

Manifolds II

January 6, 2025

Recall: Tangent Bundle

Given a chart (U, ϕ) about a point p , we have coordinates (x^1, \dots, x^n) and a basis for $T_q M$ of $(\frac{\partial}{\partial x^1}|_q, \dots, \frac{\partial}{\partial x^n}|_q)$ for $q \in U$.

Then given $TM \xrightarrow{\pi} M$, we may write $v_q = v^i \frac{\partial}{\partial x^i}|_q$.

Definition:

For M a topological manifold. A (real) vector bundle of rank k over M is a topological space E with a surjective continuous map $\pi : E \rightarrow M$ such that

1. $\forall p \in M$, the fiber $\pi^{-1}(p) =: E_p$ is endowed with the structure of a (real) vector space of dimension k .
2. $\forall p \in M$, there exists a neighborhood U of p in M and a homeomorphism $\Phi : \pi^{-1}(U) \rightarrow U \times \mathbb{R}^k$ called a local trivialization.

$$\begin{array}{ccc} \Phi : \pi^{-1}(U) & \xrightarrow{\quad} & U \times \mathbb{R}^k \\ & \searrow \pi & \swarrow \pi_U \\ & U & \end{array}$$

and $\Phi|_{E_q} : E_q \rightarrow \{q\} \times \mathbb{R}^k$ is a linear isometry.

Examples

1. $TM \xrightarrow{\pi} M$
2. $E = M \times \mathbb{R}^k$ with a global trivialization.
3. The Mobius bundle over S^1 . $\gamma : \mathbb{R}^2 \rightarrow \mathbb{R}^2$ by $(x, y) \mapsto (x+1, (-1) \cdot y)$. Then $\langle \gamma \rangle \cong \mathbb{Z}$ a subgroup acting freely and isometrically on \mathbb{R}^2 . Then $E = \mathbb{R}^2 / \langle \gamma \rangle \xrightarrow{\pi} S^1 = \mathbb{R} / \mathbb{Z}$ by $\overline{(x, y)} \mapsto \bar{x}$ is a vector bundle.

IMAGE 1

- We want to show that $\pi^{-1}(U) \cong U \times \mathbb{R}$

$$\begin{array}{ccc} \mathbb{R}^2 & \xrightarrow{\gamma} & E \\ \downarrow \pi & & \downarrow \pi \\ \mathbb{R} & \xrightarrow{\varepsilon} & S^1 \end{array} \quad \begin{array}{ccc} (x, y) & \mapsto & \overline{(x, y)} \\ \downarrow & & \downarrow \\ x & \mapsto & e^{(2\pi i)x} \end{array}$$

Then let $p \in S^1$. We choose U a neighborhood of p such that U is evenly covered by ε . This means $\varepsilon^{-1}(U)$ is a disjoint union of open sets diffeomorphic to U .

IMAGE 2

Let \tilde{U} be a component in $\pi^{-1}(U)$. Then $\pi|_{\tilde{U}} : \tilde{U} \rightarrow U$ is a diffeomorphism and $\pi^{-1}(U)$ is diffeomorphic to $U \times \mathbb{R}$.

Definition: Transition Function

Take $E \xrightarrow{\pi} M$ with $U, V \subseteq M$ admitting trivializations $\phi : \pi^{-1}(U) \rightarrow U \times \mathbb{R}^k$ and $\Psi : \pi^{-1}(V) \rightarrow V \times \mathbb{R}^k$. Let $w = U \cap V (\neq \emptyset)$.

$$\Phi \circ \Psi^{-1} : \begin{array}{ccccc} W \times \mathbb{R}^k & \longrightarrow & \pi^{-1}(W) & \longrightarrow & W \times \mathbb{R}^k \\ & \searrow & \downarrow & \swarrow & \\ & & W & & \end{array}$$

Then $\Phi \circ \Psi^{-1}|_{\{p\} \times \mathbb{R}^k}$ by $\{p\} \times \mathbb{R}^k \rightarrow \{p\} \times \mathbb{R}^k$ is a linear isomorphism.

$\Phi \circ \Psi^{-1}(p, v) = (p, \tau(p)v)$ by $\tau : p \mapsto \tau(p)$ and $\tau(p) \in GL(k, \mathbb{R})$ gives a smooth map $W \rightarrow GL(k, \mathbb{R})$.

Definition:

Let $\{E_1, \dots, E_k\}$ be a basis of \mathbb{R}^k . Then

$$\tau(p) \cdot E_i = \sum_j \tau(p)_i^j E_j$$

with $\tau(p) = (\tau(p)_i^j)$ and $\tau(p)_i^j \in \mathbb{R}$. It suffices to show each $\tau(p)_i^j$ mapping $W \rightarrow \mathbb{R}$ and $p \mapsto (\tau(p)_i^j)$ is smooth. Then if $\sigma(p, v) := \Phi \circ \Psi^{-1}(p, v)$, $\tau(p)_i^j = \pi_j(\sigma(p, E_i))$ and π_j is a projection to the j -th component in \mathbb{R}^k .

Lemma 10.6 (Vector Bundle Chart Lemma)

Given M a smooth manifold, suppose that $\forall p \in M$ we are given a vector space E_p of dimension k . Let $E = \coprod_{p \in M} E_p$ (as a set) and $\pi : E \rightarrow M$ a mapping E_p to p . Suppose also that we have

1. $\{U_\alpha\}_{\alpha \in A}$ an open cover of M with a countable subcover.
2. $\forall \alpha \in A$ we have a bijection $\Phi_\alpha : \pi^{-1}(U_\alpha) \rightarrow U_\alpha \times \mathbb{R}^k$ such that $\Phi_\alpha|_{E_p} : E_p \rightarrow \{p\} \times \mathbb{R}^k$ is a linear isomorphism.
3. $\forall \alpha, \beta \in A$ with $U_{\alpha\beta} := U_\alpha \cap U_\beta \neq \emptyset$ we have a smooth map $\tau_{\alpha\beta} : U_{\alpha\beta} \rightarrow GL(k, \mathbb{R})$ such that $\Phi_\alpha \circ \phi_\beta^{-1} : U_{\alpha\beta} \times \mathbb{R}^k \rightarrow U_{\alpha\beta} \times \mathbb{R}^k$ by $(p, v) \mapsto (p, \tau(p)v)$.

Then $E \xrightarrow{\pi} M$ is a vector bundle.

Example (Whitney Sum):

Suppose we have $E' \xrightarrow{\pi'} M$ and $E'' \xrightarrow{\pi''} M$ two vector bundles over M .

Define $E = E' \oplus E''$ a new vector bundle over M by $E_p = E'_p \oplus E''_p$. Let $\{U_\alpha\}_{\alpha \in A}$ be a countable open cover of M such that each U_α admits trivializations for E' and E'' . Then for $\pi : E \rightarrow M$, define $\Phi_\alpha : \pi^{-1}(U_\alpha) \rightarrow U_\alpha \times \mathbb{R}^{k'} \times \mathbb{R}^{k''}$ by $(v', v'')_p \mapsto (p, \pi_2 \circ \Phi_\alpha^{-1}(v'), \pi_2 \circ \Phi_\alpha''(v''))$ where

$$\pi'(U_\alpha) \xrightarrow{\Phi'_\alpha} U_\alpha \times \mathbb{R}^{k'} \xrightarrow{\pi_2} \mathbb{R}^{k'}$$

Note that π_2 is the projection into the second component. Then $\tau : U_{\alpha\beta} \rightarrow G(k' + k'', \mathbb{R})$ by

$$p \mapsto \begin{pmatrix} \tau'(p) & 0 \\ 0 & \tau''(p) \end{pmatrix}$$

Example

For $\tau_{\alpha\beta} : U_{\alpha\beta} \rightarrow GL(k, \mathbb{R})$ by $p \mapsto \tau_{\alpha\beta}(p)$, we can write $U_{\alpha\beta\gamma} = U_\alpha \cap U_\beta \cup U_\gamma (\neq \emptyset)$ and get $\tau_{\alpha\beta} \cdot \tau_{\beta\gamma} = \tau_{\alpha\gamma}$.

Note that this is $\Phi_\alpha \circ (\phi_\beta^{-1} \circ \phi_\beta) \circ \Phi_\gamma^{-1}$.

Without loss of generality, we assume each U_α is a chart for M . Then we want to show that we satisfy Lemma 1.35 from Lee

$$\pi^{-1}(U_\alpha) \xrightarrow{\Phi_\alpha} U_\alpha \times \mathbb{R}^k \xrightarrow{\phi_\alpha \times \text{id}} \phi_\alpha(U_\alpha) \times \mathbb{R}^k \subseteq \mathbb{R}^{n+k}$$

$(\pi^{-1}(U_\alpha) \cdot \tilde{\phi}_\alpha = (\phi_\alpha \times \text{id}) \circ \Phi_\alpha)_{\alpha \in A}$ which satisfies (1).

Since

$$\pi^{-1}(U_\alpha) \cap \pi^{-1}(U_\beta) = \pi^{-1}(U_\alpha \cap U_\beta) \rightarrow \phi_\alpha(U_{\alpha\beta}) \times \mathbb{R}^k$$

we have that (2) is satisfied.

Finally, for (3),

$$\tilde{\phi}_\beta \circ \tilde{\phi}_\alpha^{-1} = (\Phi_\beta \circ (\phi_\beta \times \text{id})) \circ ((\phi_\alpha \times \text{id})^{-1} \circ \Phi_\alpha^{-1}) = \Phi_\beta \circ ((\phi_\beta \circ \phi_\alpha) \times \text{id}) \circ \Phi_\alpha^{-1}$$

gives $(x, c) \mapsto ((\phi_\beta \circ \phi_\alpha^{-1})x, (\Phi_\beta \circ \Phi_\alpha^{-1})c)$ a diffeomorphism.

(4) and (5) are trivial, and this is indeed a smooth manifold. Now we wish to show that it is a vector bundle. To show that $\pi : E \rightarrow M$ is smooth,

$$\begin{array}{ccc} \pi^{-1}(U_\alpha) & \xrightarrow{\pi} & U_\alpha \\ \tilde{\phi}_\alpha^{-1} \uparrow & & \downarrow \phi_\alpha \\ \phi_\alpha(U_\alpha) \times \mathbb{R}^k & & \phi_\alpha(U_\alpha) \end{array}$$

We have $\tilde{\phi}_\alpha^{-1} = (\phi_\alpha \times \text{id})^{-1} \circ \Phi_\alpha^{-1}$.

$$\begin{array}{ccc} \pi^{-1}(U_\alpha) & \xrightarrow{\Phi_\alpha} & U_\alpha \times \mathbb{R}^k \\ \tilde{\phi}_\alpha^{-1} \uparrow & & \downarrow \phi_\alpha \times \text{id} \\ \phi_\alpha(U_\alpha) \times \mathbb{R}^k & & \phi_\alpha(U_\alpha \times \mathbb{R}^k) \end{array}$$

Definition: Section of a Bundle

A (smooth) section of $E \xrightarrow{\pi} M$ is a (smooth) map $\sigma : M \rightarrow E$ such that $\pi \circ \sigma = \text{id}_M$.

$\Gamma(E) = \{\text{smooth sections of } E \xrightarrow{\pi} M\}$ and $\Gamma(E)$ is a $C^\infty(M)$ -module.

The zero section $Z : M \rightarrow E$ is given by $p \mapsto 0_p \in E_p$.

If U has a local trivialization, $\Phi : \pi^{-1}(U) \rightarrow U \times \mathbb{R}^k$.

$$\Phi : \begin{array}{ccccc} \pi^{-1}(U) & \xrightarrow{\quad} & U \times \mathbb{R}^k & \xleftarrow{\Phi^{-1}} & (p, e_i) \\ & \nwarrow \text{dashed} & \nearrow & \searrow \tilde{e}_i & \uparrow p \\ & U & & p & \end{array}$$

Define $\sigma_i : U \rightarrow \pi^{-1}(U)$ by $\sigma_i = \Phi^{-1} \circ \tilde{e}_i$ gives a local section that is non-zero on U .

$\{\sigma_1, \dots, \sigma_n\}$ form a local frame on U (i.e. form a basis in E_p , $\forall p \in U$).

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Recall

Last time we had a vector bundle $E \xrightarrow{\pi} M$ of rank k satisfying

1. $\pi^{-1}(p) = E_p$ has a (real) vector space structure of dimension k .
2. We have a local trivialization, $\forall p \in M$ there exists a neighborhood U and a diffeomorphism Φ

$$\begin{array}{ccc} \pi^{-1}(U) & \xrightarrow{\Phi} & U \times \mathbb{R}^k \\ & \searrow \pi & \swarrow \pi_U \\ & U & \end{array}$$

and $\Phi|_{E_p} : E_p \rightarrow \{p\} \times \mathbb{R}^k$ is a linear isomorphism.

A section $\sigma : M \rightarrow E$ is a smooth map such that $\pi \circ \sigma = \text{id}_M$.

We say that a collection of sections $\{\sigma_1, \dots, \sigma_k : U \rightarrow E\}$ is linearly independent if $\{\sigma_1(x), \dots, \sigma_k(x)\}$ is linearly independent for each $x \in U$. This is a (local) frame if it is a basis.

If $U \subseteq M$ admits a trivialization

$$\Phi : \begin{array}{ccc} \pi^{-1}(U) & \xrightarrow{\quad} & U \times \mathbb{R}^k \\ & \searrow & \swarrow \\ & U & \end{array}$$

then there is a local frame $\{\sigma_1, \dots, \sigma_k\}$ defined on U . Precisely, with $\tilde{e}_i(x) = (x, e_i)$, $\sigma_i = \Phi^{-1} \circ \tilde{e}_i$.

Proposition 10.19

If $U \subseteq M$ admits a local frame, then $\pi^{-1}(U)$ admits a local trivialization.

Remember

If $E \xrightarrow{\pi} M$ admits a global frame, then $E = \pi^{-1}(M)$ has a trivialization. In other words, E is diffeomorphic to a trivial vector bundle $M \times \mathbb{R}^k$.

Examples

Example 1

Mobius bundle over S^1 .

IMAGE 1

To check whether it is a trivial bundle of S^1 , it suffices to check whether there exists a nowhere zero (global) section. This cannot happen (by intermediate value theorem), hence it is not $S^1 \times \mathbb{R}$.

Example 2

TS^2 because there is no non-vanishing vector field over S^2 , hence $TS^2 \neq S^2 \times \mathbb{R}^2$.

Example 3

Let G be a Lie group. Every $X \in T_e G (\cong \mathfrak{g})$ uniquely determines a (left-invariant) vector field $\tilde{X} \in \mathfrak{X}(G)$. Starting with a basis $\{E_i\} \subseteq T_e G$ we get a global frame $\{\tilde{E}_i\}$ for TG . Hence TG is a trivial vector bundle $G \times \mathbb{R}^n$ ($n = \dim G$). In particular, $TS^1 = S^1 \times \mathbb{R}$, $TS^3 = S^3 \times \mathbb{R}^3$.

Proof of Proposition

Define $\Psi : (x, v^1, \dots, v^k) \in U \times \mathbb{R}^k \rightarrow \pi^{-1}(U) \ni v_x$ where $v_x = v^i \sigma_i(x)$.

Ψ is a bijection. Note that $\Psi|_{E_x} : E_x \rightarrow \{x\} \times \mathbb{R}^k$ is a linear isomorphism because $\{\sigma_i(x)\}$ is a basis. Then to show that Ψ is a diffeomorphism, it suffices to show then that Ψ is a local diffeomorphism.

Let $x \in U$ and let V be a neighborhood of x such that $\pi^{-1}(V) \xrightarrow{\Phi} V \times \mathbb{R}^k$.

$$V \times \mathbb{R}^k \xrightarrow{\Psi|_{V \times \mathbb{R}^k}} \pi^{-1}(V) \xrightarrow{\Psi} V \times \mathbb{R}^k$$

We show that this composition is a diffeomorphism. Since $\Phi(\sigma_i(x)) = (x, \sigma_i^1(x), \dots, \sigma_i^k(x))$

$$\begin{aligned} \Phi \circ \Psi|_{V \times \mathbb{R}^k}(x, v^1, \dots, v^k) &= \Phi(v^i \sigma_i(x)) \\ &= (x, v^i \sigma_i^1(x), \dots, v^i \sigma_i^k(x)) \end{aligned}$$

Each $\sigma_i^j(x)$ is smooth. Hence $\Phi \circ \Psi|_{V \times \mathbb{R}^k}$ is smooth.

Let $\vec{v} = (v^1, \dots, v^k)$ and $\sum(x) = (\sigma_i^j(x))$, then $\Phi \circ \Psi(x, \vec{v}) = (x, \vec{v} \cdot \sum(x))$. Its inverse

$$(\Phi \circ \Psi)^{-1}(x, \vec{w}) = (x, \vec{w} \cdot \sum(x))$$

is also smooth. This shows that $\Phi \circ \Psi|_{V \times \mathbb{R}^k}$ is a diffeomorphism. Hence $\Psi|_{V \times \mathbb{R}^k}$ is a diffeomorphism ($V \subseteq U$) and $\Psi : U \times \mathbb{R}^k \rightarrow \pi^{-1}(U)$ is also a diffeomorphism.

Definition: Bundle Morphism

A bundle morphism between is a pair of smooth maps (f, F) such that this diagram commutes

$$\begin{array}{ccc} E & \xrightarrow{F} & E' \\ \downarrow \pi & & \downarrow \pi' \\ M & \xrightarrow{f} & M' \end{array}$$

and $F|_{E_p} : E_p \rightarrow E'_{f(p)}$ is a linear map ($\forall p \in M$).

If it admits an inverse which is itself a bundle morphism, it is a bundle isomorphism.

Remember that f is smooth because $f = \pi' \circ F \circ Z$

$$p \xrightarrow{Z} 0_p \xrightarrow{F} 0_{f(p)} \xrightarrow{\pi'} f(p)$$

Remark

$$\begin{array}{ccc} E & \xrightarrow{F} & E' \\ \searrow \pi & & \swarrow \pi' \\ & M & \end{array}$$

commutes and $F|_{E_p} : E_p \rightarrow E'_{f(p)}$ is linear ($\forall p$).

Remark

$\text{rank}(F|_{E_p})$ may depend on $p \in M$.

$$\begin{array}{ccc} TM & \xrightarrow{Df} & TR \\ \downarrow \pi & & \downarrow \pi \\ M & \xrightarrow{f} & \mathbb{R} \end{array}$$

e.g. $M = \mathbb{R}^2$, $E = E' = TR^2 (= \mathbb{R}^4)$, $F((u, v)_{(x, y)}) = (u, xv)$. For $x \neq 0$, $\text{rank}(F|_{(x, y)}) = 2$ but for $x = 0$ $\text{rank}(F|_{(0, y)}) = 1$.

Proposition 10.26

$$\begin{array}{ccc} E & \xrightarrow{F} & E' \\ \searrow \pi & & \swarrow \pi' \\ & M & \end{array}$$

If F is a bijective, smooth bundle homomorphism, then it is a bundle isomorphism. Proof left as an exercise. We need to show that F^{-1} is smooth.

Definition: Fiber Bundle

$F \rightarrow E \xrightarrow{\pi} M$ with fiber F such that $E_x = \pi^{-1}(x)$ is diffeomorphic to F . This diagram commutes.

$$\begin{array}{ccc} \pi^{-1}(U) & \xrightarrow{\Phi} & U \times F \\ \searrow \pi & & \swarrow \pi_U \\ & U & \end{array}$$

Fact

If $N \xrightarrow{F} M$ is a submersion from compact manifolds, then F is a fiber bundle.

Chapter 11: Cotangent Bundles

Review: Linear Algebra

Suppose we have a real vector space V of dimension n . Then $V^* = \{f : V \rightarrow \mathbb{R} \text{ linear}\}$.

If V has a basis $\{E_1, \dots, E_n\}$, then we may define the dual basis for V^* $\{e^1, \dots, e^n\}$ by $e^j(E_i) = \delta_i^j = \begin{cases} 1 & i = j \\ 0 & i \neq j \end{cases}$.

Remember $V^{**} \cong V$ by $\xi : V \rightarrow V^{**}$ by $v \mapsto \xi(v) : V^* \rightarrow \mathbb{R}$ and $\omega \mapsto \omega(v)$.

Remember also that if A is a linear map $V \rightarrow W$ then we may define $A^* : W^* \rightarrow V^*$ by $v \in V \mapsto \mathbb{R} \ni \omega(Av)$ (ie. $(A^*\omega)(v) = \omega(Av)$).

Definition: Cotangent Bundle

Let M^n be a smooth manifold, and let (U, ϕ) be a chart. Then $T_p M$ has a basis

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

for every $p \in U$. Take its dual basis

$$\{\lambda^1|_p, \dots, \lambda^n|_p\}$$

for $T_p^* M$. The cotangent bundle $T^* M = \coprod_{p \in M} T_p^* M$.

Similar to the TM case, if $T^* M \xrightarrow{\pi} M$, then $\omega|_p \in \pi^{-1}(U) \xrightarrow{\Phi} U \times \mathbb{R}^n \ni (p, a_1, \dots, a_n)$ where a_i is given by $\omega|_p = a_i \lambda^i|_p$.

In other words, $a_i = \omega|_p \left(\frac{\partial}{\partial x^i} \Big|_p \right)$.

Computing Dual Transition

Suppose $(U, (x^1, \dots, x^n))$ and $(V, (y^1, \dots, y^n))$ are two charts ($W = U \cap V \neq \emptyset$). Then $\left\{ \frac{\partial}{\partial x^i} \Big|_p \right\}$ gives a dual $\{\lambda^i|_p\}$ and $\left\{ \frac{\partial}{\partial y^j} \Big|_p \right\}$ gives $\{\mu^j|_p\}$.

Then, recall, $\frac{\partial}{\partial y^j} \Big|_p = \frac{\partial x^i}{\partial y^j} \frac{\partial}{\partial x^i} \Big|_p$ and $x^j(y^1, \dots, y^n)$ is a j -component of $(y^1, \dots, y^n) \rightarrow M \rightarrow (x^1, \dots, x^n)$.

If $\omega \in T_p^* M$, $\omega = a_i \lambda^i|_p = b_j \mu^j|_p$

$$a_i = \omega|_p \left(\frac{\partial}{\partial x^i} \Big|_p \right) = \omega|_p \left(\frac{\partial y^j}{\partial x^i} \frac{\partial}{\partial y^j} \Big|_p \right) = \frac{\partial y^j}{\partial x^i} \omega \left(\frac{\partial}{\partial y^j} \Big|_p \right) = \frac{\partial y^j}{\partial x^i} b_j$$

In particular, $\mu^j = \omega$, then $a_i = \frac{\partial y^j}{\partial x^i} b_j = \frac{\partial y^j}{\partial x^i} \mu^j$. Hence $\mu^j = \omega = a_i \lambda^i = \frac{\partial y^j}{\partial x^i} \lambda^i$.

Definition: Smooth Covector Field

A smooth covector field is a smooth section of $T^* M$, call it $\Omega^1(M) = \Gamma(T^* M)$.

Given $f \in C^\infty(M)$, we can define a smooth covector field $df \in \Omega^1(M)$ by $df(v|_p) = (v_p)(f)$.

$df(X) = Xf$ is smooth if X and f are smooth.

Differential

Given a local chart $(U, (x^1, \dots, x^n))$ and a smooth function $f : U \rightarrow \mathbb{R}$, $df_p = a_i(p) \lambda^i|_p$.

$$\frac{\partial f}{\partial x^j} = df_p \left(\frac{\partial}{\partial x^j} \Big|_p \right) = a_i(p) \lambda^i|_p \left(\frac{\partial}{\partial x^j} \Big|_p \right) = a_i(p) \delta_j^i = a_j(p)$$

That is, $df_p = \frac{\partial f}{\partial x^j}(p) \lambda^j|_p$. In particular, if we consider the coordinate function $x^i : U \rightarrow \mathbb{R}$, then $dx^i|_p = \frac{\partial x^i}{\partial x^j}(p) \lambda^j|_p = \lambda^i|_p$ for each $p \in U$ (i.e. $dx^i = \lambda^i$ on U).

With this, we can write $df = \frac{\partial f}{\partial x^i} dx^i$ and $dy^j = \frac{\partial y^j}{\partial x^i} dx^i$.

Proposition 11.22

For $f \in C^\infty(M)$, then $df = 0$ if and only if f is constant on every component of M .

Proof

(\Leftarrow) is trivial.

(\Rightarrow) We assume M is connected. Fix $p \in M$, define $\mathcal{A} = \{q \in M : f(p) = f(q)\}$ is closed.

Now let $q \in \mathcal{A}$ and U a local chart around q . Then $0 = df = \frac{\partial f}{\partial x^i} dx^i$ (i.e. $\frac{\partial f}{\partial x^i} \equiv 0, \forall i$).

Hence f is constant on U and $f(q) = f(p)$ for $U \in \mathcal{A}$.

Proposition 11.23

Take $\gamma : J \rightarrow M$ a smooth curve $f \in C^\infty(M)$. Then $(df|_{\gamma(t)})(\gamma'(t)) = (\gamma'(t))f = (f \circ \gamma)'(t)$.

IMAGE 2

Recall that if $v \in T_p M$ and $f \in C^\infty(M)$ then $vf = (f \circ \gamma)'(0)$ where $\gamma : (-\varepsilon, \varepsilon) \rightarrow M$, $\gamma(0) = p$ and $\gamma'(0) = v$ ($f \circ \gamma : \mathbb{R} \rightarrow \mathbb{R}$).

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Recall

T^*M and $\Omega^1(M) = \Gamma(T^*M)$. Let $(U, (x^1, \dots, x^n))$ be a chart. Then inside U , we may write $\omega = \omega_i dx^i$. $\{dx^i|_p\}$ is a dual basis of $\{\frac{\partial}{\partial x^i} \subseteq T_p M\}$.

They are also $x^i : U \rightarrow \mathbb{R}$ coordinates functions where dx^i is the differential of x^i .

Given $f \in C^\infty(M)$ or $C^\infty(U)$, $df \in \Omega^1(M)$ or $\Omega^1(U)$ is defined by $df(X_p) = (Xf)(p)$.

Inside a chart, $df = \frac{\partial f}{\partial x^i} dx^i$.

We have a change of coordinates where $(U, (x^1, \dots, x^n))$ and $(V, (y^1, \dots, y^n))$ and $W = U \cap V \neq \emptyset$ gives $dy^j = \frac{\partial y^j}{\partial x^i} dx^i$.

Recall (Linear Algebra)

If $A : V \rightarrow W$ is a linear map with $w \in W^*$ and $v \in V$, then $A^* : W^* \rightarrow V^*$ is the dual map defined by $(A^* w)(v) := w(Av)$.

Dual of the Tangent Space

Let $F : M \rightarrow N$ be a smooth map between manifolds.

$$\begin{aligned} DF_p : T_p M &\rightarrow T_{F(p)} N \\ (DF_p)^* : T_{F(p)}^* N &\rightarrow T_p^* M \end{aligned}$$

and $(DF_p^* \omega)(v) = \omega(DF_p(v))$ for $\omega \in T_{F(p)}^* N$ and $v \in T_p M$.

Definition: Pullback

Given $\omega \in \Omega^1(N)$, we can define $F^* \omega$, a section of T^*M , by $(F^* \omega)_p(v) = \omega(DF_p(v))$ or $(F^* \omega)_p = DF_p^* \omega$. We call this the pullback of ω by F .

Recall that for $u \in C^\infty(N)$, $M \xrightarrow{F} N \xrightarrow{u} \mathbb{R}$. Then we can define $F^*u \in C^\infty(M)$ by $F^*u = u \circ F$.

Proposition

If $F : M \rightarrow N$ is smooth, $u \in C^\infty(N)$ and $\omega \in \Omega^l(N)$, then

1. $F^*(u\omega) = (F^*u)(F^*\omega)$.
2. $F^*(du) = d(F^*u)$.

Proof of 1

$\forall p \in M, \forall v \in T_p M$,

$$(F^*(u\omega))_p(v) = DF_p^*(u\omega)(v) = u_{F(p)}\omega_{F(p)}(DF_p(v)) = (u \circ F(p))\omega(DF_p(v)) = (F^*u)(F^*\omega)$$

Proof of 2

$$(F^*(du))(v) = du(DF_p(v)) = (DF_p(v))u = (du)_{F(p)}DF_p(v) = d(u \circ F)(v) = d(F^*u)(v)$$

Change of Coordinates

Locally, $F : M \rightarrow N$. Let $(U, (x^1, \dots, x^n))$ be a chart around p and $(V, (y^1, \dots, y^n))$ a chart around $F(p)$. For $\omega \in \Omega^l(N)$, in V $\omega = \omega_i dy^i$ and

$$F^*\omega = F^*(\omega_i dy^i) = (F^*\omega_i)(F^*dy^i) = (F^*\omega_i)d(F^*y^i) = (\omega_i \circ F)(dF^i)$$

where $F^i = y^i \circ F$ is the i th component of F .

When F is smooth and $\omega \in \Omega^l(N)$, then $F^*\omega \in \Omega^l(M)$. In fact, locally, $F^*\omega = (\omega_i \circ F)d(F^i)$. Hence $F^*\omega$ is smooth.

Example 1

Take $F : \mathbb{R}^3 \rightarrow \mathbb{R}^2$ by $(x, y, z) \mapsto (u(x, y, z), v(x, y, z)) = (x^2 y, y \sin(z))$.

Then $\omega = u dv + v du \in \Omega^1(\mathbb{R}^2)$. So

$$\begin{aligned} F^*\omega &= F^*(u dv + v du) \\ &= (F^*u)d(F^*v) + (F^*v)d(F^*u) \\ &= x^2 y d(y \sin(z)) + (y \sin(z)) d(x^2 y) \\ &= x^2 y (\sin(z) dy + y \cos(z) dz) + y \sin(z) (2xy dx + x^2 dy) \end{aligned}$$

Example 2

$M = \mathbb{R}^2 - \{0\}$ and $\gamma : [0, 2\pi] \rightarrow M$ by $t \mapsto (r \cos(t), r \sin(t))$ for $r > 0$. Take $\omega = \frac{x dy - y dx}{x^2 + y^2} \in \Omega^1(M)$

$$\begin{aligned} \gamma^*\omega &= \frac{1}{r^2} (r \cos(t) d(r \sin(t)) - r \sin(t) d(r \cos(t))) \\ &= \cos(t)(\cos(t)) dt - \sin(t)(\sin(t)) dt \\ &= dt \end{aligned}$$

Definition: Line Integral

If $\eta \in \Omega'(\mathbb{R})$ or $\Omega'(I)$ (where $I \subseteq \mathbb{R}$ is an interval), η can be written as $\eta(t) = f(t) dt$ and define

$$\int_I \eta = \int_a^b f(t) dt$$

Let $\gamma : [a, b] \rightarrow M$ be a smooth curve on M . Let $\omega \in \Omega'(I)$. Define

$$\int_\gamma \omega = \int_a^b \gamma^* \omega$$

with $\gamma^*(\omega) \in \Omega'([a, b])$.

Proposition 11.31

Take $\phi : I \rightarrow J$ a diffeomorphism between intervals with $\phi' > 0$. Then

$$\int_J \phi^* \omega = \int_{\phi(I)} \omega$$

Write s for coordinates on J and t for coordinates on I . Then $\omega = f(t) dt \in \Omega^1(I)$ and

$$\phi^* \omega = (\phi^* f) d(\phi^* t) = (f \circ \phi) d(t \circ \phi) = f(\phi(s)) d(\phi(s)) = f(\phi(s)) \phi'(s) ds$$

Then

$$\int_J \phi^* \omega = \int_J f(\phi(s)) \phi'(s) ds \stackrel{t=\phi(s)}{=} \int_I f(t) dt = \int_I \omega$$

Proposition 11.37: Independence of Reparameterization

Suppose $\gamma : I \rightarrow M$ is a smooth curve and $\phi : J \rightarrow I$ is a diffeomorphism with $\phi' > 0$. Then $\tilde{\gamma} := \gamma \circ \phi : J \rightarrow M$ is a reparameterization of γ and

$$\int_\gamma \omega = \int_{\tilde{\gamma}} \omega$$

If $\phi' < 0$, then $\int_\gamma \omega = - \int_{\tilde{\gamma}} \omega$.

Proof

$$\int_\gamma \omega = \int_I \gamma^* \omega = \int_J \phi^* \gamma^* \omega = \int_J (\gamma \circ \phi)^* \omega = \int_{\tilde{\gamma}} \omega$$

Example

Take $\gamma : [0, 2\pi] \rightarrow M = \mathbb{R}^2 - \{0\}$ by $t \mapsto (r \cos(t), r \sin(t))$ with $r > 0$. If $\omega = \frac{x dy - y dx}{x^2 + y^2}$, then $\gamma^* \omega = dt$ and

$$\int_\gamma \omega = \int_0^{2\pi} \gamma^* \omega = \int_0^{2\pi} dt = 2\pi$$

Proposition 11.38

For $\gamma : I \rightarrow M$

$$\int_{\gamma} \omega = \int_I \omega_{\gamma(t)}(\dot{\gamma}(t)) dt$$

Proof

In a local chart $(U, (x^1, \dots, x^n))$, we can write $\omega = \omega_i dx^i$. Then $\gamma(t) = (\gamma^1(t), \dots, \gamma^n(t))$ and

$$\begin{aligned} \gamma^* \omega &= \gamma^*(\omega_i dx^i) \\ &= (\gamma^* \omega_i) d(\gamma^* x^i) \\ &= (\omega_i \circ \gamma) d\gamma^i \\ &= \omega_i(\gamma(t)) \frac{d\gamma^i}{dt} dt \\ &= \omega_i(\gamma(t)) \dot{\gamma}^i(t) dt \end{aligned}$$

Since $\omega = \omega_i dx^i$ and $\dot{\gamma}(t) = (\dot{\gamma}^1(t), \dots, \dot{\gamma}^n(t)) = \dot{\gamma}^i(t) \frac{\partial}{\partial x^i}$, $\omega_{\gamma(t)}(\dot{\gamma}(t)) = \omega_i(\gamma(t)) \dot{\gamma}^i(t)$ and

$$\omega_i(\gamma(t)) \dot{\gamma}^i(t) dt = \omega_{\gamma(t)}(\dot{\gamma}(t)) dt$$

Hence $\int_{\gamma} \omega = \int_I \gamma^* \omega = \int_I \omega_{\gamma(t)}(\dot{\gamma}(t)) dt$.

Corollary

Then, if $f : M \rightarrow \mathbb{R}$ is a smooth function,

$$\int_{\gamma} df = \int_I (df)_{\gamma(t)}(\dot{\gamma}(t)) dt = \int_I (f \circ \gamma)'(t) dt = f(\gamma(b)) - f(\gamma(a))$$

Therefore $\int_{\gamma} df$ only depends on the value of f at the endpoints of γ .

Definition: Exact and Conservative Forms

Let $\omega \in \Omega^1(M)$. We say that ω is . . .

1. exact if there exists $f \in C^{\infty}(M)$ such that $\omega = df$.
2. conservative if $\int_C \omega = 0$ for any closed, piecewise-smooth curve in M

f is called the potential of ω .

Remark

If $\int_C \omega = 0$, we may write C as the concatenation of curves γ then $-\sigma$. Then

$$0 = \int_C \omega = \int_{\gamma} \omega + \int_{-\sigma} \omega = \int_{\gamma} \omega - \int_{\sigma} \omega$$

Remark

Exact implies conservative.

Theorem

If $\omega \in \Omega^1(M)$ is conservative, then it is exact.

Proof

Fix a base point $p_0 \in M$.

We have that $\int_p^q \omega = \int_\gamma \omega$ is well-defined by the conservative assumption, and we define $f(p) = \int_{p_0}^p \omega$.

Let $q_0 \in M$ and let $(U, (x^1, \dots, x^n))$ be a chart centered at q_0 . Inside U , $\omega = \omega_i dx^i$ and $df = \frac{\partial f}{\partial x^i} dx^i$.

We need to show that $\frac{\partial f}{\partial x^i} = \omega_i$ for each i . Fix an index i and consider a curve $\sigma : (-\varepsilon, \varepsilon) \rightarrow U$ by $t \mapsto (0, \dots, t, \dots, 0)$.

IMAGE 1

Let $q_- = \sigma(-\varepsilon)$, then

$$f(q_0) = \int_{p_0}^q \omega = \int_{p_0}^{q_-} \omega + \int_{q_-}^q \omega =: \tilde{f}(q)$$

so $f(q_0) = \text{constant} + \tilde{f}(q)$. Hence $\frac{\partial f}{\partial x^j} = \frac{\partial \tilde{f}}{\partial x^j}$ in U . Therefore

$$\begin{aligned} \tilde{f}(\sigma(s)) &= \int_{q_-}^{\sigma(s)} \omega \\ &= \int_{\sigma|_{[-\varepsilon, s]}} \omega \\ &= \int_{-\varepsilon}^s \omega_{\sigma(t)}(\dot{\sigma}(t)) dt \\ &= \int_{-\varepsilon}^s \omega_{\sigma(t)} \left(\frac{\partial}{\partial x^i} \right) dt \\ &= \int_{-\varepsilon}^s \omega_i(\sigma(t)) dt \end{aligned}$$

and

$$\left. \frac{\partial f}{\partial x^i} \right|_{q_0} = \left. \frac{\partial \tilde{f}}{\partial x^i} \right|_{q_0} = (\tilde{f} \circ \sigma)'(0) = \left. \frac{d}{ds} \right|_{s=0} \left(\int_{-\varepsilon}^s \omega_i(\sigma(t)) dt \right) = \omega_i(\sigma(0)) = \omega_i(q_0)$$

Remark

Take $\omega = df \in \Omega^1(M)$ which is $\omega_i dx^i$ locally or $\omega_i = \frac{\partial f}{\partial x^i}$ when exact.

$$\frac{\partial \omega_i}{\partial x^j} = \frac{\partial^2 f}{\partial x^i \partial x^j} = \frac{\partial \omega_j}{\partial x^i}$$

Note: $\frac{\partial \omega_i}{\partial x^j} = \frac{\partial \omega_j}{\partial x^i}$ does not, in general, imply $\omega = df$.

January 15, 2025

Recall

If $\omega \in \Omega^1(M)$ and $\gamma: \mathbb{R} \supseteq I \rightarrow M$ a (piecewise) smooth curve, then

$$\int_{\gamma} \omega = \int_I \gamma^* \omega$$

If df is the differential of a smooth function, then

$$\int_{\gamma} df = f(\gamma(b)) - f(\gamma(a))$$

only depends on endpoints. In particular, along a closed (piecewise) smooth curve

$$\int_C df = 0$$

We have that ω is exact if $\omega = df$ and conservative if $\int_C \omega = 0$ for every closed curve. ω is exact if and only if it is also conservative.

Recall: Checking Exactness

Take $\omega \in \Omega^1(M)$,

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

Then

$$\frac{\partial^2 f}{\partial x^i \partial x^j} = \frac{\partial^2 f}{\partial x^j \partial x^i}$$

That is, $\frac{\partial \omega_i}{\partial x^j} = \frac{\partial \omega_j}{\partial x^i}$.

Definition: Closed 1-Form

We say $\omega \in \Omega^1(M)$ is closed if in every chart $(U, (x^i))$, $\omega = \omega_i dx^i$ satisfies $\frac{\partial \omega_i}{\partial x^j} = \frac{\partial \omega_j}{\partial x^i}$. Exact implies closed, however the converse is not true in general.

Example

$\exists \omega \in \Omega^1(\mathbb{R}^2 - \{0\})$ such that ω is closed but $\int_C \omega = 2\pi$.

Corollary 11.50

If $\omega \in \Omega^1(M)$ is closed, then $\forall p \in M$ there exists a chart U at p such that $\omega_U = df$ for some $f \in C^\infty(U)$

Proposition 11.45

For $\omega \in \Omega^1(M)$, the following are equivalent

1. ω is closed.
2. ω satisfies $\frac{\partial \omega_i}{\partial x^j} = \frac{\partial \omega_j}{\partial x^i}$ in some chart at every point.
3. For every open $U \subseteq M$ and $X, Y \in \mathfrak{X}(U)$, it holds that

$$X(\omega(Y)) - Y(\omega(X)) = \omega([X, Y])$$

The proof that 1 implies 2 is trivial.

Proof 3 Implies 1

Pick U as a chart, $X = \frac{\partial}{\partial x^i}$, and $Y = \frac{\partial}{\partial x^j}$. Then, since $\omega = \omega_i dx^i$,

$$X(\omega(Y)) = X(\omega_j) = \frac{\partial \omega_j}{\partial x^i}$$

Similarly, $Y(\omega(X)) = \frac{\partial \omega_i}{\partial x^j}$. Then $[X, Y] = \left[\frac{\partial}{\partial x^i}, \frac{\partial}{\partial x^j} \right] = 0$ and

$$\frac{\partial \omega_j}{\partial x^i} - \frac{\partial \omega_i}{\partial x^j} = 0$$

Proof 2 Implies 3

Fix any $p \in U$. We have a chart $(V, (x^i))$ at p such that $\frac{\partial \omega_i}{\partial x^j} = \frac{\partial \omega_j}{\partial x^i}$. Then

$$X(\omega(Y)) = X\left(\left(\omega_i dx^i\right)\left(Y^j \frac{\partial}{\partial x^j}\right)\right) = X(\omega_i Y^i) = (X\omega_i)Y^i + \omega_i(XY^i) = x^j \frac{\partial \omega_i}{\partial x^j} Y^i + \omega_i(XY^i) = X^j Y^i \frac{\partial \omega_j}{\partial x^i}$$

Similarly,

$$Y(\omega(X)) = Y(\omega_i x^i) = Y^j \frac{\partial \omega_i}{\partial x^j} x^i - \omega_i(YX^i) = X^i Y^j \frac{\partial \omega_i}{\partial x^j}$$

which is equivalent under a change of indicies. Hence

$$X(\omega(Y)) - Y(\omega(X)) = \omega_i(XY^i) - \omega_i(YX^i) = \omega_i(XY^i - YX^i) = \omega([X, Y])$$

Lemma

Suppose $F : M \rightarrow N$ is a local diffeomorphism. Then $F^* : \Omega^1(N) \rightarrow \Omega^1(M)$ sends exact (or closed) 1-forms to exact (or closed) ones.

Proof of Exact

If $\omega = df \in \Omega^1(N)$, then $F^*\omega = F^*(df) = d(F^*f)$ is exact on M .

Proof of Closed

If $\omega \in \Omega^1(N)$ is closed, then $\frac{\partial \omega_i}{\partial x^j} = \frac{\partial \omega_j}{\partial x^i}$ in every chart of N .
For any $p \in M$, we consider a chart at p by $(V, \phi \circ F)$

IMAGE 1

Therefore $\phi \circ F \circ (\phi \circ F)^{-1} = \text{id}$ and $F^* = \text{id}$ so $F^* \omega$ is closed.

Poincaré Lemma

Let $\omega \in \Omega^1(M)$ be closed. Fix $p \in M$, and let (U, ϕ) be a chart at p such that $\phi(U) = B_1(0) \subseteq \mathbb{R}^n$.

IMAGE 2

Assuming the above, every closed 1-form on $B_1(0)$ is exact. $(\phi^{-1})^*(\omega|_U) = df$ for some $f \in C^\infty(B_1(0))$ where $\omega|_U = \phi^*(df) = d(\phi^*f) \in C^\infty(U)$

Definition: Star-Shaped Domain

We say that $U \subseteq \mathbb{R}^n$ open is star-shaped with a center $c \in U$ (wlog $c = 0$) if for any $x \in U$, the segment γ_x from c to x is contained in U .

IMAGE 3

If $x = (x^i)$, then $\gamma_x(t) = (tx^i)$.

Theorem 11.49 (Poincaré Lemma)

If $U \subseteq \mathbb{R}^n$ is star-shaped, then every closed 1-form is exact.

Recall

If ω is an exact 1-form, then $f(q) = \int_{p_0}^q \omega$ is a potential.

We also have that $\int_\gamma \omega = \int_I \omega_{\gamma(t)}(\dot{\gamma}(t)) dt$.

Proof

Let $\omega \in \Omega^1(U)$ be a closed 1-form.

We need to construct $f \in C^\infty(U)$ such that $df = \omega$. That is, for all i , $\frac{\partial f}{\partial x^i} = \omega^i$. Define

$$f(x) = \int_{\gamma_x} \omega = \int_0^1 \omega_{\gamma_x(t)}(\dot{\gamma}_x(t)) dt = \int_0^1 \omega_i|_{\gamma_x(t)} dx^i(x^1, \dots, x^n) dt = \int_0^1 \omega_i|_{tx} x^i dt$$

Since everything is smooth,

$$\begin{aligned}
\frac{\partial f}{\partial x^j}(x) &= \int_0^1 \frac{\partial}{\partial x^j}(\omega_i(tx) \cdot x^i) dt \\
&= \int_0^1 \frac{\partial \omega_i(tx)}{\partial x^j} \cdot x^i + \omega_i(tx) \frac{\partial x^i}{\partial x^j} dt \\
&= \int_0^1 \left(\frac{\partial \omega_i}{\partial x^j} \right) \Big|_{(tx)} tx^i + \omega_j(tx) dt \\
&= \int_0^1 \frac{\partial \omega_j}{\partial x^i} \Big|_{tx} tx^i + \omega_j(tx) dt \\
&= \int_0^1 \frac{d}{dt}(t\omega_j(tx)) dt \\
&= t\omega_j(tx) \Big|_0^1 \\
&= \omega_j(x)
\end{aligned}$$

Tensors: Multilinear Maps

All vector spaces will be finite dimensional in our consideration.

$$F : V_1 \times \cdots \times V_k \rightarrow W$$

linear in every component. Denote $L(V_1, \dots, V_k; W)$ to be the set of all such multilinear maps.

Given $\omega \in L(V_1; \mathbb{R}) = V_1^*$ and $\eta \in V_2^*$, we can define $\omega \otimes \eta \in L(V_1, V_2; \mathbb{R})$ by $\omega \otimes \eta(v_1, v_2) = \omega(v_1) \cdot \eta(v_2)$.

- Remark

$$(2\omega) \otimes \eta = \omega \otimes (2\eta). \text{ We assume } \otimes_{\mathbb{R}}.$$

Similarly, given $\omega_i \in V_i^*$, we can define $\omega_1 \otimes \cdots \otimes \omega_k \in L(V_1, \dots, V_k; \mathbb{R})$.

Proposition

Let V_j with dimension n_j ($j = 1, \dots, k$). Each V_j has a basis $\{E_1^{(j)}, \dots, E_{n_j}^{(j)}\}$.

Its dual basis $\{\varepsilon_{(j)}^1, \dots, \varepsilon_{(j)}^{n_j}\} \subseteq V_j^*$. Then $L(V_1, \dots, V_k; \mathbb{R})$ has a basis

$$\mathcal{B} = \{\varepsilon_{(1)}^{i_1} \otimes \cdots \otimes \varepsilon_{(k)}^{i_k} : 1 \leq i_j \leq n_j\}$$

Proof

For a multi-index $I = (i_1, \dots, i_k)$ with $i \leq i_j \leq n_j$, we write $\varepsilon^I = \varepsilon_{(1)}^{i_1} \otimes \cdots \otimes \varepsilon_{(k)}^{i_k}$.

For any $F \in L(V_1, \dots, V_k; \mathbb{R})$, define $F_I = F(E_{i_1}^{(1)}, \dots, E_{i_k}^{(k)})$. We claim that $F = F_I \varepsilon^I$.

In fact, for $(v_1, \dots, v_k) \in V_1 \times \cdots \times V_k$, $v_j = v_j^i E_i^{(j)}$. We may check that $F(v_1, \dots, v_k) = F_I \varepsilon^I(v_1, \dots, v_k)$.

Therefore \mathcal{B} spans $L(V_1, \dots, V_k; \mathbb{R})$.

Then, if $F_I \varepsilon^I = 0$, then applying it to $(E_{i_1}^{(1)}, \dots, E_{i_k}^{(k)})$ gives $F_I = 0$. Therefore \mathcal{B} is linearly independent.

In particular, $\dim L(V_1, \dots, V_k; \mathbb{R}) = \prod_{j=1}^k n_j = \prod_{j=1}^k \dim V_j$.

Definition: Formal Linear Combination

Let S be a set. Define

$$\mathcal{F}(S) = \left\{ \sum_{i=1}^m a_i s_i : a_i \in \mathbb{R}, s_i \in S \right\}$$

This is the free (real) vector space on S containing formal linear combinations of elements of S .

Define $V_1 \otimes \cdots \otimes V_k = \mathcal{F}(V_1 \times \cdots \times V_k) / R$ where R is generated by

$$\begin{aligned} (v_1, \dots, v_j + v_j', \dots, v_k) &\sim (v_1, \dots, v_j, \dots, v_k) + (v_1, \dots, v_j', \dots, v_k) \\ (v_1, \dots, c v_j, \dots, v_k) &\sim c(v_1, \dots, v_k) \end{aligned}$$

In other words, in the quotient $v_1 \otimes \cdots \otimes v_k = \prod (v_1, \dots, v_k)$.

Proposition

$V_1 \otimes \cdots \otimes V_k$ has a basis $\{E_{i_1}^{(1)} \otimes \cdots \otimes E_{i_k}^{(k)} : 1 \leq i_j \leq n_j\}$.

Proposition

There exists a canonical isomorphism $(V_1 \otimes V_2) \otimes V_3 \cong V_1 \otimes (V_2 \otimes V_3)$ by sending $(v_1 \otimes v_2) \otimes v_3 \mapsto v_1 \otimes (v_2 \otimes v_3)$.

Proposition

$$L(V_1, \dots, V_k; \mathbb{R}) \cong V_1^* \otimes \cdots \otimes V_k^*.$$

Proof Sketch

Define $\Phi : V_1^* \times \cdots \times V_k^* \rightarrow L(V_1, \dots, V_k; \mathbb{R})$ by $(\omega^1, \dots, \omega^k) \mapsto \omega^1 \otimes \cdots \otimes \omega^k$. By multilinearity, this induces an isomorphism

$$\Phi : V_1^* \otimes \cdots \otimes V_k^* \cong L(V_1, \dots, V_k; \mathbb{R})$$

Recall

$V^{**} \cong V$ for finite dimensional vector spaces, so $V_1 \otimes \cdots \otimes V_k = L(V_1^*, \dots, V_k^*; \mathbb{R})$.

Definition: Tensor

A tensor of (k, l) -type is an element in $\underbrace{V \otimes \cdots \otimes V}_k \otimes \underbrace{V^* \otimes \cdots \otimes V^*}_l$.

The collection of such elements in $T^{(k,l)}V$. Most of the time we consider $T^{(0,l)}V$.

Examples

A vector in V is a $(1, 0)$ -tensor.

A covector in V^* is a $(0, 1)$ -tensor.

A linear map $A \in L(V)$ is a $(1, 1)$ -tensor.

An inner product is a $(0, 2)$ -tensor.

Symmetric Tensor

We say that $\alpha \in T^{(0,l)}V$ is symmetric if $\alpha(\dots, v_i, \dots, v_j, \dots) = \alpha(\dots, v_j, \dots, v_i, \dots)$.

Alternating Tensor

We say that $\alpha \in T^{(0,l)}V$ is alternating if $\alpha(\dots, v_i, \dots, v_j, \dots) = -\alpha(\dots, v_j, \dots, v_i, \dots)$.

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Alternating/Symmetric Tensors

Let $\sigma \in S_l$ and $\alpha \in T^{(0,l)}V$.

Define σ_α or $(\sigma \cdot \alpha)$ as a new $(0, l)$ -tensor by $(\sigma \cdot \alpha)(v_1, \dots, v_l) := \alpha(v_{\sigma(1)}, \dots, v_{\sigma(l)})$.

Then α is symmetric if and only if $\sigma \cdot \alpha = \alpha$.

α is alternating if and only if $\sigma \cdot \alpha = (\text{sign } \sigma) \cdot \alpha$.

Define $\text{Sym} : T^{(0,l)}V \rightarrow S^l V$ by

$$\text{Sym}(\alpha) = \frac{1}{l!} \sum_{\sigma \in S^l} (\sigma \cdot \alpha)$$

Then $\text{Sym}(\alpha)$ is symmetric for all $\alpha \in T^{(0,l)}V$.

Define $\text{Alt} : T^{(0,l)}V \rightarrow \Lambda^l V$, the set of alternating (anti)-tensors by

$$\text{Alt}(\alpha) = \frac{1}{l!} \sum_{\sigma \in S^l} (\text{sign } \sigma)(\sigma \cdot \alpha)$$

Definition: Tensor Bundles

Recall that $T_p M \simeq T_p M$ and $T_p^* M \simeq T_p^* M$.

Then $T^{(k,l)} T_p M \simeq T^{(k,l)} T_p M$ a tensor bundle.

Mostly, we will consider $T^{(0,l)} T_p M$.

Inside a chart $(U, (x^1, \dots, x^n))$, $T^{(k,l)} T_p M$ has a local frame

$$\left\{ \frac{\partial}{\partial x^{i_1}} \otimes \dots \otimes \frac{\partial}{\partial x^{i_k}} \otimes dx^{j_1} \otimes \dots \otimes dx^{j_l} \right\}$$

Definition: Smooth Tensor Field

A smooth tensor field of type (k, l) is a smooth section of $T^{(k,l)} T_p M$.

To check that a (k, l) -tensor field A is smooth, we can do either of the following

1. Write A in a local chart, then $A = A_I dx^I$ where A_I are functions in U and $dx^I = dx^{i_1} \otimes \dots \otimes dx^{i_l}$ with $I = (i_1, \dots, i_l)$. Then A is smooth if and only if A_I is smooth for all I .
2. Check A testing on any l many smooth vector fields results in a smooth function.

Remark

Every $(0, l)$ -tensor field A defines a map

$$\mathcal{A} = \underbrace{\mathfrak{X}(M) \times \cdots \times \mathfrak{X}(M)}_l \rightarrow C^\infty(M)$$

by $A(x_1, \dots, x_l)(p) = A_p(X_1(p), \dots, X_l(p))$. This map \mathcal{A} is $C^\infty(M)$ -multilinear.

Lemma 12.24

Every $C^\infty(M)$ -multilinear map $\mathcal{A} : \mathfrak{X}(M) \times \cdots \times \mathfrak{X}(M) \rightarrow C^\infty(M)$ defines a smooth $(0, l)$ -tensor field

$$A_p(v_1, \dots, v_l) = (\mathcal{A}(X_1, \dots, X_l))(p)$$

Example

Given $\omega \in \Omega^1(M)$, define $\mathcal{A} : \mathfrak{X}(M) \times \cdots \times \mathfrak{X}(M) \rightarrow C^\infty(M)$ by $(X, Y) \mapsto \omega(L_X Y)$. If X, Y and X', Y' only agree at a point p , then in general $(L_X Y)(p) \neq (L_{X'} Y')(p)$.

Proof

\mathcal{A} acts locally only depending on the value of X_1, \dots, X_l in a neighborhood of p , call it U .

It suffices to show that if $X_i = 0$ for some i on U , then $\mathcal{A}(X_1, \dots, X_l)(p) = 0$.

Let ψ be a bump function with $\text{supp } \psi \subseteq U$ and $\psi(p) = 1$. Let also $V \subseteq U$ such that $\bar{V} \subseteq U$.

Then $\psi X_i \equiv 0$ on M . Then

$$0 = \mathcal{A}(X_1, \dots, \psi X_i, \dots, X_l)(p) = \psi(p) \mathcal{A}(X_1, \dots, X_l)(p) = \mathcal{A}(X_1, \dots, X_l)(p)$$

Now \mathcal{A} acts pointwisely. Write $X_i = a_i^j \frac{\partial}{\partial x^j}$ in U .

Extend each $\frac{\partial}{\partial x^j} \Big|_V$ to $E_j \in \mathfrak{X}(M)$ and each $a_i^j|_V$ to $f_i^j \in C^\infty(M)$.

Then inside V ,

$$\mathcal{A}(X_1, \dots, X_l)(p) = \mathcal{A}(X_1, \dots, f_i^j E_j, \dots, X_l)(p) = f_i^j(p) \mathcal{A}(X_1, \dots, X_l)(p)$$

Now let $v_1, \dots, v_l \in T_p M$. Define A a $(0, l)$ -tensor field by $A_p(v_1, \dots, v_l) = \mathcal{A}(X_1, \dots, X_l)$ where $X_i \in \mathfrak{X}(M)$ extends v_i .

By assumption, $\mathcal{A}(X_1, \dots, X_l)$ is a smooth function if $X_1, \dots, X_l \in \mathfrak{X}(M)$ hence A is a smooth $(0, l)$ -tensor field.

Definition:

Write $\mathcal{T}^{(0, l)} M = \Gamma(T^{(0, l)} TM)$ where Γ is the section.

Then for $F : M \rightarrow N$ a smooth map and $A \in \mathcal{T}^{(0, l)} N$, for $v_i \in T_p M$ define $F^* A \in \mathcal{T}^{(0, l)} M$ by

$$(F^* A)_p(v_1, \dots, v_l) := A_{F(p)}(DF_p(v_1), \dots, DF_p(v_l))$$

Lie Derivatives

Recall that if $X, Y \in \mathfrak{X}(M)$, we define $(L_X Y)_p$ where X generates a flow $\phi_t : M \rightarrow M$

IMAGE 1

$(\phi_{-t})_* Y_{\phi_t(p)} = ((\phi_{-t})_* Y)_p \in T_p M$ for $Y_p \in T_p M$. Then $L_X Y = \frac{d}{dt} \Big|_{t=0} ((\phi_{-t})_* Y)_p$.
If $A \in \mathcal{T}^{(0,l)} M$,

IMAGE 2

$$(\phi_t^* A)_p = (\phi_t)^* (A_{\phi_t(p)}) \in T^{(0,l)} T_p M$$

$$\text{So } L_V A = \frac{d}{dt} \Big|_{t=0} (\phi_t^* A)_p.$$

Properties

1. $L_V f = Vf$ (where $f \in C^\infty(M)$ can be thought of as a smooth $(0,0)$ -tensor field). Then

$$(L_V f)(p) = \frac{d}{dt} \Big|_{t=0} (\phi_t^* f)_p = \frac{d}{dt} \Big|_{t=0} (f \circ \phi_t(p)) = (Vf)_p$$

$$1. L_V(fA) = (Vf)A + fL_V A.$$

$$2. L_V(A \otimes B) = (L_V A) \otimes B + A \otimes (L_V B).$$

$$3. L_V(A(X_1, \dots, X_l)) = (L_V A)(X_1, \dots, X_l) + A(L_V X_1, \dots, X_l) + \dots + A(X_1, \dots, L_V X_l) \text{ for } A \in \mathcal{T}^{(0,l)} M \text{ and } X_i \in \mathfrak{X}(M).$$

Proof of 2

We have $O := \{p \in M : V_p \neq 0\}$ open in M and $\text{supp } V = \overline{\{p \in M : V_p \neq 0\}}$.

1. (2) holds on O .

Recall that if $V_p \neq 0$, then there exists a local chart $(U, (x^i))$ centered at p such that on U , $V = \frac{\partial}{\partial x^1}$. In particular, its flow ϕ_t is $(x^1, \dots, x^n) \mapsto (x^1 + t, x^2, \dots, x^n)$.

Then take some chart $U \subseteq O$ centered at p such that $V = \frac{\partial}{\partial x^1}$ in U . Inside U , write $A = A_I dx^I$, and

$$\begin{aligned} \phi_t^*(fA) &= (\phi_t^* f)(\phi_t^* A) \\ &= (f \circ \phi_t) \phi_t^*(A_I dx^I) \\ &= f(x^1 + t, x^2, \dots, x^n) A_I(x^1 + t, \dots, x^n) \phi_t^* dx^I \\ &= f(x^1 + t, x^2, \dots, x^n) A_I(x^1 + t, \dots, x^n) dx^I \end{aligned}$$

2. (2) holds on $\text{supp } V$ by taking limits.

3. (2) holds outside $\text{supp } V$, since $V \equiv 0$ on open $M \setminus \text{supp } V$ and hence $\phi_t \equiv \text{id}$. So both sides are identically zero.

January 27, 2025

Recall: Prop 12.32(2)

$$L_V(fA) = (Vf)A + fL_V A$$

Proof Step 1:

Show that the equality holds on $\{p \in M : V(p) \neq 0\}$.

Let $p \in M$ with $V(p) \neq 0$.

Take any chart (U, x^i) centered at p such that $V = \frac{\partial}{\partial x^1}$ on U . Then its flow is

$$\theta_t : (x^1, \dots, x^n) \mapsto (x^1 + t, x^2, \dots, x^n)$$

in U . In U , we write $A = A_I dx^I$ (where $dx^I = dx^{i_1} \otimes \dots \otimes dx^{i_l}$). Recall that

$$\theta_t^*(dx^i) = d(\theta_t^* x^i) = d(x^i \theta_t) = \begin{cases} d(x^1 + t) = dx^1 & i = 1 \\ d(x^i) & i \neq 1 \end{cases}$$

Write the pullback of θ_t

$$\begin{aligned} \theta_t^*(fA) &= (\theta_t^* f)(\theta_t^* A_I dx^I) \\ &= (f \circ \theta_t)(A_I \circ \theta_t)(dx^I) \\ &= f(x^1 + t, x^2, \dots, x^n) A_I(x^1 + t, \dots, x^n) dx^I \end{aligned}$$

So for $p = (x^i)$,

$$\begin{aligned} (L_V(fA))_p &= \left. \frac{d}{dt} \right|_{t=0} f(x^1 + t, x^2, \dots, x^n) A_I(x^1 + t, \dots, x^n) dx^I \\ &= \underbrace{\frac{\partial f}{\partial x^1}(x^1, \dots, x^n)}_{Vf} \underbrace{A_I(x^1, \dots, x^n) dx^I}_{\theta_t^* A} + f(x^1, \dots, x^n) \frac{\partial A_I}{\partial x^1(x^1, \dots, x^n) dx^I} \end{aligned}$$

inside U . Hence $Vf = \frac{\partial f}{\partial x^1}$.

Corollary

$L_V(df) = d(L_V f)$ for $f \in C^\infty(M)$.

- Proof

For all $X \in \mathfrak{X}(M)$,

$$(L_V(df))(X) = V(df(X)) - df(L_V X) = VXf - [V, X]f = VXf - (VXf - XVf) = XVf$$

and

$$(d(L_V f))(X) = X(L_V f) = XVf.$$

Proof Step 2:

Show that the equality holds on $\overline{\{p \in M : V(p) \neq 0\}}$.

Proof Step 3:

Show that the equality holds elsewhere.

Recall: Invariance

For two vector fields, X and Y , Y is invariant under the flow of X if $L_X Y \equiv 0$.

We say a $(0, l)$ -tensor field A is invariant under a map $F : M \rightarrow M$ if $F^* A = A$. Equivalently, if under a flow $\theta_t : M \rightarrow M$ if $\theta_t^* A = A$ for all t .

Theorem 12.37

A is invariant under θ_t , $\forall t$, if and only if $L_V A = 0$.

Note

$$\left. \frac{d}{dt} \right|_{t=t_0} (\theta_t^* A)_p = (\theta_{t_0}^* (L_V A))_p = \theta_{t_0}^* (L_V A)_{\theta_{t_0}^*(p)}$$

So

$$\begin{aligned} \left. \frac{d}{dt} \right|_{t=t_0} (\theta_t^* A)_p &= \left. \frac{d}{dt} \right|_{t=t_0} (\theta_t^*) A_{\theta_t(p)} \\ &\stackrel{t=s+t_0}{=} \left. \frac{d}{ds} \right|_{s=0} \theta_{s+t}^* A_{\theta_{s+t_0}(p)} \\ &= \left. \frac{d}{ds} \right|_{s=0} \theta_{t_0}^* \circ \theta_s^* A_{\theta_{t_0}(\theta_s(p))} \\ &= \theta_{t_0}^* (L_V A)_{\theta_{t_0}(p)} \end{aligned}$$

Therefore, if A is invariant under θ_t , then $\theta_t^* A = A$ and

$$L_V A = \left. \frac{d}{dt} \right|_{t=0} (\theta_t^* A)_p = \left. \frac{d}{dt} \right|_{t=0} A_p = 0.$$

In the other direction, if $L_V A \equiv 0$, we show that $(\theta_t^* A)_p = A_p$ for every p and each t . From above,

$$\left. \frac{d}{dt} \right|_{t=t_0} (\theta_t^* A)_p = \theta_{t_0}^* \underbrace{(L_V A)_{\theta_{t_0}(p)}}_{=0} = 0$$

Hence $(\theta_t^* A)_p$ is a constant A_p .

Special Tensors (for this course)

Riemannian Metric

g a $(0, 2)$ -tensor, symmetric and positive definite. That is, at each point p

$$g_p : T_p M \times T_p M \rightarrow \mathbb{R}$$

which is bilinear, symmetric and positive definite. This is an inner product.

K (Differential) Form

ω a $(0, k)$ -tensor, alternating.

Riemannian Metric

In a chart $(U, (x^i))$, $g = g_{ij} dx^i \otimes dx^j$.

Since it is symmetric, $g(\partial_i, \partial_j) = g(\partial_j, \partial_i)$ (i.e. $g_{ij} = g_{ji}$). We write $dx^i dx^j = \text{Sym}(dx^i \otimes dx^j)$. In this case

$$\text{Sym}(dx^i \otimes dx^j) = \frac{1}{2} (dx^i \otimes dx^j + dx^j \otimes dx^i)$$

So we may write $g = g_{ij} dx^i dx^j$ and, sometimes, $(dx^1)^2 = dx^1 dx^1$.

We have also that g_{ij} corresponds to a positive definite, symmetric $n \times n$ matrix.

Example

In \mathbb{R}^n , $g_E = \delta_{ij} dx^i dx^j$. For $v = v^k \partial_k$ and $w = w^l \partial_l$,

$$g_E(v, w) = \delta_{ij} dx^i dx^j (v^k \partial_k w^l \partial_l) = v^k w^l \delta_{ij} \underbrace{dx^i(\partial_k)}_{\delta_k^i} \underbrace{dx^j(\partial_l)}_{\delta_l^j} = v^1 w^1 + \dots + v^n w^n$$

Example

Consider $S^2 \subseteq \mathbb{R}^3$ embedded such that $T_p S^2 \hookrightarrow T_p \mathbb{R}^3 \cong \mathbb{R}^3$.

Then $g_p(v, w) = v \cdot w$ defines a Riemannian metric on S^2 .

Proposition

Any smooth manifold admits a Riemannian metric.

Proof 1

Embed M into \mathbb{R}^N with N sufficiently large. Then M is an embedded submanifold in \mathbb{R}^N which induces a Riemannian metric on M .

Proof 2

Let $\{U_i\}$ be a countable cover of M (with each U_i a chart) and $\{\psi_i\}$ be a partition of unity with respect to this cover.

IMAGE 1

So $\phi_i^* g_E$ defines a Riemannian metric on U_i and we construct $\sum_i \psi_i (\phi_i^* g_E)$.

Example: Metric Product

Take (M_1, g_1) and (M_2, g_2) and construct $g_1 \oplus g_2$ on $M_1 \times M_2$ by either

$$g_1 \oplus g_2 = \begin{pmatrix} g_1 & 0 \\ 0 & g_2 \end{pmatrix}$$

or

$$(g_1 + g_2)((v_1, v_1), (w_1, w_2)) = g_1(v_1, w_1) + g_2(v_2, w_2)$$

e.g. $S^1 \subseteq \mathbb{R}^2$ gives (S^1, g_1) , then on the n -torus we construct $(\mathbb{T}^n, g_1 \oplus \cdots \oplus g_1)$.

Example: Warped Product

IMAGE 2

Take $f : M \rightarrow \mathbb{R}^+$ smooth, (M, g) and (N, h) .

Define a new metric \tilde{g} on $M \times N$ by

$$\tilde{g}_{(x,y)} = g_x + f(x)h_y$$

An example in polar coordinates is

$$(dx)^2 + (dy)^2 = (d(r \cos \theta))^2 + (d(r \sin \theta))^2 = (\cos \theta dr - r \sin \theta d\theta)^2 + (\sin \theta dr + r \cos \theta d\theta)^2 = dr^2 + r^2 d\theta^2$$

Imagine fixing a direction r and at each point attaching a circle of radius r .

IMAGE 3

Recall: Gradient

If $f \in C^\infty(\mathbb{R}^n)$, then

$$\nabla f = \frac{\partial f}{\partial x^i} \frac{\partial}{\partial x^i}$$

Note that this violates our Einstein summation.

If $f \in C^\infty(M)$, its differential df is a 1-form and not a vector field. Why? Because in \mathbb{R}^n we are implicitly using the Euclidean metric.

If we have an inner product on a TVS, say $(V, (\cdot, \cdot))$, then we can construct an isomorphism $V \cong V^*$ by $v \mapsto (v, \cdot)$.

On (M, g) we use g to construct a bundle isomorphism between TM and T^*M by $(p, v) \mapsto g_p(v, \cdot)$.

With this, given $df \in \Omega^1(M)$, we can define a vector field $\nabla f \in \mathfrak{X}(M)$ by

$$g(\nabla f, X) = (df)(X) = Xf$$

In a chart $(U, (x^i))$, set $\nabla f = b^i \frac{\partial}{\partial x^i}$. Then

$$g\left(\nabla f, \frac{\partial}{\partial x^j}\right) = g\left(b^i \frac{\partial}{\partial x^i}, \frac{\partial}{\partial x^j}\right) = b^i g_{ij} = (df)\left(\frac{\partial}{\partial x^j}\right) = \frac{\partial f}{\partial x^j}$$

Let g^{ij} be the inverse of g_{ij} , then

$$b^k = b^i \delta_i^k = b^i g_{ij} g^{jk} = \frac{\partial f}{\partial x^j} g^{jk}$$

so

$$\nabla f = b^k \frac{\partial}{\partial x^k} = \frac{\partial f}{\partial x^j} g^{jk} \frac{\partial}{\partial x^k}$$

Then from above, we actually have

$$\nabla f = \frac{\partial f}{\partial x^i} \delta_{ij} \frac{\partial}{\partial x^j}$$

which satisfies our summation convention.

Example

If $g_E = dr^2 + r^2 d\theta^2$ in polar coordinates,

$$(g_{ij}) = \begin{pmatrix} 1 & 0 \\ 0 & r^2 \end{pmatrix} \quad \text{and} \quad (g^{ij}) = \begin{pmatrix} 1 & 0 \\ 0 & 1/r^2 \end{pmatrix}$$

So

$$\nabla f = \frac{\partial f}{\partial x^j} g^{jk} \frac{\partial}{\partial x^k} = \frac{\partial f}{\partial r} \frac{\partial}{\partial r} + \frac{\partial f}{\partial \theta} \frac{1}{r^2} \frac{\partial}{\partial \theta}$$

Isometric Metrics

We say that (M, g) and (N, h) are isometric if there is a diffeomorphism $F : M \rightarrow N$ such that $F^* h = g$.

With g , we can define (for $v \in T_p M$), $\|v\|_g = (g_p(v, v))^{1/2}$ and (for $v, w \in T_p M$)

$$\cos(v, w) = \frac{g_p(v, w)}{\|v\|_g \|w\|_g}$$

Definition: Length

Let $\gamma : I \rightarrow M$ be a (piecewise) smooth curve.

Define $\text{length}_g(\gamma) = \int_I \|\gamma'(t)\|_g dt$.

Remember that $\text{length}_g(\gamma)$ is independent of reparameterization. That is

$$J \xrightarrow{\phi} I \xrightarrow{\gamma} M \quad \text{with } \tilde{\gamma} = \gamma \circ \phi \text{ we have}$$

$$\begin{aligned} \int_J \|\tilde{\gamma}'(t)\| dt &= \int_J \|(\gamma \circ \phi)'(t)\| dt \\ &= \int_J \|\gamma'(\phi(t)) \cdot \phi'(t)\| dt \\ &\stackrel{\phi' > 0}{=} \int_J \|\gamma'(\phi(t))\| |\phi'(t)| dt \\ &\stackrel{s=\phi(t)}{=} \int_I \|\gamma'(s)\| ds \end{aligned}$$

Definition: Distance

Given (M, g) , define

$$d_g(p, q) = \inf \{ \text{length}_g(\gamma) : \gamma \text{ is piecewise smooth from } p \text{ to } q \}$$

Theorem

(M, d_g) is a metric space.

Moreover, it induces a metric topology that coincides with the manifold topology.

Theorem: Hopf-Rinow

The following are equivalent.

1. (M, d_g) is a complete metric space.
2. $\forall p, q \in M$, there exists a length-minimizing curve (a geodesic) from p to q .

Definition: Geodesic

A curve such that the second derivative along $\gamma \equiv 0$.