2.57](#),  $f$  is an embedding.  $\square$

## 2.7 The second countability axiom, the Whitney embedding theorem, and the existence of a partition of unity

Let  $(X, \mathcal{T})$  be a topological space. Recall that a subset  $\mathcal{B} \subset \mathcal{T}$  is called a basis of  $\mathcal{T}$  if any point in  $X$  has a neighbourhood  $U \in \mathcal{B}$ . Equivalently, this means that any open subset in  $X$  can be represented as a union of subsets from  $\mathcal{B}$ .

**Definition 2.59.**  $X$  is said to satisfy the second axiom of countability (or, simply,  $X$  is second countable) if  $X$  admits a countable basis of its topology.

For example, the set  $\{B_r(x) \mid r \in \mathbb{Q}_{>0}, x \in \mathbb{Q}^n\}$  is a countable basis of the standard topology of  $\mathbb{R}^n$ . In particular,  $\mathbb{R}^n$  is second countable.

Notice that any subspace of a second countable space is itself second countable.

Coming back to manifolds, notice that if a smooth manifold  $M$  can be embedded into some Euclidean space,  $M$  must be second countable. However, albeit any manifold according to Definition 2.5 is locally second countable, there may be no global countable base of its topology. Indeed, since any disjoint union of manifolds is again a manifold, the disjoint union of an uncountable family of manifolds is not second countable, and therefore does not admit an embedding into an Euclidean space. For this reason as well as some other ones, it is customary to restrict attention to second countable manifolds. With this in mind, from now on we replace Definition 2.5 by the following one.

**Definition 2.60.** A Hausdorff *second countable* topological space  $M$  is said to be a topological manifold of dimension  $k \in \mathbb{N}_0$ , if  $M$  is locally homeomorphic to  $\mathbb{R}^k$ . A smooth manifold is a topological manifold equipped with a smooth atlas (structure).

Of course, strictly speaking, at this point we should check that all constructions of manifolds we met before yield second countable manifolds if we start with second countable ones. I leave this as a (simple) exercise to the reader.

It turns out that adding the second countability to the definition of a manifold suffices to prove the following generalization of [Theorem 2.58](#).

**Theorem 2.61** (Whitney's embedding theorem). *Any smooth manifold admits an embedding into some Euclidean space.* □

The proof of the above theorem is omitted here, but an interested reader may consult [[War83](#)] for a detailed discussion of these matters.

Another topic related to this one is the existence of a partition of unity (subordinate to a given covering). We have seen in the preceding chapter that partitions of unity are useful objects: Besides allowing one to define the notion of integral, this is an indispensable tool for various existence questions which were not discussed here because of lack of time. I just mention two examples here: Using the existence of partitions of unity one can show, and rather trivially, that any abstract manifold admits a Riemannian metric and that any smooth function on a submanifold can be obtained as a restriction of a smooth function on an ambient manifold.

Observe that Whitney's embedding theorem implies the existence of partitions of unity. Indeed, we have seen that  $\mathbb{R}^n$  admits a partition of unity subordinate to any open covering. If  $M$  is embedded into  $\mathbb{R}^n$ , one can simply restrict a given partition of unity to  $M$  to obtain the existence on  $M$ .

**Exercise 2.62.** Check that the proof of [Theorem 1.101](#) goes through for any compact manifold thus proving directly that compact manifolds admit partitions of unity subordinate to any given open covering.

Whitney's embedding theorem shows that any (abstract) manifold  $M$  can be thought of as a submanifold of an Euclidean space. In other words, we could have defined manifolds as subspaces of Euclidean spaces admitting charts<sup>2</sup> at each point. Some authors do take this point

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<sup>2</sup>More precisely, admitting adapted charts.

of view arguing that this yields the same pool of examples. While it is true of course that this yields the same pool of examples, manifolds often do not arise as subsets of Euclidean spaces. For example, the real projective space is not obviously contained in any Euclidean space (and it is even not so obvious how to construct an embedding). Even if one decides to work with submanifolds of Euclidean spaces only, one finds pretty soon that certain useful constructions, for example taking quotients by group actions, are incompatible with this setting. More importantly, it is useful to distinguish “inner” properties of manifolds from those of an embedding. All these reasons led to the necessity to separate abstract manifolds from their particular realizations as submanifolds.

## 2.8 The tangent bundle

It is convenient to recall certain constructions from linear algebra first. Thus, let  $V$  be a vector space of dimension  $k$ . Any basis  $v = (v_1, \dots, v_k)$  of  $V$  yields an isomorphism

$$\mathbb{R}^k \longrightarrow V, \quad y \longmapsto \sum_{j=1}^k y_j v_j = v \cdot y$$

Conversely, if  $\varphi: \mathbb{R}^k \longrightarrow V$  is a linear isomorphism, then the image of the standard basis of  $\mathbb{R}^k$  is a basis of  $V$ . This yields a bijective correspondence between the set of all bases of  $V$  and the set of all isomorphisms  $\mathbb{R}^k \rightarrow V$ .

If  $w = (w_1, \dots, w_k)$  is another basis of  $V$ , we obtain the change-of-basis matrix  $B$  as follows. Writing

$$w_j = \sum_{i=1}^k b_{ij} v_i \tag{2.63}$$

we set  $B = (b_{ij})$ . Then (2.63) is equivalent to

$$w = v \cdot B$$

where  $\cdot$  represents matrix multiplication.

With these preliminaries at hand, suppose that  $M$  is a manifold of dimension  $k$ . Pick a point  $m \in M$  and a chart  $(U, \varphi)$  such that  $m \in U$ . Denote  $p := \varphi(m) \in \mathbb{R}^k$ . We obtain a basis of  $T_m M$  as follows:

$$v_\varphi = v := ([\gamma_1], \dots, [\gamma_k]), \tag{2.64}$$

where  $\gamma_j(t) = \varphi^{-1}(p + te_j)$  and  $e = (e_1, \dots, e_k)$  is the standard basis of  $\mathbb{R}^k$ , see Remark 2.27.

*Remark 2.65.* As we have seen in the preceding chapter, for a surface  $S \subset \mathbb{R}^3$  a choice of a parametrization  $\psi = \psi(u, v)$  yields a basis  $(\partial_u \psi, \partial_v \psi)$  of  $T_{\psi(u,v)} S$ . For abstract manifolds (2.64) plays a rôle similar to the one  $(\partial_u \psi, \partial_v \psi)$  plays for surfaces.

If  $(\widehat{U}, \widehat{\varphi})$  is another chart such that  $m \in \widehat{U}$ , we obtain another basis

$$v_{\widehat{\varphi}} = \widehat{v} := ([\widehat{\gamma}_1], \dots, [\widehat{\gamma}_k]),$$

where  $\widehat{\gamma}_j(t) = \widehat{\varphi}^{-1}(\widehat{p} + te_j)$  and  $\widehat{p} = \widehat{\varphi}(m)$ .

**Proposition 2.66.** *Let  $\theta := \widehat{\varphi} \circ \varphi^{-1}: \mathbb{R}^k \longrightarrow \mathbb{R}^k$  be the coordinate transformation map. Then the change-of-basis matrix between  $v$  and  $\widehat{v}$  is  $D_p \theta$ :  $v = \widehat{v} \cdot D_p \theta$ .*

*Proof.* Without loss of generality we can assume  $p = 0 = \widehat{p}$ . We have

$$\widehat{\varphi} \circ \gamma_j(t) = \underbrace{\widehat{\varphi} \circ \varphi^{-1}}_{\theta} \circ \underbrace{\varphi \circ \gamma_j(t)}_{te_j} = \theta(te_j).$$

Hence,

$$d_m \widehat{\varphi}[\gamma_j] = \left. \frac{d}{dt} \right|_{t=0} \theta(te_j) = \sum_{i=1}^k \frac{\partial \theta_i}{\partial x_j} e_i, \quad (2.67)$$

where the partial derivatives are evaluated at the origin (suppressed in the notations).

Notice, however,

$$\widehat{\varphi} \circ \widehat{\gamma}_i(t) = te_i \quad \implies \quad d_m \widehat{\varphi}[\widehat{\gamma}_i] = e_i.$$

Hence, by (2.67) we obtain

$$d_m \widehat{\varphi}[\gamma_j] = \sum_{i=1}^k \frac{\partial \theta_i}{\partial x_j} d_m \widehat{\varphi}([\widehat{\gamma}_i]) = d_m \widehat{\varphi} \left( \sum_{i=1}^k \frac{\partial \theta_i}{\partial x_j} [\widehat{\gamma}_i] \right).$$

where the second equality holds by the linearity of  $d_m \widehat{\varphi}$ .

Since  $\widehat{\varphi}: \widehat{U} \rightarrow \widehat{\varphi}(\widehat{U}) \subset \mathbb{R}^k$  is a diffeomorphism,  $d_m \widehat{\varphi}$  is an isomorphism. Hence,

$$[\gamma_j] = \sum_{i=1}^k \frac{\partial \theta_i}{\partial x_j} [\widehat{\gamma}_i],$$

which finishes the proof. □

Consider the set

$$TM = \bigsqcup_{m \in M} T_m M,$$

where the symbol  $\bigsqcup$  denotes the disjoint union.

This comes equipped with the map

$$\pi: TM \longrightarrow M, \quad \pi(v) = m \iff v \in T_m M.$$

**Example 2.68.** Just as in Exercise 2.32 for a vector space  $V$  with the help of the canonical isomorphism  $T_v V \cong V$  we obtain

$$TV = \bigsqcup_{v \in V} \{v\} \times V = V \times V$$

and  $\pi(v, w) = v$  is the projection onto the first component.

Furthermore, for any chart  $(U, \varphi)$  on  $M$  we have a basis  $v_{\varphi(m)}$  of  $T_m M$  for each  $m \in U$ . Therefore, we obtain the bijection

$$U \times \mathbb{R}^k \longrightarrow \pi^{-1}(U) = \bigsqcup_{m \in U} T_m M, \quad (m, y) \longmapsto v_{\varphi(m)} \cdot y = \sum_{j=1}^k y_j [\gamma_j^m],$$

where  $\gamma_j^m(t) = \varphi^{-1}(\varphi(m) + te_j)$ . Combining this with  $\varphi: U \rightarrow \varphi(U)$ , which is also a bijection, we obtain a bijective map

$$\tau = \tau_{\varphi}: \varphi(U) \times \mathbb{R}^k \longrightarrow \pi^{-1}(U), \quad (x, y) \longmapsto v_{\varphi(m)} \cdot y = \sum_{j=1}^k y_j [\gamma_j^m],$$

where  $m = \varphi^{-1}(x)$ .

**Theorem 2.69.** Let  $\mathcal{U} = \{ (U_\alpha, \varphi_\alpha) \mid \alpha \in A \}$  be a smooth atlas on  $M$ . There exists a unique Hausdorff second countable topology on  $TM$  such that

$$\mathcal{V} = \{ (\pi^{-1}(U_\alpha), \tau_\alpha^{-1}) \mid \alpha \in A \}$$

is a  $C^0$ -atlas on  $TM$ , where  $\tau_\alpha = \tau_{\varphi_\alpha}$ . In fact,  $\mathcal{V}$  is a smooth atlas so that  $TM$  is a smooth manifold of dimension  $2k$ . Moreover,  $\pi$  is a smooth map with surjective differential at each point.

*Proof.* The proof consists of the following steps.

**Step 1.** For the coordinate transformation  $\Theta_{\alpha\beta} = \tau_\alpha^{-1} \circ \tau_\beta$  on  $TM$  we have

$$\Theta_{\alpha\beta}(x, y) = (\theta_{\alpha\beta}(x), D_x \theta_{\alpha\beta} \cdot y).$$

In particular,  $\Theta_{\alpha\beta}$  is smooth.

Denote  $\tau_\beta(x, y) = v$  that is  $\varphi_\beta(\pi(v)) = x$  and  $v = v_\beta(\varphi_\beta^{-1}(x)) \cdot y$ . Denoting  $m = \varphi_\beta^{-1}(x)$  and recalling **Proposition 2.66**, we obtain

$$v_\beta(m) = v_\alpha(m) D_x \theta_{\alpha\beta}.$$

Denoting also  $\tau_\alpha^{-1}(v) = (s, t) \in \mathbb{R}^k \times \mathbb{R}^k$ . Since  $v = v_\beta(m) \cdot y = v_\alpha \cdot D\theta_{\alpha\beta} \cdot y$ , we obtain

$$s = \varphi_\alpha^{-1}(\pi(v)) = \varphi_\alpha(\varphi_\beta^{-1}(x)) = \theta_{\alpha\beta}(x) \quad \text{and} \quad t = D\theta_{\alpha\beta} \cdot y.$$

**Step 2.** There is a unique Hausdorff second countable topology on  $TM$  such that each  $\tau_\alpha$  is a homeomorphism onto its image.

Declare a set  $V \subset TM$  open if and only if  $\tau_\alpha^{-1}(V)$  is open in  $\mathbb{R}^{2k}$  for any  $\alpha \in A$ . We have

- (i)  $\emptyset$  is open and  $\tau_\alpha^{-1}(TM) = \varphi_\alpha(U_\alpha) \times \mathbb{R}^k$  is open.
- (ii)  $V_1, V_2$  are open  $\Rightarrow \tau_\alpha^{-1}(V_1 \cap V_2) = \tau_\alpha^{-1}(V_1) \cap \tau_\alpha^{-1}(V_2)$  is open  $\Rightarrow V_1 \cap V_2$  is open
- (iii) Each  $V_\beta, \beta \in B$ , is open  $\Rightarrow \tau_\alpha^{-1}(\cup_{\beta \in B} V_\beta) = \cup_{\beta \in B} \tau_\alpha^{-1}(V_\beta)$  is open  $\Rightarrow \cup_{\beta \in B} V_\beta$  is open.

Hence, we obtain a topology on  $TM$  such that each  $(\pi^{-1}(U_\alpha), \tau_\alpha^{-1})$  is a chart on  $TM$  and, moreover,  $\pi$  is a continuous map.

This topology is Hausdorff. Indeed, pick  $v_1, v_2 \in TM, v_1 \neq v_2$  and consider the following cases:

- (a) If  $\pi(v_1) \neq \pi(v_2)$ , choose open subsets  $U_1, U_2 \subset M$  such that  $U_1$  and  $U_2$  separate  $\pi(v_1)$  and  $\pi(v_2)$ . Then  $\pi^{-1}(U_1)$  and  $\pi^{-1}(U_2)$  separate  $\pi(v_1)$  and  $\pi(v_2)$ .
- (b) If  $\pi(v_1) = \pi(v_2) =: m$ . Pick any chart  $(U, \varphi)$  such that  $m \in U$ . Then  $\tau(U \times V_1)$  and  $\tau(U \times V_2)$  separate  $v_1$  and  $v_2$  if  $V_1, V_2 \subset \mathbb{R}^k$  separate  $\pi_2(\tau^{-1}(v_1))$  and  $\pi_2(\tau^{-1}(v_2))$ .

Furthermore, the constructed topology is second countable for the following reason: Let  $U_i$  be a countable basis of the topology of  $M$  and  $V_j$  be a countable basis for  $\mathbb{R}^k$ . Without loss of generality we can assume that each  $U_i$  is contained in some chart  $U_{\alpha_i}$ . Then the collection of all sets of the form

$$\tau_{\alpha_i}(\varphi_{\alpha_i}(U_i) \times V_j)$$

is a countable basis for the topology of  $TM$ .

**Step 3.** We finish the proof of this theorem.

Pick a chart  $(U_\alpha, \varphi_\alpha)$  on  $M$ , hence also a chart  $(\pi^{-1}(U_\alpha), \tau_\alpha^{-1})$  on  $TM$ . The coordinate representation of  $\pi$  with respect to these charts is

$$\varphi_\alpha \circ \pi \circ \tau_\alpha(x, y) = \varphi_\alpha(\varphi_\alpha^{-1}(x)) = x \quad \implies \quad \varphi_\alpha \circ \pi \circ \tau_\alpha = \pi_1.$$

Hence,  $\pi$  is smooth and  $d_v\pi$  is surjective. □

Let  $M \subset \mathbb{R}^n$  be a submanifold. To simplify the exposition somewhat, assume that  $M = f^{-1}(0)$ , where  $f \in C^\infty(\mathbb{R}^n)$  and  $0$  is a regular value of  $f$  (and, hence,  $M$  is a hypersurface).

Let  $v$  be any tangent vector at  $m \in M$  represented by a curve  $\gamma$  through  $m$ . Thinking of  $\gamma$  as a curve in  $\mathbb{R}^n$ , we obtain a natural well-defined map  $p: TM \rightarrow \mathbb{R}^n$  given by  $p(v) = \dot{\gamma}(0)$ . Combining this with the projection  $\pi$ , we obtain the map

$$i: TM \longrightarrow \mathbb{R}^n \times \mathbb{R}^n, \quad i(v) = (\pi(v), p(v)).$$

Define  $\Phi: \mathbb{R}^n \times \mathbb{R}^n \rightarrow \mathbb{R}^2$  by  $\Phi(x, y) = (f(x), \langle \nabla f(x), y \rangle)$ . The reader should check that  $0$  is a regular value of  $\Phi$ . Moreover,  $\Phi^{-1}(0) = i(TM)$  and  $i$  is an embedding. In particular, the tangent bundle of a hypersurface is an embedded submanifold.

For example, for  $M = S^k \subset \mathbb{R}^{k+1}$ , we have

$$TS^k = \{(x, y) \in S^k \times \mathbb{R}^{k+1} \mid \langle x, y \rangle = 0\} \subset \mathbb{R}^{2k+2}.$$

In particular, for  $k = 1$  we obtain that  $TS^1$  is a 2-submanifold of  $\mathbb{R}^4$ .

In fact, we can realize  $TS^1$  as a submanifold of  $\mathbb{R}^3$  in the following sense. Consider the map

$$f: S^1 \times \mathbb{R} \rightarrow \mathbb{R}^4, \quad f(x_0, x_1; t) = (x_0, x_1, tx_1, -tx_0).$$

One can check that  $f$  is a diffeomorphism between  $S^1 \times \mathbb{R} \subset \mathbb{R}^3$  and  $TS^1$  so that we can in fact identify  $TS^1$  with an infinite cylinder.

It is not too hard to generalize the above arguments to show that if  $M \subset \mathbb{R}^n$  is any embedded submanifold, then  $i: TM \rightarrow \mathbb{R}^{2n}$  is an embedding. I leave it to the reader to work out the details of this statement.

## 2.9 Vector fields and their integral curves

**Definition 2.70.** A smooth map  $v: M \rightarrow TM$  such that

$$\pi \circ v = id_M \quad \iff \quad v(m) \in T_m M$$

is called a (smooth) *vector field* on  $M$ .

For example, the map

$$v: S^1 \rightarrow \mathbb{R}^2, \quad v(x) = (x, (-x_1, x_0))$$

is a (smooth) vector field on  $S^1$ . Since the first component of  $v$  must be  $x$  by the very definition of a vector field, usually one omits the first component and writes simply

$$v(x) = (-x_1, x_0). \tag{2.71}$$

Denote

$$\mathfrak{X}(M) := \{v: M \rightarrow TM \text{ is a vector field}\}.$$

Clearly,  $\mathfrak{X}(M)$  is a real vector space with respect to the following operations:

- $(v_1 + v_2)(m) := v_1(m) + v_2(m)$ , where  $v_1, v_2 \in \mathfrak{X}(M)$ ;
- $(\lambda v)(m) = \lambda v(m)$ , where  $v \in \mathfrak{X}(M)$  and  $\lambda \in \mathbb{R}$ .

In fact, any vector field can be multiplied by any smooth function:

$$(f \cdot v)(m) = f(m)v(m), \quad \text{where } v \in \mathfrak{X}(M) \text{ and } f \in C^\infty(M).$$

We summarize this in the following.

**Proposition 2.72.** *The set  $\mathfrak{X}(M)$  of all vector fields on  $M$  has the structure of a module over  $C^\infty(M)$  with respect to the pointwise addition and multiplication.* □

**Example 2.73.** Consider  $M = \mathbb{R}^k$ . We have seen that  $T\mathbb{R}^k \cong \mathbb{R}^k \times \mathbb{R}^k$  and that the natural projection equals  $\pi_1$ . Hence, a vector field is a map of the form

$$v(x) = (x, y(x)),$$

where  $y \in C^\infty(\mathbb{R}^k; \mathbb{R}^k)$ . Hence, we can identify  $\mathfrak{X}(\mathbb{R}^k)$  with  $C^\infty(\mathbb{R}^k; \mathbb{R}^k)$  via the map

$$v = (id_{\mathbb{R}^k}, y) \mapsto y.$$

More formally, this map is an isomorphism of  $C^\infty(M)$ -modules.

Generalizing the above example slightly, pick a chart  $(U, \varphi)$  on a manifold  $M$ . Since

$$v_\varphi(m) := ([\gamma_1^m], \dots, [\gamma_k^m]), \quad \text{where } \gamma_j^m(t) := \varphi^{-1}(\varphi(m) + te_j),$$

is a basis of  $T_m M$ , we can find the coordinates  $(y_1(m), \dots, y_k(m))$  of  $v(m)$  with respect to this basis. In other words,  $y: U \rightarrow \mathbb{R}^k$  is a map such that

$$v(m) = v_\varphi(m) \cdot y(m)$$

holds at any point  $m \in U$ . Notice that the map  $y$  is well defined even if  $v$  is not necessarily smooth. This map is called *the coordinate (or local) representation of  $v$*  with respect to the chart  $(U, \varphi)$ .

**Proposition 2.74.** *The map  $v: M \rightarrow TM$  satisfying  $\pi \circ v = id_M$  is a smooth vector field if and only if for each chart  $(U, \varphi)$  as above the coordinate representation  $y$  of  $v$  is smooth.*

*Proof.* Recall that for any chart  $(U, \varphi)$  on  $M$  as above we constructed a chart  $(\pi^{-1}(U), \tau_\varphi^{-1})$  on  $TM$ . Just by the definitions of  $\tau_\varphi$  and  $y$ , for the coordinate representation of  $v$  with respect to these charts we have

$$\tau_\varphi^{-1} \circ v \circ \varphi^{-1}(x) = (x, y \circ \varphi^{-1}(x)).$$

Hence,  $v$  is smooth if and only if  $y$  is smooth. □

Thus, locally over each chart  $U$  vector fields can be identified with smooth vector-valued maps just as in Example 2.73. It turns out, however, that in general no such identification can exist.

Let  $\gamma: (a, b) \rightarrow M$  be a smooth curve. At any point  $t \in (a, b)$  we define *the tangent vector*  $\dot{\gamma}(t) \in T_{\gamma(t)}M$  to  $\gamma$  by

$$\dot{\gamma}(t) := [s \mapsto \gamma_t(s)] \quad \text{where } \gamma_t(s) := \gamma(t + s).$$



**Definition 2.75** (Integral curves). A (smooth) curve  $\gamma$  is called an *integral curve* of a vector field  $v$  if

$$\dot{\gamma}(t) = v(\gamma(t))$$

holds for any  $t \in (a, b)$ .

**Example 2.76.** Consider the curve  $\gamma: \mathbb{R} \rightarrow S^1$ ,  $\gamma(t) = (\cos t, \sin t)$ . We have  $\dot{\gamma}(t) = (-\sin t, \cos t)$ . Furthermore, if  $v$  is given by (2.71), then

$$v \circ \gamma(t) = (-\sin t, \cos t).$$

Hence,  $\gamma$  is an integral curve of (2.71).

Let us consider integral curves on  $\mathbb{R}^k$  in some detail. Thus, represent a vector field  $v \in \mathfrak{X}(\mathbb{R}^k)$  by a smooth map  $y: \mathbb{R}^k \rightarrow \mathbb{R}^k$  just as in Example 2.73 above. A map  $\gamma: (a, b) \rightarrow \mathbb{R}^k$  is an integral curve of  $v$  if and only if

$$\dot{\gamma}(t) = y(\gamma(t)) \iff \begin{cases} \dot{\gamma}_1(t) = y_1(\gamma_1(t), \dots, \gamma_k(t)), \\ \dots\dots\dots \\ \dot{\gamma}_k(t) = y_k(\gamma_1(t), \dots, \gamma_k(t)), \end{cases} \quad (2.77)$$

holds for any  $t \in (a, b)$ . In other words, an integral curve of a vector field is a solution of a system of ordinary differential equations (ODEs). Notice that the map  $y$  does not depend on  $t$ , that is (2.77) is an *autonomous* system of ODEs.

Conversely, any system of ODEs as above, is uniquely specified by a map  $y \in C^\infty(\mathbb{R}^k; \mathbb{R}^k)$ . In view of Example 2.73,  $y$  corresponds to a vector field  $v$ , whose integral curves are solutions of the initial system of ODEs. Thus, at least for Euclidean spaces, integral curves of vector fields and solutions of autonomous systems of ODEs are synonymous.

**Exercise 2.78.** Show that if  $\gamma$  is a  $C^1$ -curve satisfying (2.77), then  $\gamma$  is smooth.

Notice that for autonomous systems we have the following property: If  $\gamma$  is a solution of (2.77) such that  $\gamma(t_0) = m_0$ , then for any  $c \in (a, b)$

$$\gamma_c(t) := \gamma(t + c), \quad t \in (a - c, b - c)$$

is also a solution. In other words, the integral curve  $\gamma_1$  of  $v$  such that  $\gamma_1(t_1) = m_0$  satisfies

$$\gamma_1(t) = \gamma(t + t_0 - t_1),$$

that is  $\gamma_1$  differs from  $\gamma$  just by a shift of time. For this reason, one often chooses  $t_0 = 0$  as the initial time for integral curves of vector fields.

By the main theorem of ODEs [Hal80, Sec.I.3], we obtain the following existence and uniqueness result.

**Theorem 2.79.** Let  $v$  be a smooth vector field on an open subset  $\Omega \subset \mathbb{R}^k$ . For any point  $m_0 \in \Omega$  there exists a neighbourhood  $V \subset \Omega$  of  $m_0$  and a number  $\varepsilon > 0$  with the following property: For any  $m \in V$  there exists an integral curve

$$\gamma = \gamma_m: (-\varepsilon, \varepsilon) \rightarrow \Omega \quad \text{such that} \quad \gamma(0) = m.$$

This integral curve is unique in the following sense: If  $\beta: (-\delta, \delta) \rightarrow M$  is any other integral curve such that  $\beta(0) = m$ , then  $\beta$  and  $\gamma_m$  coincide on  $(-\varepsilon, \varepsilon) \cap (-\delta, \delta)$ . Moreover, the map

$$\Phi: (-\varepsilon, \varepsilon) \times V \rightarrow \mathbb{R}^k, \quad \Phi(t, m) := \gamma_m(t) \quad (2.80)$$

is smooth. □

**Definition 2.81.** An integral curve  $\gamma: (a, b) \rightarrow M$  of a vector field  $v$  is called *maximal*, if the following property holds: For any other integral curve  $\beta: (c, d) \rightarrow M$  of  $v$  such that for some  $t_0 \in (a, b) \cap (c, d)$  we have  $\gamma(t_0) = \beta(t_0)$ , then:

- (i)  $(c, d) \subset (a, b)$ ;
- (ii)  $\beta = \gamma|_{(c,d)}$ .

It is a well-known fact from the theory of ODEs, that for any  $m_0 \in \mathbb{R}^k$  there is a unique maximal solution of (2.77) through  $m_0$ . A straightforward corollary is, that for any vector field  $v$  on any manifold  $M$  there is a unique maximal integral curve  $\gamma$  of  $v$  through a given point.

**Corollary 2.82.** *If  $M$  is compact, then a maximal integral curve of any vector field is defined on all of  $\mathbb{R}$ .*

*Proof.* For each point  $m \in M$  pick a chart  $(U, \varphi)$  containing  $m$ . Hence, we obtain the coordinate representation of the vector field  $v$  via the map  $y: \Omega := \varphi(U) \rightarrow \mathbb{R}^k$ . Then  $\gamma: (a, b) \rightarrow U$  is an integral curve of  $v$  if and only if for  $\Gamma := \varphi \circ \gamma$  we have

$$\dot{\Gamma}(t) = y(\Gamma(t)) \quad \text{for } t \in (a, b),$$

cf. (2.77). By **Theorem 2.79**, there exists a neighborhood  $V_m$  such that for each  $\hat{m} \in V_m$  the integral curve  $\gamma_{\hat{m}}$  through  $\hat{m}$  is defined on  $(-\varepsilon_m, \varepsilon_m)$ . By the compactness of  $M$ , we can find a finite collection of points  $\{m_1, \dots, m_\ell\}$  such that the corresponding collection of neighbourhoods  $\{V_j := V_{m_j} \mid 1 \leq j \leq \ell\}$  covers all of  $M$ . Set

$$\varepsilon := \frac{\min\{\varepsilon_{m_j} \mid 1 \leq j \leq \ell\}}{2} > 0.$$

Let  $\gamma: (a, b) \rightarrow M$  be a maximal integral curve of  $v$ . Assuming  $b < \infty$ , the point  $m_0 := \gamma(b - \varepsilon)$  lies in some  $V_j$ . By the construction of  $\varepsilon$ , there is a unique integral curve  $\gamma_{m_0}$ , which is well-defined on  $(-2\varepsilon, 2\varepsilon)$  and satisfies  $\gamma_{m_0}(0) = m_0$ . Set

$$\hat{\gamma}: (a, b + \varepsilon) \rightarrow M, \quad \hat{\gamma}(t) = \begin{cases} \gamma(t) & \text{for } t \in (a, b - \varepsilon), \\ \gamma_{m_0}(t - b + \varepsilon) & \text{for } t \in [b - \varepsilon, b + \varepsilon). \end{cases}$$

Notice that  $\hat{\gamma}$  is continuous since  $\gamma_{m_0}(b - \varepsilon) = m_0 = \gamma(b - \varepsilon)$ . In fact, by construction  $\hat{\gamma}$  is an integral curve of  $v$  on  $(a, b - \varepsilon) \cup (b - \varepsilon, b + \varepsilon)$ . It follows that  $\hat{\gamma}$  is a  $C^1$ -integral curve of  $v$  and therefore smooth by **Exercise 2.78**. Thus,  $\hat{\gamma}$  is an integral curve of  $v$  defined on a larger interval. This contradicts the maximality of  $\gamma$ .  $\square$

## 2.10 Flows and 1-parameter groups of diffeomorphisms

In this section I assume that  $M$  is a compact manifold.

For a vector field  $v$  define *the flow* of  $v$  to be the map

$$\Phi: \mathbb{R} \times M \rightarrow M, \quad \Phi(t, m) = \gamma_m(t).$$

Of course, this is just the map  $\Phi$  of **Theorem 2.79** extended to the whole real line. Sometimes, (2.80) is referred to as *the local flow* of  $v$ .

Beside the flow, for each fixed  $t \in \mathbb{R}$  it is also convenient to consider

$$\Phi_t: M \rightarrow M, \quad \Phi_t(m) = \Phi(t, m) = \gamma_m(t).$$

**Proposition 2.83.** *The following holds:*

- (i) Each  $\Phi_t$  is a diffeomorphism. Moreover,  $\Phi_t^{-1} = \Phi_{-t}$ ;
- (ii) For any  $t, s \in \mathbb{R}$  we have  $\Phi_t \circ \Phi_s = \Phi_{t+s} = \Phi_s \circ \Phi_t$ ;
- (iii)  $\Phi_0 = id_M$ ;

*Proof.* For  $m \in M$  and  $t \in \mathbb{R}$  denote  $\Phi_t(m) = \hat{m}$ . This means that  $\gamma_m(t) = \hat{m}$ , where  $\gamma_m$  is an integral curve of  $v$  such that  $\gamma_m(0) = m$ .

Consider the curve  $\beta$  defined by  $\beta(s) = \gamma_m(s + t)$ . Then  $\beta$  is an integral curve of  $v$  and  $\beta(0) = \gamma_m(t) = \hat{m}$ , that is  $\beta = \gamma_{\hat{m}}$ . Hence,

$$\Phi_s(\hat{m}) = \gamma_{\hat{m}}(s) = \beta(s) = \gamma_m(s + t) = \Phi_{s+t}(m) \iff \Phi_s \circ \Phi_t = \Phi_{s+t}.$$

Since (iii) holds by the very definition of  $\Phi_t$ , by (ii) we obtain

$$\Phi_{-t} \circ \Phi_t = id_M = \Phi_t \circ \Phi_{-t}.$$

In particular, each  $\Phi_t$  is a diffeomorphism and  $\Phi_t^{-1} = \Phi_{-t}$  □

**Definition 2.84.** A 1-parameter group of diffeomorphisms is any smooth map  $\Phi: \mathbb{R} \times M \rightarrow M$  such that Properties (i)–(iii) of Proposition 2.83 hold.

To explain the above definition, notice that the set

$$\text{Diff}(M) := \{f: M \rightarrow M \mid f \text{ is a diffeomorphism}\}$$

is a group with respect to the composition operation.  $\text{Diff}(M)$  is called *the diffeomorphism group* of  $M$ . With this understood, a 1-parameter group of diffeomorphisms is simply a homomorphism of groups

$$\mathbb{R} \rightarrow \text{Diff}(M), \quad t \mapsto \Phi_t$$

such that  $\Phi_t(m) = \Phi(t, m)$  depends smoothly on  $(t, m)$ .

Thus, Proposition 2.83 states that each vector field on a compact manifold generates a 1-parameter group of diffeomorphisms. Conversely, it turns out that any 1-parameter group of diffeomorphisms generates a vector field in the following sense.

**Proposition 2.85.** *For any 1-parameter group of diffeomorphisms  $\Phi$  there exists a vector field  $v$ , whose 1-parameter group of diffeomorphisms coincides with  $\Phi$ .*

*Proof.* For any  $m \in M$  denote

$$\gamma_m: \mathbb{R} \rightarrow M, \quad \gamma_m(t) := \Phi(t, m) \quad \text{and} \quad v(m) := \dot{\gamma}_m(0).$$

The reader should check that  $v$  is a smooth vector field.

Furthermore, denote  $\gamma_m(t) = \hat{m}$  and observe that

$$\gamma_{\hat{m}}(s) = \Phi_s(\hat{m}) = \Phi_s(\Phi_t(m)) = \Phi_{t+s}(m) = \gamma_m(t + s). \quad (2.86)$$

Hence,

$$v(\gamma_m(t)) = v(\hat{m}) = \dot{\gamma}_{\hat{m}}(0) = [\dot{\gamma}_{\hat{m}}(s)]_{s=0} = [\dot{\gamma}_m(t + s)]_{s=0} = \dot{\gamma}_m(t),$$

where it is straight-forward to obtain all above equalities from the corresponding definitions. Thus,  $\gamma_m$  is an integral curve of  $v$ . Therefore, the 1-parameter group of diffeomorphisms generated by  $v$  is

$$(t, m) \mapsto \gamma_m(t) = \Phi(t, m),$$

In other words, the 1-parameter group of diffeomorphisms generated by  $v$  coincides with  $\Phi$ . □

To sum up, for compact manifolds there is a natural bijective correspondence between vector fields and 1-parameter groups of diffeomorphisms.

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