

Differentiable Manifolds

§4. Differential Forms on \mathbb{R}^n

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Differential 1-Forms and the Differential of a Function

Definition (Cotangent Space)

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

Remark

In other words an element of $T_p^*(\mathbb{R}^n)$ is just a covector or linear form on $T_p(\mathbb{R}^n)$.

Definition (Differential 1-Forms)

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

$$\omega : U \longrightarrow \bigcup_{p \in U} T_p^*(\mathbb{R}^n), \quad p \longrightarrow \omega_p \in T_p^*(\mathbb{R}^n).$$

Differential 1-Forms and the Differential of a Function

Definition (Differential of a Function)

The *differential* of a C^∞ function $f : U \rightarrow \mathbb{R}$ is the 1-form df defined by

$$(df)_p(v) = D_v f \quad \text{for all } p \in U \text{ and } v \in T_p(\mathbb{R}^n).$$

Remarks

- ① If $X = \sum a^j \frac{\partial}{\partial x^j}$ is any vector field on U , then

$$(df)_p(X_p) = X_p f = (Xf)(p) = \sum a^j(p) \frac{\partial f}{\partial x^j}(p).$$

- ② We also denote by $df|_p$ the value of df at p .

Differential 1-Forms and the Differential of a Function

Example

- If x^1, \dots, x^n are the coordinate functions, then

$$(dx^i)_p(v) = v^i \quad \text{for any } v = \sum v^j \frac{\partial}{\partial x^j} \Big|_p \text{ in } T_p(\mathbb{R}^n).$$

- In particular, we have

$$(dx^i)_p\left(\frac{\partial}{\partial x^j} \Big|_p\right) = \delta_j^i = \begin{cases} 1 & \text{for } j = i, \\ 0 & \text{for } j \neq i. \end{cases}$$

Proposition (Proposition 4.1)

$\{(dx^1)_p, \dots, (dx^n)_p\}$ is a basis of the cotangent space $T_p^*(\mathbb{R}^n)$.
This is the dual basis of the basis $\{\frac{\partial}{\partial x^1} \Big|_p, \dots, \frac{\partial}{\partial x^n} \Big|_p\}$ of the tangent space $T_p(\mathbb{R}^n)$.

Differential 1-Forms and the Differential of a Function

Fact

- ① If ω is a 1-form on U , then, for every $p \in U$, we have a unique decomposition,

$$\omega_p = \sum a_i(p)(dx^i)_p, \quad a_i(p) \in \mathbb{R}.$$

- ② We write

$$\omega = \sum a_i dx^i,$$

where the coefficients a^i now are functions on U .

Definition

We say that the 1-form ω is C^∞ when all the coefficient functions a_1, \dots, a_n are all C^∞ on U .

Differential 1-Forms and the Differential of a Function

Proposition (Proposition 4.2; the differential in coordinates)

If $f : U \rightarrow \mathbb{R}$ is a C^∞ function, then

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

Corollary

If f is a C^∞ function on U , then its differential df is a C^∞ 1-form.

Remark

The definition of dx^1, \dots, dx^n as 1-forms gives a rigorous meaning to this notation in elementary calculus.

Definition

A differential form of degree k (or a k -form) is a function ω that assigns to each $p \in U$ an alternating k -linear form on the tangent space $T_p(\mathbb{R}^n)$, i.e., $\omega_p \in A_k(T_p(\mathbb{R}^n))$.

Remarks

- ① As $A_1(T_p(\mathbb{R}^n)) = T_p^*(\mathbb{R}^n)$, this generalizes the notion of 1-form.
- ② As $A_0(T_p(\mathbb{R}^n)) = \mathbb{R}$, a 0-form is just a function on U .
- ③ There are no non-zero forms of degree $k > n$, since $\dim T_p(\mathbb{R}^n) = n$, and hence $A_k(T_p(\mathbb{R}^n)) = \{0\}$ for $k > n$.

Differential k -Forms

Example

If $I = (i_1, \dots, i_k)$ is an ascending k -index $i_1 < \dots < i_k$ the k -form dx^I is defined by

$$(dx^I)_p = dx_p^{i_1} \wedge \cdots \wedge dx_p^{i_k}, \quad p \in U.$$

Reminder (see Proposition 3.29)

At each point p the k -covectors dx_p^I form a basis of $A_k(T_p(\mathbb{R}^n))$.

Differential k -Forms

Facts

- 1 If ω is a k -form, then, at each point p , we have a unique decomposition,

$$\omega_p = \sum a_I(p) dx_p^I, \quad a_I(p) \in \mathbb{R},$$

where the summation goes over all ascending k -indices.

- 2 We write

$$\omega = \sum a_I dx^I,$$

where the coefficients a_I now are functions on U .

Definition

We say that the k -form is C^∞ on U when the coefficient functions a_I are all C^∞ on U .

Differential k -Forms

Definition

$\Omega^k(U)$ is the vector space of all C^∞ k -forms on U .

Remark

$\Omega^0(U) = C^\infty(U)$, since 0-forms are functions.

Differential k -Forms

Definition (Wedge Product)

Given a k -form ω and an ℓ -form τ , their *wedge product* is defined pointwise,

$$(\omega \wedge \tau)_p = \omega_p \wedge \tau_p, \quad p \in U.$$

Remarks

- ① If we write $\omega = \sum a_I dx^I$ and $\tau = \sum b_J dx^J$, then

$$\omega \wedge \tau = \sum_{I,J} a_I b_J dx^I \wedge dx^J.$$

- ② If I and J are not disjoint, then $dx^I \wedge dx^J = 0$. Thus,

$$\omega \wedge \tau = \sum_{I,J \text{ disjoint}} a_I b_J dx^I \wedge dx^J.$$

Facts

- The wedge product is a bilinear map,

$$\wedge : \Omega^k(U) \times \Omega^\ell(U) \longrightarrow \Omega^{k+\ell}(U).$$

- This bilinear map is anticommutative and associative (cf. Proposition 3.21 and Proposition 3.25).
- As $\Omega^0(U) = C^\infty(U)$, for $k = 0$ the wedge product reduces to the pointwise multiplication of differential forms by functions,

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

Thus, if $f \in C^\infty(U)$ and $\omega \in \Omega^\ell(U)$, then $f \wedge \omega = f\omega$.

Differential k -Forms

Example

Let x, y, z be the coordinates in \mathbb{R}^3 .

- The C^∞ 1-forms on \mathbb{R}^3 are

$$fdx + gdy + hdz, \quad f, g, h \in C^\infty(\mathbb{R}^3).$$

- The C^∞ 2-forms on \mathbb{R}^3 are

$$fdx \wedge dy + gdx \wedge dz + hdy \wedge dz, \quad f, g, h \in C^\infty(\mathbb{R}^3).$$

- The C^∞ 3-forms on \mathbb{R}^3 are

$$fdx \wedge dy \wedge dz, \quad f \in C^\infty(\mathbb{R}^3).$$

Facts

Define

$$\Omega^*(U) = \bigoplus_{k=0}^{\infty} \Omega^k(U) = \bigoplus_{k=0}^n \Omega^k(U).$$

- ① With the wedge product as multiplication and the degree of a form as grading, $\Omega^*(U)$ is an anticommutative graded algebra.
- ② With respect to the pointwise multiplication of functions, this is also a module over the ring $C^\infty(U)$.

Differential Forms as Multilinear Functions on Vector Fields

Definition

If ω is C^∞ 1-form and X is a C^∞ vector field on an open subset $U \subset \mathbb{R}^n$, the function $\omega(X)$ on U is defined by

$$\omega(X)_p = \omega_p(X_p), \quad p \in U.$$

Fact

- In coordinates, if $\omega = \sum a_i dx^i$ and $X = \sum b^j \frac{\partial}{\partial x^j}$ with $a_i, b^j \in C^\infty(U)$, then

$$\omega(X) = \sum a_i b^i.$$

- This shows that $\omega(X)$ is a C^∞ function on U .

Fact

Let ω be a C^∞ 1-form on U .

- Given any function $f \in C^\infty(U)$ and any vector field $X \in \mathcal{X}(U)$, we have

$$\omega(fX) = f\omega(X).$$

- Set $\mathcal{F}(U) = C^\infty(U)$. Then the 1-form ω defines an $\mathcal{F}(U)$ -linear map,

$$\mathcal{X}(U) \ni X \longrightarrow \omega(X) \in \mathcal{F}(U).$$

Fact

Similarly, any C^∞ k -form ω on U defines a k -linear map over $\mathcal{F}(U)$,

$$\underbrace{\mathcal{X}(U) \times \cdots \times \mathcal{X}(U)}_{k \text{ times}} \rightarrow \mathcal{F}(U), \quad (X_1, \dots, X_k) \mapsto \omega(X_1, \dots, X_k),$$

where

$$\omega(X_1, \dots, X_k)_p = \omega_p((X_1)_p, \dots, (X_k)_p), \quad p \in U.$$

Exterior Derivative

Definition (Exterior Derivative)

The *exterior derivative* of a C^∞ k -form on U is defined as follows:

- For $k = 0$ the exterior derivative of a 0-form (i.e., a C^∞ function) f on U is its differential,

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

- For $k \geq 1$, the exterior derivative of $\omega = \sum a_I dx^I \in \Omega^k(U)$ is

$$d\omega = \sum da_I \wedge dx^I = \sum_I \left(\sum_j \frac{\partial a_I}{\partial x^j} dx^j \right) \wedge dx^I.$$

Remark

- If $\omega \in \Omega^k(U)$, then $d\omega \in \Omega^{k+1}(U)$.
- In particular, $d\omega = 0$ for all $\omega \in \Omega^n(U)$.

Exterior Derivative

Example

Let $\omega = f dx + g dy$ be a 1-form on \mathbb{R}^2 , where $f, g \in C^\infty(\mathbb{R}^2)$. Set $f_x = \partial f / \partial x$ and $f_y = \partial f / \partial y$. Then

$$\begin{aligned} d\omega &= df \wedge dx + dg \wedge dy \\ &= (f_x dx + f_y dy) \wedge dx + (g_x dx + g_y dy) \wedge dy \\ &= f_y dy \wedge dx + g_x dx \wedge dy \\ &= (g_x - f_y) dx \wedge dy. \end{aligned}$$

Exterior Derivative

Definition (Antiderivation of a Graded Algebra)

Let $A = \bigoplus_{k=0}^{\infty} A^k$ be a graded algebra over a field \mathbb{K} .

- An *antiderivation* of A is any linear map $D : A \rightarrow A$ such that

$$D(ab) = (Da)b + (-1)^k aDb \quad \text{for all } a \in A^k \text{ and } b \in A.$$

- We say that D has *degree* m when $D(A^k) \subset A^{k+m}$ for all k .

Remark

- We can extend the grading to negative integers by setting $A^k = \{0\}$ for $k < 0$.
- This allows the degree m to be negative.

Exterior Derivative

Reminder

$\Omega^*(U) = \bigoplus \Omega^k(U)$ is a graded algebra over \mathbb{R} .

Proposition (Proposition 4.7)

The exterior derivative $d : \Omega^*(U) \rightarrow \Omega^*(U)$ has the following properties:

- (i) It is an antiderivation of degree 1, i.e., it is a linear map such that

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

- (ii) $d^2 = 0$, i.e., $d(d\omega) = 0$ for all $\omega \in \Omega^*(U)$.

- (iii) If $f \in C^\infty(U)$ and $X \in \mathcal{X}(U)$, then $(df)(X) = Xf$.

Proposition (Proposition 4.8)

The exterior derivative is the unique map $D : \Omega^*(U) \rightarrow \Omega^*(U)$ with the properties (i)–(iii) above.

Closed and Exact Forms

Definition

Let $\omega \in \Omega^k(U)$.

- ① We say that ω is *closed* when $d\omega = 0$.
- ② We say that ω is *exact* when there is $\tau \in \Omega^{k-1}(U)$ such that $\omega = d\tau$.

Remarks

- ① As $d(d\tau) = 0$ any exact k -form on U is closed. The converse may or may not hold depending on U .
- ② We have

$$\omega \text{ is closed} \iff \omega \in \ker d,$$

$$\omega \text{ is exact} \iff \omega \in \text{ran } d.$$

Example

If f is a C^∞ function on U , then

$$df = 0 \iff \sum \frac{\partial f}{\partial x^i} dx^i = 0 \iff \frac{\partial f}{\partial x^1} = \cdots = \frac{\partial f}{\partial x^n} = 0.$$

Thus, $df = 0$ if and only if f is constant on each connected component of U .

Closed and Exact Forms

Example (see Exercise 4.9)

Consider the following 1-form on $\mathbb{R}^2 \setminus 0$,

$$\omega = \frac{-y}{x^2 + y^2} dx + \frac{x}{x^2 + y^2} dy.$$

Then ω is closed, but it is not exact.

Remark

- If $f \in C^\infty(\mathbb{R}^2 \setminus 0)$ is such that $df = \omega$, then it can be checked that $\frac{d}{dt}f(\cos t, \sin t) = 1$.
- This implies that $\int_0^{2\pi} \frac{d}{dt}f(\cos t, \sin t) dt = 2\pi \neq 0$.
- This is impossible, since

$$\int_0^{2\pi} \frac{d}{dt}f(\cos t, \sin t) dt = f(\cos t, \sin t)|_{t=2\pi} - f(\cos t, \sin t)|_{t=0} = 0.$$

Theorem (Poincaré Lemma; see Corollary 27.13)

If U is star-shaped about a point and $k \geq 1$, then every closed form $\omega \in \Omega^k(U)$ is exact.

Remarks

- ① In particular, any closed k -form on \mathbb{R}^n or an open ball with $k \geq 1$ is exact.
- ② Poincaré Lemma is a special case of a more general result for “contractible manifolds” (see Section 27 of Tu’s book).
- ③ A direct proof of Poincaré Lemma can be found in the book *Introduction to Smooth Manifolds* by John M. Lee.

Applications to Vector Calculus

Definition

A *vector valued function* on an open subset $U \subset \mathbb{R}^3$ is a function,

$$\mathbf{F} = \langle P, Q, R \rangle : U \longrightarrow \mathbb{R}^3.$$

Remark

A vector valued function assigns to each $p \in U$ a vector

$$\mathbf{F}_p \in \mathbb{R}^3 \simeq T_p(\mathbb{R}^3)$$

Therefore, a vector valued function on U can also be thought of as a vector field on U .

Applications to Vector Calculus

Reminder

Gradient, curl and divergence are operators on scalar-valued functions and vector-valued functions,

$$\{\text{scal. func.}\} \xrightarrow{\text{grad}} \{\text{vect. func.}\} \xrightarrow{\text{curl}} \{\text{vect. func.}\} \xrightarrow{\text{div}} \{\text{scal. func.}\},$$

$$\text{grad } f = \begin{bmatrix} \partial/\partial x \\ \partial/\partial y \\ \partial/\partial z \end{bmatrix} f = \begin{bmatrix} f_x \\ f_y \\ f_z \end{bmatrix},$$

$$\text{curl} \begin{bmatrix} P \\ Q \\ R \end{bmatrix} = \begin{bmatrix} \partial/\partial x \\ \partial/\partial y \\ \partial/\partial z \end{bmatrix} \times \begin{bmatrix} P \\ Q \\ R \end{bmatrix} = \begin{bmatrix} R_y - Q_z \\ -(R_x - P_z) \\ Q_x - P_y \end{bmatrix},$$

$$\text{div} \begin{bmatrix} P \\ Q \\ R \end{bmatrix} = \begin{bmatrix} \partial/\partial x \\ \partial/\partial y \\ \partial/\partial z \end{bmatrix} \cdot \begin{bmatrix} P \\ Q \\ R \end{bmatrix} = P_x + Q_y + R_z.$$

Facts

① We identify 1-forms and vector fields on U via

$$Pdx + Qdy + Rdz \longleftrightarrow \begin{bmatrix} P \\ Q \\ R \end{bmatrix}.$$

② Under this identification, for any $f \in C^\infty(U)$, we have

$$df = f_x dx + f_y dy + f_z dz \longleftrightarrow \begin{bmatrix} f_x \\ f_y \\ f_z \end{bmatrix} = \text{grad } f.$$

Applications to Vector Calculus

Facts

① We also identify 2-forms with vector fields,

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

② For any 1-form $\omega = Pdx + Qdy + Rdz$, we have

$$d\omega = (R_y - Q_z)dy \wedge dz - (R_x - P_z)dz \wedge dx + (Q_x - P_y)dx \wedge dy.$$

Thus,

$$d\omega \longleftrightarrow \begin{bmatrix} R_y - Q_z \\ -(R_x - P_z) \\ Q_x - P_y \end{bmatrix} = \text{curl} \begin{bmatrix} P \\ Q \\ R \end{bmatrix}.$$

Facts

- 1 We identify 3-forms with functions

$$fdx \wedge dy \wedge dz \longleftrightarrow f$$

- 2 For any 2-form $\omega = Pdy \wedge dz + Qdz \wedge dx + Rdx \wedge dy$ we have

$$d\omega = (P_x + Q_y + R_z)dx \wedge dy \wedge dz.$$

Thus,

$$d\omega \longleftrightarrow P_x + Q_y + R_z = \operatorname{div} \begin{bmatrix} P \\ Q \\ R \end{bmatrix}.$$

Applications to Vector Calculus

Summary

If U is an open subset of \mathbb{R}^3 , then, under the identification of differential forms with functions and vector fields, the exterior derivative corresponds to the operators **grad**, **curl** and **div**:

$$\begin{array}{ccccccc} \Omega^0(U) & \xrightarrow{d} & \Omega^1(U) & \xrightarrow{d} & \Omega^2(U) & \xrightarrow{d} & \Omega^3(U) \\ \downarrow \wr & & \downarrow \wr & & \downarrow \wr & & \downarrow \wr \\ C^\infty(U) & \xrightarrow{\text{grad}} & \mathcal{X}(U) & \xrightarrow{\text{curl}} & \mathcal{X}(U) & \xrightarrow{\text{div}} & C^\infty(U). \end{array}$$

Applications to Vector Calculus

Consequence

If U is an open subset of \mathbb{R}^3 , then the equality $d \circ d = 0$ on $\Omega^0(U)$ and $\Omega^1(U)$ translates into the following:

Proposition (Proposition A)

For every function $f \in C^\infty(U)$, we have

$$\operatorname{curl}(\operatorname{grad} f) = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}.$$

Proposition (Proposition B)

For every vector field $\mathbf{F} \in \mathcal{X}(U)$, we have

$$\operatorname{div}(\operatorname{curl} \mathbf{F}) = 0.$$

Applications to Vector Calculus

Consequence

- If U is an open subset of \mathbb{R}^3 , then a C^∞ vector field $\mathbf{F} = \langle P, Q, R \rangle$ on U is the gradient of a function $f \in C^\infty(U)$ if and only if the corresponding 1-form $Pdx + Qdy + Rdz$ is df .
- Therefore, Poincaré Lemma for 1-forms translates into:

Proposition (Proposition C)

Assume that U is a star shaped open subset of \mathbb{R}^3 . Then a C^∞ vector field \mathbf{F} on U is the gradient of a function $f \in C^\infty(U)$ if and only if $\text{curl } \mathbf{F} = 0$.

Convention on Subscripts and Superscripts

Convention (Covectors)

- Coordinates x^1, \dots, x^n and multicovectors/forms $\omega^1, \dots, \omega^k$ are indexed by *superscripts*.
- The coordinates of k -forms with respect to the basis $\{dx^I\}$ are indexed by *subscripts*,

$$\omega = \sum a_i dx^i, \quad \omega = \sum a_I dx^I.$$

- The subscripts in a_i and a_I “cancel out” the superscripts in dx^i and dx^I .

Convention on Subscripts and Superscripts

Convention (Vectors)

- Coordinate vector fields $\frac{\partial}{\partial x^1}, \dots, \frac{\partial}{\partial x^n}$ are considered to have subscripts, since the index i in $\frac{\partial}{\partial x^i}$ is in the lower half of the fraction.
- Vectors v_1, \dots, v_k and vector fields X_1, \dots, X_k are indexed by *subscripts*.
- Coordinates of a vector v in a given basis $\{e_i\}$ or a vector field in the basis $\{\frac{\partial}{\partial x^i}\}$ are indexed by *superscripts*,

$$v = \sum v^i e_i, \quad X = \sum X^i \frac{\partial}{\partial x^i}.$$

- The superscripts in v^i and X^i “cancel out” the subscripts in e_i and $\frac{\partial}{\partial x^i}$.