

Notes

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December 9, 2019

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1 Differential Geometry

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1.1 Directional Derivative

Elements of the *tangent space* $T_p(\mathbb{R}^n)$ anchored at a point $p = (p^1, \dots, p^n) \in \mathbb{R}^n$ can be visualized as arrows emanating from p . These arrows are called *tangent vectors* and represented by column vectors:

$$\mathbf{v} = \begin{bmatrix} v^1 \\ \vdots \\ v^n \end{bmatrix} \quad (1)$$

The line through a point p with direction \mathbf{v} has parameterization

$$c(t) = (p^1 + tv^1, \dots, p^n + tv^n) \quad (2)$$

If $f \in C^\infty$ in a neighborhood of p and \mathbf{v} is a tangent vector at p , the *directional derivative* of f in the direction of \mathbf{v} at p is defined

$$D_{\mathbf{v}}f = \lim_{t \rightarrow 0} \frac{f(c(t)) - f(p)}{t} = \left. \frac{d}{dt} f(c(t)) \right|_{t=0} \quad (3)$$

By the chain rule

$$D_v f = \sum_{i=1}^n \frac{\partial f}{\partial x^i} \bigg|_p \frac{dc^i}{dt} \bigg|_{t=0} \quad (4)$$

$$= \sum_{i=1}^n \frac{dc^i}{dt} \bigg|_{t=0} \frac{\partial f}{\partial x^i} \bigg|_p \quad (5)$$

$$= \sum_{i=1}^n v^i \frac{\partial f}{\partial x^i} \bigg|_p \quad (6)$$

(7)

The directional derivative operator at p is defined

$$D_v = \sum_{i=1}^n v^i \frac{\partial}{\partial x^i} \bigg|_p \quad (8)$$

The association $v \mapsto D_v$ offers a way to *isomorphically* identify tangent vectors with operators on functions. The following makes this rigorous.

1.2 Derivations

For each tangent vector v at a point $p \in \mathbb{R}^n$, the directional derivative at p gives a map of vector spaces

$$D_v: C_p^\infty \rightarrow \mathbb{R}$$

D_v is a linear map that satisfies the *Leibniz rule*

$$D_v(fg) = (D_v f)g(p) + f(p)(D_v g) \quad (9)$$

because the partial derivative satisfy the product rule. In general, any linear map $L: C_p^\infty \rightarrow \mathbb{R}$ that satisfies the Leibniz rule is called a *derivation* at p . Denote the set of all derivations at p by $\mathcal{D}_p(\mathbb{R}^n)$. **This set is also a real vector space.**

So far we know directional derivatives D_v at p are derivations at p . Thus, there is a map

$$\begin{aligned} \phi: T_p(\mathbb{R}^n) &\rightarrow \mathcal{D}_p(\mathbb{R}^n) \\ v &\mapsto D_v \end{aligned}$$

Theorem 1.1

The linear map ϕ is an isomorphism of vector spaces.

The implication is that we may identify tangent vectors at p with derivations at p (by way of directional derivatives against germs). Under this isomorphism $T_p(\mathbb{R}^n) \simeq \mathcal{D}_p(\mathbb{R}^n)$, the standard basis $\{e_1, \dots, e_n\}$ for $T_p(\mathbb{R}^n)$ maps to

$$\left\{ \frac{\partial}{\partial x^1} \bigg|_p, \dots, \frac{\partial}{\partial x^n} \bigg|_p \right\} \quad (10)$$

Therefore from now on we write a tangent vector as

$$v = \sum_{i=1}^n v^i \frac{\partial}{\partial x^i} \bigg|_p \quad (11)$$

The point being that, while not as geometrically intuitive as arrows, $\mathcal{D}_p(\mathbb{R}^n)$ generalizes to manifolds.

1.3 Vector Fields

A *vector field* X on an open $U \subset \mathbb{R}^n$ is function that assigns to $p \in U$ a tangent vector $X_p \in T_p(\mathbb{R}^n)$. Notice, carefully, that the vector field assigns at each point a vector in the tangent space anchored at that point. Using the tangent basis (eqn. (10))

$$X: p \mapsto \sum_i a^i(p) \frac{\partial}{\partial x^i} \bigg|_p \quad (12)$$

Note that both the coefficients **and** the partial derivatives are evaluated at p . Having said that, we often omit p in the specification of a vector field when it clear from context.

Example 1.1. On $\mathbb{R}^n - \{0\}$, let $p = (x, y)$. Then

$$\begin{aligned} X &= \frac{-y}{\sqrt{x^2 + y^2}} \frac{\partial}{\partial x} + \frac{x}{\sqrt{x^2 + y^2}} \frac{\partial}{\partial y} \\ &= \begin{bmatrix} \frac{-y}{\sqrt{x^2 + y^2}} \\ \frac{x}{\sqrt{x^2 + y^2}} \end{bmatrix} \\ &= \begin{bmatrix} \frac{-y}{\sqrt{x^2 + y^2}} & \frac{x}{\sqrt{x^2 + y^2}} \end{bmatrix}^T \end{aligned}$$

See figure ??

In general we can identify vector fields with parameterized column vectors

$$X = \sum_i a^i(p) \frac{\partial}{\partial x^i} \bigg|_p \leftrightarrow \begin{bmatrix} a^1(p) \\ \vdots \\ a^n(p) \end{bmatrix} \quad (13)$$

1.4 Dual Space

The *dual space* V^\wedge of V is the set of all real-valued linear functions on V i.e. all $f: V \rightarrow \mathbb{R}$. Elements of V^\wedge are called *covectors*.

Assume V is finite dimensional and let $\{e_1, \dots, e_n\}$ be a basis V . Recall that $e_i := \partial_{x^i}$. Then $X = \sum a^i \partial_{x^i}$ for all $X \in T_p$. Let $\alpha^i: V \rightarrow \mathbb{R}$ be the linear function that picks out the i th coordinate of a **vector**, i.e. $\alpha^i(X) = a^i(p)$. Note that

$$\alpha^i(\partial_j) = \alpha^i(1 \cdot \partial_j) \quad (14)$$

$$= \begin{cases} 1 & \text{if } i = j \\ 0 & \text{if } i \neq j \end{cases} \quad (15)$$

$$= \delta_j^i \quad (16)$$

Note that position of indices is important – upper indices are for covectors.

Proposition 1.1

$\{\alpha^i\}$ form a basis for V^\wedge .

Proof. We first prove that $\{\alpha^i\}$ span V^\wedge . If $f \in V^\wedge$ and $X = \sum a^i \partial_{x_i} \in V$, then

$$f(X) = \sum a^i f(\partial_{x_i}) \quad (17)$$

$$= \sum \alpha^i(X) f(\partial_{x_i}) \quad (18)$$

$$= \sum f(\partial_{x_i}) \alpha^i(X) \quad (19)$$

which shows that any f can be expanded as a linear sum of α^i . To show linear independence, suppose $\sum c_i \alpha^i = 0$ with at least one c_i non-zero. Applying this to an arbitrary ∂_{x_i} gives

$$0 = \left(\sum_i c_i \alpha^i \right) (\partial_{x_i}) = \sum_i c_i \alpha^i(\partial_{x_i}) = \sum_i c_i \delta_j^i = c_j \quad (20)$$

which is a contradiction. Hence α^i are linearly independent. \square

This basis $\{\alpha^i\}$ for V^\wedge is said to be *dual* to the basis $\{\partial_{x_i}\}$ for V .

Example 1.2. Coordinate functions With respect to a basis $\{\partial_{x_i}\}$ for V , every $X \in V$ can be written uniquely as a linear combination $X = \sum a^i \partial_{x_i}$ with $a^i \in \mathbb{R}$. Let $\{\alpha^i\}$ be the dual basis (i.e. the basis for V^\wedge). Then

$$\begin{aligned} \alpha^i(X) &= \alpha^i \left(\sum_j a^j \partial_{x_j} \right) \\ &= \sum_j a^j \alpha^i(\partial_{x_j}) \\ &= \sum_j a^j \delta_j^i \\ &= a^i \end{aligned}$$

Thus, the dual basis $\{\alpha^i\}$ to $\{\partial_{x_i}\}$ is the set of coordinate functions. The sense here is that since tangent vectors are directional derivatives (i.e. operators on functions) and the dual space is a mapping from those operators to \mathbb{R} , then a mapping from operators to scalars means hitting an operator with a function (or vice-versa). **And** the coordinate functions are constant with respect to each other coordinate (and hence partials wrt them are naturally zero).

1.5 Differential Forms on \mathbb{R}^n

A differential k -form assigns a k -covector from the dual space at each point p . The wedge product (alternation of tensor product) of differential forms is defined pointwise (as the wedge product of multi-covectors). Differential

forms exist on an open set (why?) there is a notion of differentiation (called exterior derivative). Exterior derivative is coordinate independent and intrinsic to a manifold; it is the abstraction of gradient, curl, divergence to arbitrary manifolds. Differential forms extend Grassmann's exterior algebra (graded algebra of multi-covectors) from the tangent space at a point globally, i.e. to the entire manifold (how? bundles?).

1.5.1 Differential of a Function

Definition 1.1: Cotangent Space

The *cotangent space* to \mathbb{R}^n at p , denoted $T_p^*(\mathbb{R}^n)$, is defined to be the dual space $(T_p(\mathbb{R}^n))^\vee$ of the tangent space $T_p(\mathbb{R}^n)$.

Thus, an element of the cotangent space $T_p^*(\mathbb{R}^n)$ is a **covector of linear functional on tangent space**.

Definition 1.2: Differential 1-form

A *covector field* or a *differential 1-form* on an open subset U of \mathbb{R}^n is a function ω that assigns at each point p in U a covector $\omega_p \in T_p^*(\mathbb{R}^n)$

$$\begin{aligned} \omega: U &\rightarrow \bigcup_{p \in U} T_p^*(\mathbb{R}^n) \\ p &\mapsto \omega_p \in T_p^*(\mathbb{R}^n) \end{aligned} \quad (21)$$

We call a differential 1-form a *1-form* for short.

Definition 1.3: Differential

From any C^∞ function $f: U \rightarrow \mathbb{R}$, we can construct the 1-form df , called the *differential* of f , as follows: for $p \in U$ and $X_p \in T_p(U)$

$$(df)_p(X_p) := X_p f \quad (22)$$

In words the differential of f is the application of X_p to f or **the directional derivative of f in the direction of the tangent vector defined by the coefficients of X_p** .

Let x^1, \dots, x^n be the standard coordinates on \mathbb{R} , $\{(dx^1)_p, \dots, (dx^n)_p\}$ their differentials defined

$$(dx^i)_p(X_p) := (X_p)(x^i)$$

and

$$\left\{ \frac{\partial}{\partial x^1} \Big|_p, \dots, \frac{\partial}{\partial x^n} \Big|_p \right\}$$

be the standard basis for $T_p(\mathbb{R}^n)$.

Proposition 1.2

$\{(dx^1)_p, \dots, (dx^n)_p\}$ is the basis for $T_p^*(\mathbb{R}^n)$ dual to the coordinate basis for $T_p(\mathbb{R}^n)$.

Proof. By definition,

$$(dx^i)_p \left(\frac{\partial}{\partial x^j} \Big|_p \right) = \frac{\partial x^i}{\partial x^j} \Big|_p = \delta_j^i$$

□

If ω is a 1-form on $U \in \mathbb{R}^n$ then by proposition (1.2), at each point $p \in U$

$$\omega_p = \sum a_i(p) (dx^i)_p$$

Note the lower index on $a_i(p)$ as opposed to the upper index on $X_p = \sum a^i(p) \partial_{x^i} \Big|_p$. If $x := x^1, y := x^2, z := x^3$, then dx, dy, dz .

Proposition 1.3: df in terms of coordinates

If $f: U \rightarrow \mathbb{R}$, then

$$df = \sum \frac{\partial f}{\partial x^i} dx^i \quad (23)$$

Proof.

$$(df)_p = \sum a_i(p) (dx^i)_p$$

for some real numbers $a_i(p)$ depending on p . Thus

$$\begin{aligned} df \left(\frac{\partial}{\partial x^j} \right) &= \sum_i a_i dx^i \left(\frac{\partial}{\partial x^j} \right) \\ &= \sum_i a_i \delta_j^i = a_j \end{aligned} \quad (24)$$

On the other hand, by the definition of the differential

$$df = \left(\frac{\partial}{\partial x^j} \right) = \frac{\partial f}{\partial x^j} \quad (25)$$

Therefore

$$a_j = \frac{\partial f}{\partial x^j} \quad (26)$$

and hence

$$(df)_p = \frac{\partial f}{\partial x^i} \Big|_p (dx^i)_p$$

□

1.5.2 Differential k -forms

Definition 1.4: Differential k -forms

More generally, a *differential form* ω of degree k is a function that at each point assigns an alternating k -linear function on $T_p(\mathbb{R}^n)$, i.e. $\omega_p \in A^k(T_p(\mathbb{R}^n))$.

A basis for $A^k(T_p(\mathbb{R}^n))$ is

$$(dx^I)_p := (dx^{i_1})_p \wedge \dots \wedge (dx^{i_k})_p \quad (27)$$

where $1 \leq i_1 < \dots < i_k \leq n$.

What is the nuance here?

Therefore, at each point $p \in U$, ω_p is a linear combination

$$\omega_p = \sum_I a_I(p) (dx^I)_p \quad (28)$$

$$1 \leq i_1 < \dots < i_k \leq n$$

and a k -form ω on open U is a linear combination

$$\omega = \sum_I a_I dx^I \quad (29)$$

with function coefficients $a_I: U \rightarrow \mathbb{R}$. We say that a k -form ω is C^∞ on U if all of the coefficients a_I are C^∞ functions on U . Denote $\Omega^k(U)$ the vector space of k -forms on U . A 0-form on U assigns to each point p an element of $A^0(T_p(\mathbb{R}^n)) := \mathbb{R}$; thus, a 0-form on U is a constant function. Note there are no nonzero differential forms of degree $> n$ on U since if $\deg dx^I > n$ then at least two of the component 1-forms of dx^I must be the same and therefore $dx^I = 0$.

Definition 1.5: Wedge product of forms

The *wedge product* of a k -form ω and ℓ -form τ is defined pointwise

$$\begin{aligned} (\omega \wedge \tau)_p &:= \omega_p \wedge \tau_p \\ \omega \wedge \tau &= \sum_{I, J} (a_I b_J) dx^I \wedge dx^J \end{aligned} \quad (30)$$

where $I \cap J = \emptyset$.

Hence the wedge product is bilinear

$$\wedge: \Omega^k(U) \times \Omega^\ell(U) \rightarrow \Omega^{k+\ell}(U) \quad (31)$$

(26) The wedge product of forms is also anticommutative and associate (owing to the associativity and anticommutativity of the wedge product on multi-covectors) as therefore induces a graded algebra on $\Omega(U) := \bigoplus_k \Omega^k(U)$.

Example 1.3. In the case of

$$\wedge: \Omega^0(U) \times \Omega^\ell(U) \rightarrow \Omega^\ell$$

we have the pointwise multiplication of a C^∞ function and a C^∞ ℓ -form

$$(f \wedge \omega)_p = f(p) \wedge \omega_p = f(p) \omega_p$$

Let x, y, z be the coordinates on \mathbb{R}^3 . Then, the 1-forms are

$$f dx + g dy + h dz$$

the 2-forms are

$$f dy \wedge dz + g dx \wedge dz + h dx \wedge dy$$

and the 3-forms are

$$f dx \wedge dy \wedge dz$$

1.5.3 Differential Forms as Multilinear Functions on Vector Fields

If ω is a 1-form and X is a vector field then

$$\begin{aligned} \omega(X)|_p &:= \omega_p(X_p) \\ \omega &= \sum a_i dx^i \quad X = \sum b^j \frac{\partial}{\partial x^j} \\ \omega(X) &= \left(\sum a_i dx^i \right) \left(\sum b^j \frac{\partial}{\partial x^j} \right) \\ &= \sum a_i b^i \end{aligned} \quad (32)$$

1.5.4 Exterior Derivative

Definition 1.6: Exterior Derivative

The exterior derivative of a function $f \in C^\infty(U)$ is defined to be its differential df

$$df = \sum \frac{\partial f}{\partial x^i} dx^i$$

For $k \geq 1$, if $\omega = \sum_I a_I dx^I$ is a k -form, then

$$\begin{aligned} d\omega &:= \sum_I da_I \wedge dx^I \\ &= \sum_I \left(\sum_j \frac{\partial a_I}{\partial x^j} dx^j \right) \wedge dx^I \end{aligned} \quad (33)$$

Example 1.4. Let ω be the 1-form $f dx + g dy$ on \mathbb{R}^2 . Then

$$d\omega = df \wedge dx + dg \wedge dy \quad (34)$$

$$= \left(\frac{\partial f}{\partial x} dx + \frac{\partial f}{\partial y} dy \right) \wedge dx \quad (35)$$

$$\begin{aligned} &+ \left(\frac{\partial g}{\partial x} dx + \frac{\partial g}{\partial y} dy \right) \wedge dy \\ &= \left(\frac{\partial g}{\partial x} - \frac{\partial f}{\partial y} \right) dx \wedge dy \end{aligned} \quad (36)$$

where we use that $dx \wedge dy = -dy \wedge dx$ and $dx \wedge dx = 0$.

Definition 1.7: Antiderivation

Let $A = \bigoplus_k A^k$ be a graded algebra over a field K . An *antiderivation* of the graded algebra A is a k -linear map $D: A \rightarrow A$ such that for $a \in A^k, b \in A^\ell$

$$D(ab) = (Da)b + (-1)^k aDb \quad (37)$$

If there is an integer m such that D sends A^k to A^{k+m} for all k , then the antiderivation is of *degree* m .

Proposition 1.4: Properties of exterior differentiation

1. exterior differentiation is an antiderivation of degree 1:

$$d(\omega \wedge \tau) = (d\omega) \wedge \tau + (-1)^{\deg \omega} \omega \wedge d\tau$$

2. $d^2 = 0$

Proposition 1.5: Characterization of the exterior derivative

The properties of proposition (1.4) completely characterize exterior differentiation.

1.5.5 Closed and Exact Forms

A k -form ω is a *closed form* if $d\omega = 0$. ω is an *exact form* if there is a $k-1$ -form τ such that $\omega = d\tau$. Since $d(d\tau) = 0$, every exact form is closed.

Example 1.5. A closed 1-form on the punctured plane. Define ω on the manifold $\mathbb{R}^2 - \{0\}$ by

$$\omega(x, y) = \frac{-y}{x^2 + y^2} dx + \frac{x}{x^2 + y^2} dy$$

To show that ω is closed we take the exterior derivative using example (36):

$$\begin{aligned} d\omega &= \left(\frac{y^2 - x^2}{(x^2 + y^2)^2} - \frac{y^2 - x^2}{(x^2 + y^2)^2} \right) dx \wedge dy \\ &= 0 \end{aligned} \quad (38)$$

Definition 1.8: Differential Complex

A collection of vector spaces $\{V^0, V^1, \dots\}$ with linear maps $d_k: V^k \rightarrow V^{k+1}$ such that $d_{k+1} \circ d_k = 0$ is called a *differential complex* or a *cochain complex*. For any open subset $U \subset \mathbb{R}^3$, the exterior derivative makes the vector space $\Omega^*(U)$ of C^∞ forms on U into a cochain complex, called the *de Rham complex of U* :

$$0 \rightarrow \Omega^0(U) \xrightarrow{d} \Omega^1(U) \xrightarrow{d} \Omega^2(U) \xrightarrow{d} \dots$$

The closed forms are the elements of the kernel of d and the exact forms are the elements of the image of d .

1.5.6 Applications to Vector Calculus

Recall the three operators grad, curl, div ($\nabla, \nabla \times, \nabla \cdot$) on scalar fields and vector fields (i.e. scalar valued functions and vector valued functions) over \mathbb{R}^3 :

$$\begin{aligned} \nabla f &= \begin{bmatrix} \frac{\partial f}{\partial x} \\ \frac{\partial f}{\partial y} \\ \frac{\partial f}{\partial z} \end{bmatrix} \\ \nabla \times \begin{bmatrix} P \\ Q \\ R \end{bmatrix} &= \begin{bmatrix} \frac{\partial}{\partial y} \\ \frac{\partial}{\partial z} \\ \frac{\partial}{\partial x} \end{bmatrix} \times \begin{bmatrix} P \\ Q \\ R \end{bmatrix} = \begin{bmatrix} \frac{\partial R}{\partial y} - \frac{\partial Q}{\partial z} \\ -\left(\frac{\partial R}{\partial x} - \frac{\partial P}{\partial z}\right) \\ \frac{\partial Q}{\partial x} - \frac{\partial P}{\partial y} \end{bmatrix} \\ \nabla \cdot \begin{bmatrix} P \\ Q \\ R \end{bmatrix} &= \begin{bmatrix} \frac{\partial}{\partial x} \\ \frac{\partial}{\partial y} \\ \frac{\partial}{\partial z} \end{bmatrix} \cdot \begin{bmatrix} P \\ Q \\ R \end{bmatrix} = \frac{\partial P}{\partial x} + \frac{\partial Q}{\partial y} + \frac{\partial R}{\partial z} \end{aligned} \quad (39)$$

Note we can identify 1-forms with vector fields:

$$P dx + Q dy + R dz \longleftrightarrow \begin{bmatrix} P \\ Q \\ R \end{bmatrix}$$

Similarly 2-forms on \mathbb{R}^3

$$P dx \wedge dy + Q dz \wedge dx + R dx \wedge dy \longleftrightarrow \begin{bmatrix} P \\ Q \\ R \end{bmatrix}$$

and 3-forms on U can be identified with functions U

$$f dx \wedge dy \wedge dz \longleftrightarrow f$$

In terms of these identifications the exterior derivative of 0-form f is the 1-form df or ∇f :

$$df = \frac{\partial f}{\partial x} dx + \frac{\partial f}{\partial y} dy + \frac{\partial f}{\partial z} dz \longleftrightarrow \begin{bmatrix} \frac{\partial f}{\partial x} \\ \frac{\partial f}{\partial y} \\ \frac{\partial f}{\partial z} \end{bmatrix} = \nabla f$$

the exterior derivative of a vector field $[P \ Q \ R]^T$ (i.e. 1-form) is the 2-form $\nabla \times [P \ Q \ R]^T$

$$\begin{aligned} d(P dx + Q dy + R dz) &= \\ &+ \left(\frac{\partial R}{\partial y} - \frac{\partial Q}{\partial z} \right) dy \wedge dz \\ &- \left(\frac{\partial R}{\partial x} - \frac{\partial P}{\partial z} \right) dz \wedge dx \\ &+ \left(\frac{\partial Q}{\partial x} - \frac{\partial P}{\partial y} \right) dx \wedge dy \end{aligned} \quad (40)$$

$$\longleftrightarrow \nabla \times \begin{bmatrix} P \\ Q \\ R \end{bmatrix}$$

and the exterior derivative of a 2-form is

$$\begin{aligned} d(P dx \wedge dy + Q dz \wedge dx + R dx \wedge dy) &= \\ \left(\frac{\partial P}{\partial x} dx + \frac{\partial Q}{\partial y} dy + \frac{\partial R}{\partial z} dz \right) dx \wedge dy \wedge dz \\ &\longleftrightarrow \nabla \cdot \begin{bmatrix} P \\ Q \\ R \end{bmatrix} \end{aligned} \quad (41)$$

Thus, the exterior derivatives on 0-forms (functions) is the grad operator, on 1-forms is the curl operator, and on 2-forms is the divergence operator.

$$\begin{array}{ccccccc} \Omega^0(U) & \xrightarrow{d} & \Omega^1(U) & \xrightarrow{d} & \Omega^2(U) & \xrightarrow{d} & \Omega^3(U) \\ \cong \downarrow & & \cong \downarrow & & \cong \downarrow & & \cong \downarrow \\ C^\infty(U) & \xrightarrow{\nabla} & \mathfrak{X}(U) & \xrightarrow{\nabla \times} & \mathfrak{X}(U) & \xrightarrow{\nabla \cdot} & C^\infty(U) \end{array}$$

where $\mathfrak{X}(U)$ is the *Lie algebra* of C^∞ vector fields on U .

Proposition 1.6: grad, curl, div properties

1. $\nabla \times \nabla f = 0$
2. $\nabla \cdot (\nabla \times [P \ Q \ R]^T) = 0$
3. On \mathbb{R}^3 , a vector field \mathbf{F} is the gradient of some scalar function iff $\nabla \times \mathbf{F} = 0$

Properties (1,2) express that $d^2 = 0$ Property (3) expresses the fact that a 1-form on \mathbb{R}^3 is exact iff it is closed; it need not be true on a region other than \mathbb{R}^3 . It turns out that whether proposition (3) is true depends on the topology of U . One measure of the failure of a closed k -form to be exact is the quotient vector space

$$H^k(U) := \frac{\{\text{closed } k\text{-forms on } U\}}{\{\text{exact } k\text{-forms on } U\}} \quad (42)$$

called the k th *de Rham cohomology* of U . The generalization of proposition (3) to any differential on \mathbb{R}^n is called the *Poincare lemma*: for $k \geq 1$, every closed k -form on \mathbb{R}^n is exact. This is equivalent to the vanishing of the k th de Rham cohomology $H^k(\mathbb{R}^n)$ for $k \geq 1$.

1.5.7 Convention on Subscripts and Superscripts

Vector fields e_1, e_2, \dots have subscripts and differential forms $\omega^1, \omega^2, \dots$ have superscripts. Coordinate functions x^1, x^2, \dots , being 0-forms, have superscripts. Their differentials dx^i should also. Coordinate vector fields $\frac{\partial}{\partial x^i}$ are considered to have subscripts because the index is in the denominator. Coefficient functions have subscripts or subscripts depending on whether they're coefficients functions for vector fields or forms. This allows for "conservation of indices": if $X = \sum a^i \partial_{x^i}$ and $\omega = \sum b_j dx^j$ then

$$\omega(X) = \left(\sum b_j dx^j \right) \left(\sum a^i \frac{\partial}{\partial x^i} \right) = \sum b_i a^i$$

1.6 Manifolds

Definition 1.9: Locally Euclidean

A topological space M is *locally Euclidean of dimension n* if for every $p \in M$ there exists a neighborhood U such that there is a *homeomorphism*¹ ϕ from U **onto** an opensubset of \mathbb{R}^n . The pair $(U, \phi: U \rightarrow \mathbb{R}^n)$ is called a *chart*, with U being the *coordinate neighborhood* and ϕ the *coordinate system*.

Definition 1.10: Topological Manifold

A *topological manifold* is a *Hausdorff*², *second countable*³, locally Euclidean space.

1.6.1 Compatible Charts

Suppose $(U, \phi: U \rightarrow \mathbb{R}^n)$ and $(V, \psi: V \rightarrow \mathbb{R}^n)$ are two charts of a topological manifold; since $U \cap V$ is open and ϕ is a homeomorphism onto an open subset, the image $\phi(U \cap V)$ is also an open subset (similarly $\psi(U \cap V)$).

¹A homeomorphism is a continuous function between topological spaces that has a continuous inverse function.

²A Hausdorff space, separated space is a topological space where for any two distinct points there exists a neighbourhood of each which is disjoint from the neighbourhood of the other.

³A topological space T is second-countable if there exists some countable collection $\mathcal{U} = \{U_i\}_{i=1}^\infty$ of open subsets of T such that any open subset of T can be written as a union of elements of some subfamily of \mathcal{U} .

Definition 1.11: Charts

Two charts $(U, \phi: U \rightarrow \mathbb{R}^n)$ and $(V, \psi: V \rightarrow \mathbb{R}^n)$ of a topological manifold are *C^∞ -compatible* if the two composed maps

$$\begin{aligned} \phi \circ \psi^{-1}: \psi(U \cap V) &\rightarrow \phi(U \cap V) \\ \psi \circ \phi^{-1}: \phi(U \cap V) &\rightarrow \psi(U \cap V) \end{aligned} \quad (43)$$

See figure ?? . These two maps $\phi \circ \psi^{-1}$ and $\psi \circ \phi^{-1}$ are called the *transition functions* between the charts;

$$\begin{aligned} \phi \circ \psi^{-1}: \mathbb{R}^n &\rightarrow U \cap V \rightarrow \mathbb{R}^n \\ \psi \circ \phi^{-1}: \mathbb{R}^n &\rightarrow U \cap V \rightarrow \mathbb{R}^n \end{aligned} \quad (44)$$

Definition 1.12: Atlas

A *C^∞ atlas* on a topological manifold M is a collection $\mathfrak{A} := \{(U_i, \phi_i)\}$ of pairwise *C^∞ -compatible* charts that *cover* M , i.e. such that $M = \bigcup_i U_i$.

Example 1.6. A *C^∞ atlas* on a circle The unit circle S^1 in the complex plane \mathbb{C} maybe described as

$$\{e^{it} \in \mathbb{C} \mid 0 \leq t \leq 2\pi\}$$

Let U_1, U_2 be

$$\begin{aligned} U_1 &:= \{e^{it} \in \mathbb{C} \mid -\pi < t < \pi\} \\ U_2 &:= \{e^{it} \in \mathbb{C} \mid 0 < t < 2\pi\} \end{aligned} \quad (45)$$

and define

$$\begin{aligned} \phi_1(e^{it}) &= t \quad -\pi < t < \pi \\ \phi_2(e^{it}) &= t \quad 0 < t < 2\pi \end{aligned} \quad (46)$$

See figure 1. Both ϕ_1, ϕ_2 are homomorphisms onto their respective images; thus, U_1, ϕ_1 and U_2, ϕ_2 are charts on S^1 . The intersection $U_1 \cap U_2$ consists of two disjoint connected components

$$\begin{aligned} A &:= \{e^{it} \in \mathbb{C} \mid -\pi < t < 0\} \\ B &:= \{e^{it} \in \mathbb{C} \mid 0 < t < \pi\} \end{aligned} \quad (47)$$

with

$$\begin{aligned} \phi_1(U_1 \cap U_2) &= \phi_1(A \sqcup B) = \phi_1(A) \sqcup \phi_2(B) = (-\pi, 0) \sqcup (0, \pi) \\ \phi_2(U_1 \cap U_2) &= \phi_1(B \sqcup A) = \phi_1(B) \sqcup \phi_2(A) = (0, \pi) \sqcup (\pi, 2\pi) \end{aligned} \quad (48)$$

where \sqcup means disjoint union. The transition function

$$\left(\phi_2 \circ \phi_1^{-1} \right) (t) = \begin{cases} t + 2\pi & \text{for } t \in (-\pi, 0) \\ t & \text{for } t \in (0, \pi) \end{cases}$$

and similarly

$$\left(\phi_1 \circ \phi_2^{-1} \right) (t) = \begin{cases} t & \text{for } t \in (0, \pi) \\ t - 2\pi & \text{for } t \in (\pi, 2\pi) \end{cases}$$

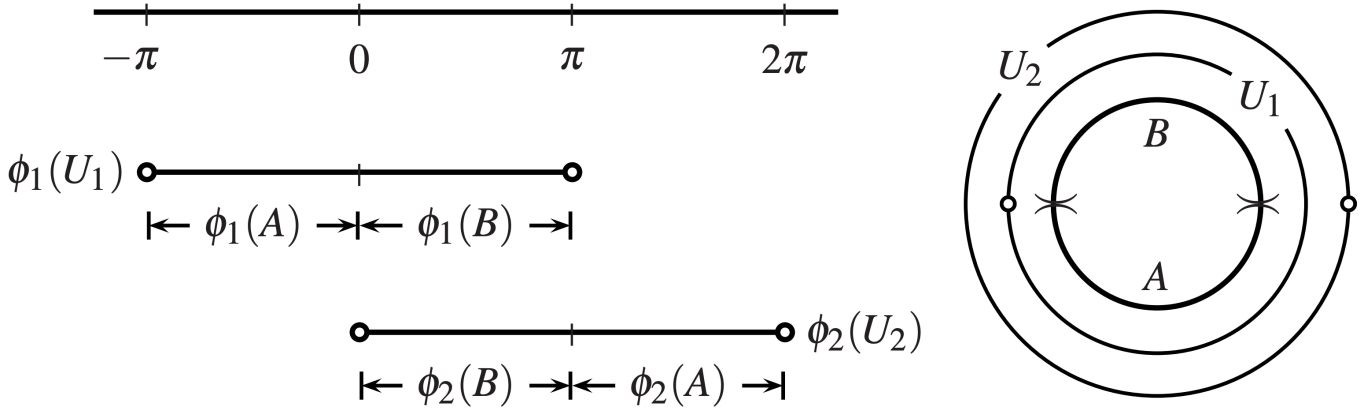


Figure 1: Atlas of charts on the circle.

Therefore, since the transition functions are C^∞ , the charts are C^∞ compatible and form an atlas on S^1 .

Although compatibility is reflexive and symmetric it is not transitive because we don't know anything about mutual intersections. On the otherhand

Lemma 1.1

Let $\{(U_i, \phi_i)\}$ be an atlas for a topological manifold. If two other charts (not in the atlas) $(V, \psi), (U, \phi)$ are both compatible with the atlas (i.e. with all charts in the atlas), then they are mutually compatible.

1.6.2 Smooth Manifolds

An atlas \mathfrak{M} on a topological manifold is said to be *maximal* if it is not strictly contained in another atlas.

Definition 1.13: Smooth Manifold

A *smooth C^∞ manifold* is a topological manifold M together with a maximal atlas. The maximal atlas is called a *differentiable structure* on M . M is said to have dimension n if all of its connected components have dimension n . A 1-dimensional manifold is called a *curve*, a 2-dimensional manifold is called a *surface*, and an n -dimensional manifold is called an n -manifold.

In the context of manifolds, we denote the standard coordinates on \mathbb{R}^n by r^1, \dots, r^n . If (U, ϕ) is a chart of a manifold, we let $x^i = r^i \circ \phi$ be the i th component of ϕ and write $\phi = (x^1, \dots, x^n)$. Thus, $x^i(p) := (r^i \circ \phi)(p)$ is a point in \mathbb{R}^n . The functions x^i are called the *local coordinates on U* . Abusing notation, sometimes (x^1, \dots, x^n) (sans p) stands for both the coordinates on U or for a point in \mathbb{R}^n .

1.6.3 Examples of Smooth Manifolds

Example 1.7. Graph of a Smooth Function For a subset $A \subset \mathbb{R}^n$ and a function $f: A \rightarrow \mathbb{R}^m$ the *graph of f* is defined

$$\Gamma(f) = \{(x, f(x)) \in A \times \mathbb{R}^m\}$$

If U is an open subset \mathbb{R}^n and $f: U \rightarrow \mathbb{R}^m$ is C^∞ , then the two maps

$$\begin{aligned} \phi: \Gamma(f) &\rightarrow U & (x, f(x)) &\mapsto x \\ (1, f): &\rightarrow \Gamma(f) & x &\mapsto (x, f(x)) \end{aligned}$$

constitute a homeomorphism. Hence, $\Gamma(f)$ has an atlas with a single $(\Gamma(f), \phi)$ and is therefore a C^∞ manifold.

Example 1.8. General Linear group Let $\mathbb{R}^{m \times n}$ be the vector space of all $m \times n$ matrices. Since $\mathbb{R}^{m \times n}$ is isomorphic to \mathbb{R}^{mn} , we give it the topology of \mathbb{R}^{mn} . The *general linear group* $\text{GL}(n, \mathbb{R})$ is defined

$$\begin{aligned} \text{GL}(n, \mathbb{R}) &:= \{A \in \mathbb{R}^{n \times n} \mid \det(A) \neq 0\} \\ &= \det^{-1}(\mathbb{R} - \{0\}) \end{aligned} \quad (49)$$

Since the determinant function $\det: \mathbb{R}^{n \times n} \rightarrow \mathbb{R}$ is continuous, $\text{GL}(n, \mathbb{R})$ is an open subset of $\mathbb{R}^{n \times n} \cong \mathbb{R}^{n^2}$ is therefore a manifold.

Example 1.9. Unit circle in the xy -plane Take S^1 as the unit circle in the real plane \mathbb{R}^2 defined by $x^2 + y^2 = 1$. We can cover S^1 by four open sets: the upper and lower semicircles U_1, U_2 and the left and right semicircles U_3, U_4 (see figure 2). On U_1, U_2 the coordinate function x is a homeomorphism onto the open interval $(-1, 1)$ on the x -axis. Thus, $\phi_i(x, y) := x$. Similarly, on U_3, U_4 , y is a homeomorphism onto the open interval $(-1, 1)$ on the y -axis, and so $\phi_i(x, y) := y$. You can check that on $U_i \cap U_j$, the transition function $\phi_j \circ \phi_i^{-1}$ is C^∞ . For example, on $U_1 \cap U_3$

$$(\phi_3 \circ \phi_1^{-1})(x) = \phi_3(x, \sqrt{1 - x^2}) = \sqrt{1 - x^2}$$

while on $U_2 \cap U_4$

$$(\phi_4 \circ \phi_2^{-1})(x) = \phi_4(x, -\sqrt{1 - x^2}) = -\sqrt{1 - x^2}$$

Thus, $\{(U_i, \phi_i)\}_{i=1}^4$ is a C^∞ atlas on S^1 .

Proposition 1.7: An atlas for a product manifold

If $\{(U_i, \phi_i)\}$ and $\{(V_i, \psi_i)\}$ are C^∞ atlases for the manifolds M, N of dimensions, respectively, then the collection

$$\{(U_i \times V_j, (\phi_i, \psi_j)) : U_i \times V_j \rightarrow \mathbb{R}^m \times \mathbb{R}^n\} \quad (50)$$

is a C^∞ atlas on $M \times N$. Therefore $M \times N$ is a C^∞ manifold of dimension $m + n$.

There n -dimensional torus $S^1 \times \cdots \times S^1$ is a manifold.

1.7 Smooths Maps on a Manifold

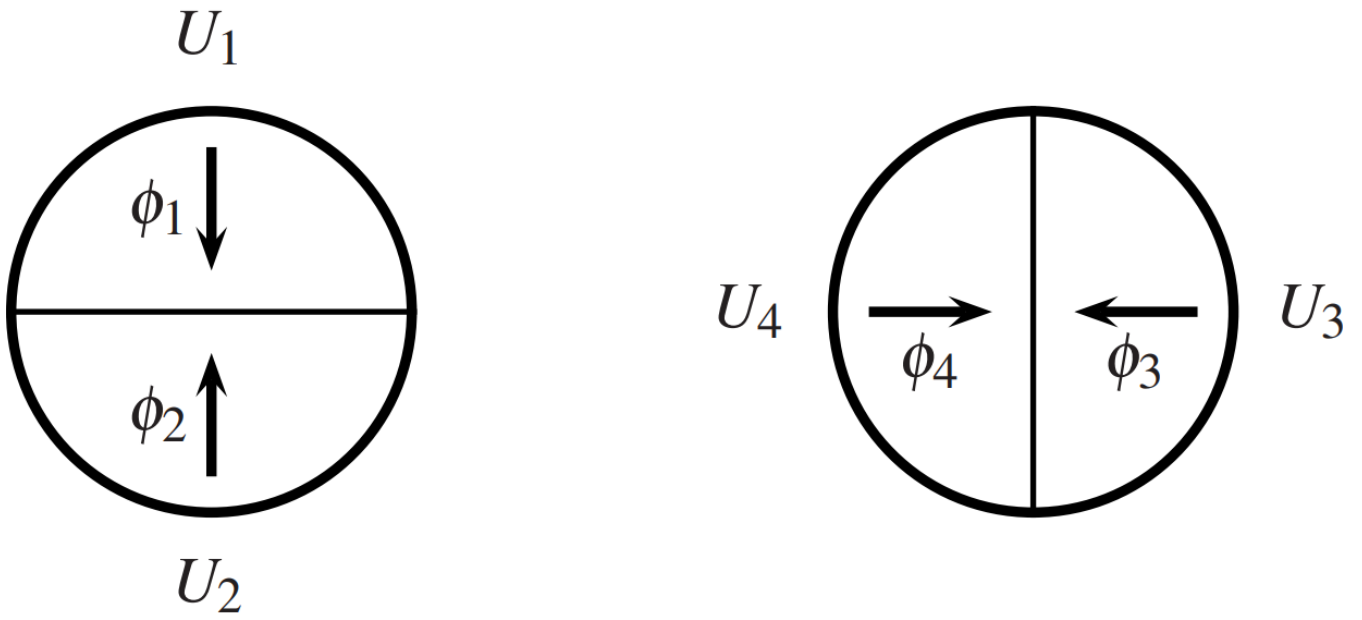


Figure 2: Atlas of charts on the circle.

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