Phys484: Quantum Theory

Yixing Gu

January 18, 2024

1 Deferential Geometry

1.1 Topology and manifold

Definition 1. Given any set X, a **topology** is a pair $(X, \mathcal{S}), \mathcal{S} \subseteq \mathcal{P}(X)$ that satisfies:

1. $\emptyset \in \mathcal{S}$
2. If $\forall \alpha, S_\alpha \in \mathcal{S}$, then $\bigcup_\alpha S_\alpha \in \mathcal{S}$
3. If $S_1, \ldots, S_n \in \mathcal{S}$, then $\bigcap_{i=1}^n S_i \in \mathcal{S}$

Definition 2. Given any set X, and a topology $(X, \mathcal{S})$, the elements in $\mathcal{S}$ are called open.

Definition 3. Given any set X, a collection of subsets $\mathcal{B} \subseteq \mathcal{P}(X)$ is said to be a basis of the topology $\mathcal{S}$ if

1. $X = \bigcup_{B \in \mathcal{B}}$
2. If $B_1, B_2 \in \mathcal{B}, x \in B_1 \cap B_2$, then $\exists B_x \in \mathcal{B}, x \in B_x \subseteq B_1 \cap B_2$
3. $\mathcal{S}$ is the collection of all unions of the elements of $\mathcal{B}$.

Definition 4. A topology space $\mathcal{S}$ is called **2nd countable** if it has a countable basis.

Definition 5. A topology space is **Hausdorff** if $\forall x \neq y \in \mathcal{S}, \exists S_x, S_y \in \mathcal{S}, x \in S_x, y \in S_y, S_x \cap S_y = \emptyset$

Definition 6. If X is a topology space, and $Y \subseteq X$, then the subspace topology on Y is obtained by $U \subseteq Y$ is open if and only if $\exists V \subseteq X$ that is open, and $U = V \cap Y$

Proposition 1.1. *If $Y \subseteq X$ with subspace topology, then if X is 2nd countable or Hausdorff, so is Y.*

Definition 7. A collection of subsets $C = \{U_\alpha \subseteq X\}_{\alpha \in A}$ is called a **cover** for X if $X \subseteq \bigcup_{\alpha \in A} U_\alpha$. A cover is called an open cover if every U_α is open in the topology of X.

Definition 8. A collection of subsets $\mathcal{X}$ is called **locally finite** if $\forall x \in X, \exists S_x \in \mathcal{S}$ an open neighborhood, such that S_x only intersects with finitely many elements in $\mathcal{X}$.

Definition 9. Given two sets X, Y, and there corresponding topology $\mathcal{S}, \mathcal{T}$, a map $f : X \to Y$ is **continuous** if $\forall T \in \mathcal{T}, f^{-1}(T) \in \mathcal{S}$. Namely, for any open set in Y, its preimage of f is also open in X.

Definition 10. Given two sets X, Y, and their corresponding topology $\mathcal{S}, \mathcal{T}$, a continuous map $f : X \to Y$ is a **homeomorphism** if it is invertible, and its inverse function is also continuous.

Remark. A homeomorphism is a map that preserves the topology structure between two sets.

Definition 11. An **atlas** $\mathcal{A} = \{(U_\alpha, \phi_\alpha)\}_\alpha$ is a collection of **local charts** (U_α, ϕ_α), where each $\phi_\alpha : U_\alpha \to \mathbb{R}^n$ is a homeomorphism onto its image $\phi_\alpha(U_\alpha) \subseteq \mathbb{R}^n$, and that $\bigcup_\alpha U_\alpha = X$.

Definition 12. A smooth atlas is an atlas such that $\forall (U_\alpha, \phi_\alpha), (U_\beta, \phi_\beta) \in \mathcal{A}$, $\phi_\beta \circ \phi_\alpha^{-1} : \phi_\alpha(U_\alpha \cap U_\beta) \to \mathbb{R}^n$ is C^∞ smooth.

Definition 13. A **smooth manifold** $M = (\mathcal{S}, \mathcal{A})$ is a 2nd-countable Hausdorff topology with a smooth atlas. The dimension n of the manifold is the dimension of $\mathbb{R}^n$ in the atlas $\mathcal{A}$.

1.2 Smooth functions and Diffeomorphism

Definition 14. Let M,N be smooth manifolds of dimension m,n, we say a function $F : M \to N$ is **smooth** at point $p \in M$ if and only if there are local charts (U_α, ϕ_α) for M and (V_β, ψ_β) for N, such that:

1. $p \in U_\alpha$
2. $F(p) \in V_\beta$
3. $U_\alpha \cap F^{-1}(V_\alpha) \subseteq M$ is open
4. The **coordinate representation** $\hat{F} := \psi_\beta \circ F \circ \phi_\alpha^{-1} : \phi_\alpha(U_\alpha \cap F^{-1}(V_\beta)) \to \mathbb{R}^m$ is smooth at $\phi_\alpha(p) \in \mathbb{R}^n$

Proposition 1.2. *If F is continuous, then 3 is always met.*

Proposition 1.3. *If 4 is met for some coordinate maps, then it is always true for any other coordinate maps. Namely, the smoothness is independent of choices of coordinate maps.*

Definition 15. If F is smooth at every $p \in M$, we say that F is a smooth function.

Definition 16. F is a **diffeomorphism** if F is invertible, and that both F, F^{-1} are smooth.

Proposition 1.4. *A diffeomorphism is always a homeomorphism.*

1.3 Bump functions

Definition 17. Given a function $f : M \to \mathbb{R}$, the **support** is $\operatorname{Supp}(f) := \overline{\{x \in M | f(x) \neq 0\}}$

Definition 18. Let M be a smooth manifold, $\mathcal{X} = \{X_\alpha\}$ is an open cover of M. A smooth **partition of unity** is $\{\psi_\alpha : M \to \mathbb{R}\}_{\alpha \in A}$, such that:

1. $0 \leq \psi_\alpha(x) \leq 1, \forall \alpha \in A, x \in M$
2. $\forall \alpha, \operatorname{Supp}(\psi_\alpha) \subseteq X_\alpha$
3. $\{\operatorname{Supp}(\psi_\alpha)\}_{\alpha \in A}$ is locally finite.
4. $\forall x \in M, \sum_{\alpha \in A} \psi_\alpha(x) = 1$

Theorem 1.5. *A partition of unity always exists for any smooth manifold M and any open cover $\mathcal{X}$ of M.*

Proposition 1.6. *Bump function*
Let $A \subseteq U \subseteq M$, where M is a smooth manifold, A is a closed set, and U is an open set. There exists a smooth map $\psi : M \to \mathbb{R}$, such that

1. $\forall x \in M, 0 \leq \psi(x) \leq 1$
2. $\forall x \in A, \psi(x) = 1$
3. $\operatorname{Supp}(\psi) \subseteq U$

Definition 19. If A is closed, then a function $f : A \to \mathbb{R}^k$ is **smooth** if $\forall x \in A, \exists W_x \subseteq M, F_x : W_x \to \mathbb{R}^k$, such that W_x is open and $x \in W_x$, and $\forall p \in W_x \cap A, F_x(p) = f(p), F_x \in C^\infty(W_x)$

Lemma 1.7. *Extension Lemma:*
Let M be a smooth manifold, and $A \subseteq M$ be a closed subset. Let $f : A \to \mathbb{R}^k$ be smooth, then $\forall U \supseteq A$ be open, $\exists \tilde{f} : M \to \mathbb{R}^k$, such that $\tilde{f}$ is smooth, and $\tilde{f}|_A = f, \operatorname{Supp}(\tilde{f}) \subseteq U$

1.4 Tangent space and derivatives

Definition 20. Let $C^\infty(M)$ be the real vector space of smooth functions from $M \to \mathbb{R}$, a **derivation** or **tangent vector** at $p \in M$ is an $\mathbb{R}-$linear map $D : C^\infty(M) \to \mathbb{R}$ satisfying the **Leibniz condition**: $\forall f, g \in C^\infty(M), D(fg) = f(p)D(g) + g(p)D(f)$

Definition 21. The **tangent space** to M at $p \in M$, T_pM, is the set of all tangent vectors at p.

Proposition 1.8. *T_pM is a real vector space where $\forall X, Y \in T_pM, c \in \mathbb{R}, f \in C^\infty(M), (X+Y)(f) := X(f) + Y(f), (cX)(f) := c \cdot X(f), (-X)(f) := -X(f), 0(f) := 0$*

Proposition 1.9. *Let $D \in T_pM$, if $\forall x \in M, f(x) = c$ is a constant function, then $D(f) = 0$*

Proposition 1.10. *If $\exists U \ni p$ be open, and $\forall x \in U, f(x) = 0$, then $\forall D \in T_pM, D(f) = 0$*

Proposition 1.11. *If $f, g \in C^\infty(M)$ and $f = g$ on some open $U \ni p$, then $\forall D \in T_pM, D(f) = D(g)$*

Definition 22. For $p, v = (v^1, \dots v^n) \in \mathbb{R}^n$, then the **directional derivative** of $f \in C^\infty(\mathbb{R}^n)$ in the direction of v is $D_v(f) := \left(\sum_{i=1}^n v^i \frac{\partial}{\partial x^i}|_p\right)(f) := \sum_{i=1}^n v^i \frac{\partial f}{\partial x^i}(p)$

Proposition 1.12. *The directional derivative is a derivation.*

Proposition 1.13. *$\forall p \in \mathbb{R}^n$, the map $L : \mathbb{R}^n \to T_p\mathbb{R}^n$, where $L(v) := D_v$ is a vector space isomorphism.*

Corollary 1.14. *$\{\partial_1|_p, \dots, \partial_n|_p\}$ is a basis for $T_p\mathbb{R}^n$.*

Definition 23. Given a smooth function $F : M \to N$, the **differential** or **derivative** of F at $p \in M$ is the map $dF_p : T_pM \to T_{F(p)}N$, given by $\forall D \in T_pM, f \in C^\infty(N), dF_p(D)(f) := D(f \circ F)$

Remark. One can check that $dF_p(D) \in T_{F(p)}N$ for any $D \in T_pM$, and that $f \circ F \in C^\infty(M)$, so the derivative of F above is well-defined.

Proposition 1.15. *Let M, N, R be smooth manifolds and $F : M \to N, G : N \to R$ are smooth maps, then for any $p \in M$, we have:*

1. *$dF_p : T_pM \to T_{F(p)}N$ is linear*
2. *$d(G \circ F)_p = dG_{F(p)} \circ dF_p : T_pM \to T_{G(F(p))}R$*
3. *$d(Id_M)_p : T_pM \to T_pM$ is an identity isomorphism.*
4. *If F is a diffeomorphism, then dF_p is an isomorphism, and $(dF_p)^{-1} = d(F^{-1})_{F(p)}$*

Proposition 1.16. *Let M be a smooth manifold, $U \subseteq M$ be open, and $i : U \to M$ be the inclusion map, then $\forall p \in U, di_p : T_pU \to T_pM$ is an isomorphism.*

Corollary 1.17. *Let M be a n-dimensional smooth manifold, for any $p \in M$, and any local chart (U, ϕ) containing p, we have $T_pM \cong T_pU \cong T_{\phi(p)}\phi(U) \cong T_{\phi(p)}\mathbb{R}^n \cong \mathbb{R}^n$, and the n-dimensional vector space T_pM has a basis of $\left\{\Upsilon_j|_p := \partial_j|_p := \frac{\partial}{\partial x^j}|_p := (di_p \circ (d\phi_p)^{-1})(\frac{\partial}{\partial x^j}|_{\phi(p)}) = (di_p \circ (d\phi_p)^{-1})(\partial_j|_{\phi(p)})\right\}_j$.*

Proposition 1.18. *Given $f \in C^\infty(M), \Upsilon_j|_p(f) = \frac{\partial(f \circ \phi^{-1})}{\partial x^j}(\phi(p))$*

Proof.

$$\begin{aligned}
\Upsilon_j|_p(f) &= (di_p \circ (d\phi_p)^{-1})(\partial_j|_{\phi(p)})(f) \\
&= (d\phi_p)^{-1}(\partial_j|_{\phi(p)})(f \circ \mathbf{i}) \\
&= d(\phi^{-1})_{\phi(p)}(\partial_j|_{\phi(p)})(f \circ \mathbf{i}) \\
&= (\partial_j|_{\phi(p)})(f \circ \mathbf{i} \circ \phi^{-1})(\phi(p)) \\
&= \frac{\partial(f \circ \phi^{-1})}{\partial x^j}(\phi(p))
\end{aligned}$$

□

Corollary 1.19. *Let $(U, \phi = (x^1, \dots, x^n))$ be a coordinate chart for M, then*

$$\Upsilon_j|_p(x^i) = \frac{\partial x^i}{\partial x^j}(p) = \frac{\partial (x^i \circ \phi^{-1})}{\partial x^j}(\phi(p)) = \delta^i_j$$

Theorem 1.20. *Let $F : M \to N$ be smooth, (U, ϕ) and (V, ψ) be local charts for M and N, such that $p \in U, F(p) \in V$, if we choose the basis $\left\{\Upsilon_j|_p\right\}_j, \left\{\Upsilon_i|_{F(p)}\right\}_i$ associated to (U, ϕ) and (V, ψ) , we have that $[dF_p]_{ij} = \frac{\partial \hat{F}^i}{\partial x^j}(\phi(p))$. Namely, $dF_p(\Upsilon_j|_p) = \sum_{i=1}^{\dim(M)} \frac{\partial \hat{F}^i}{\partial x^j}(\phi(p))\Upsilon_i|_{F(p)} \in T_{F(p)}N$, where $\hat{F} = \psi \circ F \circ \phi^{-1}$ is the coordinate representation of F.*

Definition 24. The **tangent bundle** $TM := \bigsqcup_{p \in M} T_pM$.

Proposition 1.21. *If M is a n-dimension smooth manifold, then TM is a 2n-dimension smooth manifold.*

1.5 Vector field

Definition 25. A **vector field** is a smooth function $\mathbf{v} : M \to TM$, such that $\forall p, \mathbf{v}_p := \mathbf{v}(p) \in T_pM$

Definition 26. Let $(U, \phi = (x^1, \dots, x^n))$ be a coordinate chart for M, then we can always write $\mathbf{v}_p = \sum_{i=1}^n \mathbf{v}^i(p)\Upsilon_i|_p$, since $\left\{\Upsilon_i|_p = \frac{\partial}{\partial x^i}|_p\right\}$ is a basis for T_pM. The functions $\mathbf{v}^i : M \to \mathbb{R}$ are called the **component functions**.

Definition 27. Let $(U, \phi = (x^1, \dots, x^n))$ be a coordinate chart for M, the **partial derivatives** $\Upsilon_i = \partial_i : U \to TM$ is given by $\Upsilon_i(p) = \Upsilon_i|_p$, where $\left\{\Upsilon_i|_p = \frac{\partial}{\partial x^i}|_p\right\}$ is a basis for T_pM associated to $(U, \phi = (x^1, \dots, x^n))$. One can check that $\Upsilon_i \in \mathfrak{X}(M)$

Proposition 1.22. *Given $p \in M, \boldsymbol{u} \in T_pM$, and some open $U \subseteq M$ that contains p, there is a vector field $\boldsymbol{v}$ on M, such that $\boldsymbol{v}|_p = \boldsymbol{u}$, and $\mathrm{Supp}(\boldsymbol{v}) \subseteq U$.*

Definition 28. $\mathfrak{X}(M)$ is the set of all vector fields.

Proposition 1.23. *$\mathfrak{X}(M)$ is a real vector space.*

Definition 29. Given a smooth function $f \in C^\infty(M)$, and a vector field $\mathbf{v} \in \mathfrak{X}(M)$, we define $f\mathbf{v} := f \cdot \mathbf{v} \in \mathfrak{X}(M)$ to be $(f\mathbf{v})(p) := f(p)\mathbf{v}_p \in T_pM$

Proposition 1.24. *The above definition of $\cdot : C^\infty(M) \times \mathfrak{X}(M) \to \mathfrak{X}(M)$ gives a $C^\infty(M)-$module of the vector fields.*

Corollary 1.25. *We can thus write any vector field $\boldsymbol{v} \in \mathfrak{X}(M)$ as $\sum_{i=1}^n \boldsymbol{v}^i\Upsilon_i$*

Theorem 1.26. ***Canonical form of vector field***
Let $\boldsymbol{v} \in \mathfrak{X}(M)$, and $V_p \neq 0$ for some $p \in M$, then there is a coordinate chart $(U, \phi = (x^1, \dots, x^n))$ for M, such that $p \in U, \boldsymbol{v}|_U = \frac{\partial}{\partial x^1} = \Upsilon_1$

Definition 30. Given a smooth function $f \in C^\infty(M)$, and a vector field $\mathbf{v} \in \mathfrak{X}(M)$, we define $\mathbf{v}(f) \in C^\infty(M)$ to be $\mathbf{v}(f)(p) := \mathbf{v}_p(f) \in \mathbb{R}$. Thus we can view a vector field $\mathbf{v}$ as a function $C^\infty(M) \to C^\infty(M)$ as well.

1.6 Lie Bracket

Definition 31. Given two vector fields $\mathbf{v}, \mathbf{w} \in \mathfrak{X}(M)$, the **Lie Bracket** is $[\mathbf{v}, \mathbf{w}] := \mathbf{v} \circ \mathbf{w} - \mathbf{w} \circ \mathbf{v}$

Proposition 1.27. *$[\boldsymbol{v}, \boldsymbol{w}] \in \mathfrak{X}(M)$ is a vector field.*

Proposition 1.28. *$[\boldsymbol{v}, \boldsymbol{w}]$ is bilinear.*

Proposition 1.29. *$[\boldsymbol{v}, \boldsymbol{w}] = -[\boldsymbol{w}, \boldsymbol{v}]$ is anti-symmetric*

Proposition 1.30. *$[\boldsymbol{v}, \boldsymbol{w}]$ satisfies the Jacobian Identity: $[\boldsymbol{u}, [\boldsymbol{v}, \boldsymbol{w}]] + [\boldsymbol{w}, [\boldsymbol{u}, \boldsymbol{v}]] + [\boldsymbol{v}, [\boldsymbol{w}, \boldsymbol{u}]] = 0$*

Proposition 1.31. *For any $f, g \in C^\infty(M), \boldsymbol{v}, \boldsymbol{u} \in \mathfrak{X}(M)$, we have $[f\boldsymbol{v}, g\boldsymbol{u}] = fg[\boldsymbol{v}, \boldsymbol{u}] + f(\boldsymbol{v}g)\boldsymbol{u} - g(\boldsymbol{u}f)\boldsymbol{v}$*

Proposition 1.32. *Let $(U, \phi = (x^1, \dots, x^n))$ be a coordinate chart for M, then for any two vector fields $\boldsymbol{v} = \sum_{i=1}^n \boldsymbol{v}^i\Upsilon_i, \boldsymbol{u} = \sum_{i=1}^n \boldsymbol{u}^j\Upsilon_j \in \mathfrak{X}(M)$, we have $[\boldsymbol{u}, \boldsymbol{v}] = \sum_{j=1}^n \left(\boldsymbol{v}\boldsymbol{u}^j - \boldsymbol{u}\boldsymbol{v}^j\right)\Upsilon_j$*

1.7 Curve and Flow

Definition 32. Let $J \subseteq \mathbb{R}$ be open, a smooth map $\gamma : J \to M$ is called a **smooth curve** in M. Given $t_0 \in J$, let $\frac{d}{dt}|_{t_0}$ be the coordinate basis in $T_{t_0}J \cong T_{t_0}\mathbb{R}$. The **velocity** of γ at t_0 is $\gamma'(t_0) := d\gamma_{t_0}(\frac{d}{dt}|_{t_0}) \in T_{\gamma(t_0)}\mathbb{R}^n$

Proposition 1.33. *Let $(U, \phi = (x^1, \dots, x^n))$ be a coordinate chart for M, and a curve $\gamma : J \to M$. If we let $\phi \circ \gamma(t) = (\gamma^1(t), \dots, \gamma^n(t))$, then we have $\gamma'(t_0) = d\gamma_{t_0}(\frac{d}{dt}|_{t_0}) = \sum_{i=1}^n \dot{\gamma}^i(t_0)\Upsilon_i|_{\gamma(t_0)} \in T_{\gamma(t_0)}M$*

Definition 33. Let $\mathbf{v} \in \mathfrak{X}(M)$, an **integral curve** of $\mathbf{v}$ is a curve $\gamma : J \to M$ such that $\forall t \in J, \gamma'(t) = \mathbf{v}_t$. If $0 \in J$, then $\gamma(0)$ is called the **starting point** of γ

Proposition 1.34. *An integral curve should satisfy $\forall t \in J, \sum_{i=1}^n \dot{\gamma}^i(t)\Upsilon_i|_{\gamma(t_0)} = \gamma'(t) = \boldsymbol{v}_t = \sum_{i=1}^n \boldsymbol{v}^i(\gamma(t))\Upsilon_i|_{\gamma(t_0)}$, thus $\forall i, \dot{\gamma}^i(t) = v^i \circ \phi^{-1}(\gamma^1(t), \dots, \gamma^n(t))$ gives an ODE.*

Proposition 1.35. *$\forall \boldsymbol{v} \in \mathfrak{X}(M), p \in M, \exists \epsilon > 0, \gamma : (-\epsilon, \epsilon) \to M$ that is an integral curve of $\boldsymbol{v}$ with starting point p.*

Definition 34. A **smooth global flow** on M is a smooth map $\Theta : \mathbb{R} \times M \to M$, such that $\forall s, t \in \mathbb{R}, p \in M, \Theta(0, p) = p, \Theta(t, \Theta(s, p)) = \Theta(t + s, p)$

Remark. A global flow can be thought of as a table to show where something should be after t time and starting from p.

Definition 35. For $p \in M$, we have $\Theta^{(p)} : \mathbb{R} \to M$ is a curve given by $\Theta^{(p)}(t) := \Theta(t, p)$

Definition 36. For $t \in \mathbb{R}$, we have $\Theta_t : \mathbb{R} \to M$ is a smooth map given by $\Theta_t(p) := \Theta(t, p)$

Proposition 1.36. *Given a global flow $\Theta : \mathbb{R} \times M \to M$, we define $\boldsymbol{v} : M \to TM$ by $\boldsymbol{v}_p := {\Theta^{(p)}}'(0) \in T_pM$, then $\boldsymbol{v} \in \mathfrak{X}(M)$ is a vector field, and $\Theta^{(p)}$ is an integral curve for $\boldsymbol{v}$.*

Definition 37. The $\mathbf{v} \in \mathfrak{X}(M)$ in the above proposition is called **infinitesimal generator** for the flow Θ.

Remark. The infinitesimal generator tells us how should something move at every point in M.

Definition 38. Let $D \subseteq \mathbb{R} \times M$ be open, such that $\forall p \in M, D^{(p)} := \{t \in \mathbb{R} | (t, p) \in D\}$ is an open interval containing 0. A **local flow** on M is a smooth map $\Theta : D \to M$, such that $\forall p \in M, s \in D^{(p)}, t \in D^{(\Theta(s,p))}$, s.t. $t + s \in D^{(p)}, \Theta(0, p) = p, \Theta(t, \Theta(s, p)) = \Theta(t + s, p)$

Definition 39. $\Theta^{(p)} : D^{(p)} \to M$ is a curve given by $\Theta^{(p)}(t) := \Theta(t, p)$. And for $t \in \mathbb{R}, M_t := \{p \in M | (t, p) \in D\}$, then $\Theta_t : M_t \to M$ is a smooth map given by $\Theta_t(p) := \Theta(t, p)$

Proposition 1.37. *A local flow also has an infinitesimal generator as before.*

Definition 40. An integral curve is **maximal** if it cannot be extended to an integral curve with a greater domain. A local flow is **maximal** if it cannot be extended to a local flow with a greater domain D.

Theorem 1.38. ***Fundamental theorem of flows:***
For any $\boldsymbol{v} \in \mathfrak{X}(M)$, there is a unique maximal local flow $\Theta : D \to M$, such that $\boldsymbol{v}$ is the generator of Θ. Moreover,

1. *$\forall p \in M$, $\Theta^{(p)} : D^{(p)} \to M$ is the unique maximal integral curve of $\boldsymbol{v}$ starting at p.*
2. *If $s \in D^{(p)}$, then $D^{(\Theta(s,p))} = D^{(p)} - s := \left\{t - s : t \in D^{(p)}\right\}$*
3. *$\forall t \in \mathbb{R}, M_t$ is an open subset of M, and $\Theta_t : M_t \to M_{-t}$ is a diffeomorphism with its inverse $\Theta_t^{-1} = \Theta_{-t}$*

1.8 One-form and Co-vector fields

Definition 41. Let V be a vector space, a **co-vector** on V is a linear map $f : V \to \mathbb{R}$. The set of all co-vectors is called the **dual space** V^*.

Definition 42. A **contraction** $\langle \cdot, \cdot \rangle : V^* \times V \to \mathbb{R}$ is the evaluation $\langle f, v \rangle := f(v)$

Proposition 1.39. *Given a basis $\{E_1, \ldots, E_n\}$ for a finite-dimensional V, let $E^1, \ldots, E^n \in V^*$ be defined by $\langle E^i, E_j \rangle := E^i(E_j) = \delta_{ij}$, then $\{E^i\}$ is a basis for V^*, called the* ***dual basis****.*

Definition 43. Let V, W be vector spaces, $A : V \to W$ be a linear map. The **dual map** $A^* : W^* \to V^*$ is defined by $\forall f \in W^*, v \in V, \langle A^*(f), v \rangle = A^*(f)(v) := f(A(v)) = \langle f, A(v) \rangle$

Proposition 1.40. *If $B : V \to W, A : W \to U$ are linear maps, then $(A \circ B)^* = B^* \circ A^*$*

Proposition 1.41. *$(Id_V)^*$ is the identity map for V^**

Proposition 1.42. *If $A : V \to W$ is an isomorphism, then $(A^*)^{-1} = (A^{-1})^*$*

Proposition 1.43. *Let V and W be finite-dimensional vector spaces of dimensions n and m, $A : V \to W$ be a linear map, and $[A]$ is the matrix with respect to basis $\{v_i\}_1^n, \{w_j\}_1^m$ for V, W, then $[A^*] = [A]^\dagger$*

Definition 44. Let T_pM be the tangent space to M at p, then the **cotangent space** to M at p is the dual space of T_pM, denoted by T_p^*M. The elements in T_p^*M are called **co-vectors**.

Definition 45. $T^*M := \bigsqcup_{p \in M} T_p^*M$ is called the **cotangent bundle**.

Proposition 1.44. *If M is an n-dimensional smooth manifold, then T^*M is a 2n-dimensional smooth manifold.*

Definition 46. A **one-form** or **co-vector field** is a smooth map $\omega : M \to T^*M$ such that $\forall p \in M, \omega_p := \omega(p) \in T_p^*M$

Definition 47. $\mathfrak{X}^*(M)$ is the set of all one-forms on M.

Proposition 1.45. *Let $(U, \phi = (x^1, \ldots, x^n))$ be a coordinate chart for M, we have that for each $p \in U, \{\Upsilon_1|_p, \ldots, \Upsilon_n|_p\}$ is a basis for T_pM, the dual basis for T_p^*M is $\{\Upsilon^1|_p, \ldots, \Upsilon^n|_p\}$, such that $\langle \Upsilon^i, \Upsilon_j \rangle = \delta_{ij}$. Thus $\forall \omega_p \in T_p^*M, \omega = \sum_{i=1}^n \omega_i(p) \Upsilon^i|_p$ uniquely. And $\omega_i(p)$ can be get by $\omega_i(p) = \langle \omega, \Upsilon_i \rangle$*

Definition 48. The **coordinate co-vector field** is the map $\Upsilon^i : U \to T^*M$ by $\Upsilon^i(p) := \Upsilon^i|_p$. One can check that $\Upsilon^i \in \mathfrak{X}^*(M)$ is a co-vector field.

Definition 49. Given a smooth function $f \in C^\infty(M)$, and a co-vector field $\omega \in \mathfrak{X}^*(M)$, we define $f\omega := f \cdot \omega \in \mathfrak{X}^*(M)$ to be $(f\omega)(p) := f(p)\omega_p \in T_p^*M$

Proposition 1.46. *The above definition of $\cdot : C^\infty(M) \times \mathfrak{X}^*(M) \to \mathfrak{X}^*(M)$ gives a $C^\infty(M)-$module of the co-vector fields.*

Corollary 1.47. *We can thus write any co-vector field $\omega \in \mathfrak{X}^*(M)$ as $\sum_{i=1}^n \omega_i \Upsilon^i$*

Definition 50. Given any $\omega \in \mathfrak{X}^*(M), \mathbf{v} \in \mathfrak{X}(M)$, we can define $\langle \omega, \mathbf{v} \rangle := \omega(\mathbf{v}) : M \to \mathbb{R}$ by $\langle \omega, \mathbf{v} \rangle (p) := \langle \omega_p, \mathbf{v}_p \rangle$.

Proposition 1.48. *Given any $\omega = \sum_{i=1}^n \omega_i \Upsilon^i \in \mathfrak{X}^*(M), \boldsymbol{v} = \sum_{i=1}^n \boldsymbol{v}^i \Upsilon_i \in \mathfrak{X}(M)$, $\langle \omega, \boldsymbol{v} \rangle = \sum_{i=1}^n \omega_i \boldsymbol{v}^i$*

Definition 51. Let $f \in C^\infty(M)$, the **differential** of f is $df \in \mathfrak{X}^*(M)$, such that $\forall p \in M, D \in T_pM, (df)_p(D) := Df \in \mathbb{R}$. Thus we have a function $d : C^\infty(M) \to \mathfrak{X}^*(M)$

Proposition 1.49. *Notice that $T_{f(p)}\mathbb{R} \cong \mathbb{R}$, and if we identify them canonically, we have that $(df)_p \in T_p^*M : T_pM \to \mathbb{R} \cong df_p : T_pM \to T_{f(p)}\mathbb{R}$. Namely, $\forall D \in T_pM, df_p(D) = (df)_p(D) \frac{d}{dt}|_{f(p)} \in T_{f(p)}\mathbb{R}$*

Proposition 1.50. *Let $(U, \phi = (x^1, \ldots, x^n))$ be a coordinate chart for M, then for any $f \in C^\infty(M)$, we have $df|_U = \sum_{i=1}^n \Upsilon_i(f) \Upsilon^i$*

Corollary 1.51. *Let $(U, \phi = (x^1, \ldots, x^n))$ be a coordinate chart for M, we have $d(x^j)|_U = \sum_{i=1}^n \Upsilon_i(x^j)\Upsilon^i = \sum_{i=1}^n \delta_{ij}\Upsilon^i = \Upsilon^j$. Thus we can write Υ^j as dx^j, and Υ_j as $\frac{\partial}{\partial x^j}$ or ∂_j.*

Corollary 1.52. *Let $(U, \phi = (x^1, \ldots, x^n))$ be a coordinate chart for M, then for any $f \in C^\infty(M)$, we have*

$$df|_U = \sum_{i=1}^n \frac{\partial f}{\partial x^i} dx^i = (\partial_i f) dx^i$$

Definition 52. Let $F : M \to N$ be a smooth map, the **cotangent map** of F is $dF_p^* : T_{F(p)}^* N \to T_p^* M$, which is the dual map of $dF_p : T_pM \to T_{F(p)}N$

Proposition 1.53. *Given any $\omega_{F(p)} \in T_{F(p)}^* N, v_p \in T_pM$, we have $\langle dF_p^*(\omega_{F(p)}), v_p\rangle = \langle \omega_{F(p)}, dF_p(v_p)\rangle$*

1.9 Tensors

Definition 53. Let V be a n-dimensional vector space, then $T^k(V^*) := V^* \otimes V^* \otimes \cdots \otimes V^* = (V^*)^{\otimes k}$ is a vector space of dimension n^k. An element in $T^k(V^*)$ is called a **covariant k-tensor** on V.

Definition 54. More generally, a (r, s) tensor, or a **r-variant-s-covariant-tensor** is an element from $(V)^{\otimes r} \otimes (V^*)^{\otimes s}$.

Proposition 1.54. *Let V be n-dimensional vector space, and $\{E_1, \ldots, E_n\}$ be a basis for V, then $\{E^{i_1} \otimes \cdots \otimes E^{i_k}\}_{(i_1,\ldots,i_k)\in[n]^k}$ is a basis for $T^k(V^*)$, thus any $\alpha \in T^k(V^*)$ can be uniquely written as $\sum_{(i_1,\ldots,i_k)\in[n]^k} \alpha_{i_1,\ldots,i_k} E^{i_1} \otimes \cdots \otimes E^{i_k}$*

Definition 55. We can thus view $\alpha \in T^k(V^*)$ as a function $V^k \to \mathbb{R}$ defined by
$\alpha(v_1, \ldots, v_n) := \sum_{(i_1,\ldots,i_k)\in[n]^k} \alpha_{i_1,\ldots,i_k} E^{i_1}(v_1) \cdots E^{i_k}(v_k) = \alpha_{i_1,\ldots,i_k} \langle E^{i_1}, v_1\rangle \cdots \langle E^{i_k}, v_k\rangle$

Definition 56. More generally, a (r, s) tensor $\mathcal{T} = \sum_{(i_1,\ldots,i_r,j_1,\ldots,j_s)\in[n]^{r+s}} \mathcal{T}_{j_1,\ldots,j_s}^{i_1,\ldots,i_r} E_{i_1} \otimes \cdots \otimes E_{i_r} \otimes E^{j_1} \otimes \cdots \otimes E^{j_s}$ can be viewed as a map $(V^*)^r \times V^s \to \mathbb{R}$ defined by

$$\begin{aligned}\mathcal{T}(\omega^1, \ldots, \omega^r, v_1, \ldots, v_s) &:= \sum_{(i_1,\ldots,i_r,j_1,\ldots,j_s)\in[n]^{r+s}} \mathcal{T}_{j_1,\ldots,j_s}^{i_1,\ldots,i_r} \omega^1(E_{i_1}) \cdots \omega^r(E_{i_r}) E^{j_1}(v_1) \cdots E^{j_s}(v_s) \\ &= \mathcal{T}_{j_1,\ldots,j_s}^{i_1,\ldots,i_r} \langle \omega^1, E_{i_1}\rangle \cdots \langle \omega^r, E_{i_r}\rangle \langle E^{j_1}, v_1\rangle \cdots \langle E^{j_s}, v_s\rangle\end{aligned}$$

Proposition 1.55. *The map defined by the tensors is multi-linear.*

Example 1.9.1. A vector is a (1,0) tensor.

Example 1.9.2. A co-vector is a (0,1) tensor.

Example 1.9.3. A real inner product is a (0,2) tensor.

Example 1.9.4. The determinant of a $n \times n$ real matrix is a (0,n) tensor as a function on the column/row vectors.

1.10 Alternating Tensor and wedge product

Definition 57. A covariant k-tensor is **symmetric** if $\forall 1 \le i < j \le k, v_1, \ldots, v_k \in V$,
$\alpha(v_1, \ldots, v_i, \ldots, v_j, \ldots, v_k) = \alpha(v_1, \ldots, v_j, \ldots, v_i, \ldots, v_k)$.
It is **alternating** or **anti-symmetric** if $\alpha(v_1, \ldots, v_i, \ldots, v_j, \ldots, v_k) = -\alpha(v_1, \ldots, v_j, \ldots, v_i, \ldots, v_k)$

Definition 58. The set of alternating covariant k-tensors is $\Lambda^k(V^*) \subseteq T^k(V^*)$

Definition 59. The **permutation group** S_k is the set of all permutations of $[k] := \{1, \ldots, k\}$

Definition 60. Given a permutation $\sigma \in S_k$, **sign** of it is $Sgn(\sigma) := \begin{cases} 1 & \text{permutation is got by even transposition} \\ -1 & \text{permutation is got by odd transposition} \end{cases}$

Definition 61. Given a tensor $\alpha \in T^k(V^*)$, the **alternation** of it is $Alt(\alpha) \in T^k(V^*)$, defined by $Alt(\alpha)(v_1, \dots, v_k) := \frac{1}{k!} \sum_{\sigma \in S_k} sgn(\sigma) \alpha(v_{\sigma(1)}, \dots, v_{\sigma(k)})$

Proposition 1.56. $\forall \alpha \in T^k(V^*), Alt(\alpha) \in \Lambda^k(V^*)$

Proposition 1.57. $\forall \alpha \in \Lambda^k(V^*), Alt(\alpha) = \alpha$

Definition 62. An ordered k-tuple $I = (i_1, \dots, i_k) \in [n]^k$ is called a **multi-index of length k**.

Definition 63. Let $\{E^1, \dots, E^n\}$ be a dual basis for V^*, and $I = (i_1, \dots, i_k) \in [n]^k$, then we define the **elementary alternating tensor** $E^I \in \Lambda^k(V^*)$ by $E^I(v_1, \dots, v_k) := \det \begin{pmatrix} E^{i_1}(v_1) & \dots & E^{i_1}(v_k) \\ \vdots & \ddots & \vdots \\ E^{i_k}(v_1) & \dots & E^{i_k}(v_k) \end{pmatrix}$

Definition 64. Let $I = (i_1, \dots, i_k), J = (j_1, \dots, j_k) \in [n]^k$, then $\delta^I_J := \det \begin{pmatrix} \delta^{i_1}_{j_1} & \dots & \delta^{i_1}_{j_k} \\ \vdots & \ddots & \vdots \\ \delta^{i_k}_{j_1} & \dots & \delta^{i_k}_{j_k} \end{pmatrix}$

Proposition 1.58. $\delta^I_J = \begin{cases} 0 & \textit{if I or J have repeated indices, or I is not any permutation of J} \\ 1 & \textit{if I is an even permutation of J} \\ -1 & \textit{if I is an odd permutation of J} \end{cases}$

Proposition 1.59. *If $I = (i_1, \dots, i_k)$ have any repeated indices, i.e. $\exists 1 \le l \ne m \le k, i_l = i_m$, then $E^I = 0$*

Proposition 1.60. *If $J = (i_{\sigma(1)}, \dots, i_{\sigma(k)})$, then $E^J = sgn(\sigma) E^I$*

Proposition 1.61. *Let $I = (i_1, \dots, i_k), J = (j_1, \dots, j_k) \in [n]^k$, then $E^I(E_{j_1}, \dots, E_{j_k}) = \delta^I_J$*

Definition 65. $I = (i_1, \dots, i_k) \in [n]^k$ is increasing if $i_1 < i_2 < \dots < i_k$

Proposition 1.62. *Let $\dim(V) = n, k \in \mathbb{N}^+$, if $K > n$, then $\Lambda^k(V^*) = \{0\}$, otherwise $\dim(\Lambda^k(V^*)) = \binom{n}{k}$, and a basis is given by $\mathcal{E}^k := \{E^I | I \text{ is increasing multi-index of length } k\}$*

Definition 66. The **wedge product** of two covariant tensors u, v is defined to be $u \wedge v := u \otimes v - v \otimes u$

Proposition 1.63. $\forall s, s \wedge s = 0$

Proposition 1.64. *For $u_1, \dots, u_k$, we have $u_1 \wedge \dots \wedge u_k = k! Alt(u_1 \otimes \dots \otimes u_k) = \sum_{\sigma \in S_k} sgn(\sigma) v_{\sigma(1)}, \dots, v_{\sigma(k)}$*

Proposition 1.65. $E^I = E^{i_1} \wedge \dots \wedge E^{i_k}$

Proposition 1.66. *Let $I, J \in [n]^k$ be both increasing, then $E^I \wedge E^J = (-1)^{|I| \cdot |J|} E^J \wedge E^I$*

1.11 Tensor fields or k-form

Definition 67. The bundle of all covariant k-tensors on M is $T^k T^* M := \bigsqcup_{p \in M} T^K(T^*_p M)$

Proposition 1.67. *$T^k T^* M$ is a smooth manifold of dimension n^{k+1}*

Definition 68. Given a smooth manifold M, a **covariant k-tensor field on M** or a **k-form** is a smooth map $A : M \to T^k T^* M$, s.t. $A_p := A(p) \in T^K(T^*_p M)$. The set of all k-forms is $\Gamma(T^K T^*_p M)$

Proposition 1.68. *$\Gamma(T^K T^*_p M)$ is an infinite dimensional vector space.*

Proposition 1.69. *Let $(U, \phi = (x^1, \dots, x^n))$ be a coordinate chart for M, then for covariant k-tensor field $A \in \Gamma(T^K T^*_p M)$, it can be written as $A|_U = \sum_{(i_1, \dots, i_k) \in [n]^k} A_{i_1, \dots, i_k} dx^{i_1} \otimes \dots \otimes dx^{i_k}$*

Definition 69. An **alternating covariant k-tensor field** or **alternating k-form** on M is a smooth map $A : M \to \bigsqcup_{p\in M} \Lambda^k(T_p^*M)$ such that $\forall p \in M, A_p := A(p) \in \Lambda^k(T_p^*M)$. The set of all alternating k-forms on M is $\Omega^k(M)$

Definition 70. $\Omega^0(M) := c^\infty(M)$

Definition 71. $\wedge : \Omega^k(M)\times\Omega^l(M) \to \Omega^{k+l}(M)$ is defined to be $(\zeta\wedge\eta)_p := \zeta_p\wedge\eta_p$, where $\zeta_p \in \Lambda^k(T_p^*M), \eta_p \in \Lambda^l(T_p^*M)$. For $k = 0, f \in C^\infty(M), f \wedge \eta := f\eta$

Proposition 1.70. *$\Omega^*(M) = \bigoplus_{k=0}^n \Omega^k(M)$ is an anti-commutative algebra.*

Proposition 1.71. *Let $(U, \phi = (x^1, \dots, x^n))$ be a coordinate chart for M, then for an alternating covariant k-tensor field $\omega \in \Omega^k(M)$, it can be written as $\omega|_U = \sum_{(i_1<\dots<i_k)\in[n]^k} \omega_{i_1,\dots,i_k} dx^{i_1} \wedge \dots \wedge dx^{i_k}$, where $\omega_{i_1,\dots,i_k} = \omega(\partial_{i_1}, \dots, \partial_{i_k})$, and $dx^{i_1} \wedge \dots \wedge dx^{i_k}(\partial_{j_1}, \dots, \partial_{j_k}) = \delta^I_J$*

1.12 Push-forward and Pull-back

Definition 72. Let M, N be smooth manifolds and $F : M \to N$ be a smooth function, then two vector fields $\mathbf{v} \in \mathfrak{X}(M), \mathbf{u} \in \mathfrak{X}(N)$ are **F-related** if $\forall p \in M, dF_p(\mathbf{v}_p) = \mathbf{u}_{F(p)}$

Proposition 1.72. *If $F : M \to N$ is a diffeomorphism, for every vector field $\boldsymbol{v} \in \mathfrak{X}(M)$, there is a unique vector field $F_*\boldsymbol{v} \in \mathfrak{X}(N)$ that is F-related to $\boldsymbol{v}$.*

Definition 73. The **push-forward** of a vector field $\mathbf{v} \in \mathfrak{X}(M)$ by a diffeomorphism $F : M \to N$ is the unique vector field $F_*\mathbf{v} \in \mathfrak{X}(N)$ in the previous proposition, defined by $\forall q \in N, F_*\mathbf{v}_q := dF_{F^{-1}(q)}(\mathbf{v}_{F^{-1}(q)})$

Proposition 1.73. *For any diffeomorphism $F : M \to N$, vector field $\boldsymbol{v} \in \mathfrak{X}(N), f \in c^\infty(N)$, we always have $\boldsymbol{v}(f \circ F) = ((F_*\boldsymbol{v})f) \circ F \in C^\infty(M)$*

Definition 74. Given a smooth map $F : M \to N$, and a co-vector field $\omega \in \mathfrak{X}(N)$, the **pull-back** of ω by F is $F^*\omega \in \mathfrak{X}^*(M)$ defined by $(F^*\omega)_p := dF_p^*(\omega_{F(p)}) \in T_p^*M$

Proposition 1.74. *Consider any $D \in T_pM, (F^*\omega)_p(D) = \langle dF_p^*(\omega_{F(p)}), D\rangle = \langle \omega_{F(p)}, dF_p(D)\rangle$*

Proposition 1.75. *For any smooth $F : M \to N$, co-vector field $\omega \in \mathfrak{X}(N), u \in c^\infty(N)$, we always have $(u \circ F)F^*\omega = F^*(u\omega) \in \mathfrak{X}^*(M), F^*(du) = d(u \circ F) \in \mathfrak{X}^*(M)$*

Definition 75. Given a smooth map $F : M \to N, p \in M, \alpha \in T^k(T^*_{F(p)}N)$, the **pull-back** of α by F at p is $dF_p^*(\alpha) \in T^k(T_p^*M)$, defined by $dF_p^*(\alpha)(v_1, \dots, v_k) = \alpha(dF_p(v_1), \dots, dF_p(v_k)) \in C^\infty(N)$. This way we obtain a linear map $dF_p^* : T^k(T^*_{F(p)}N) \to T^k(T_p^*M)$

Definition 76. Let $A \in \Lambda(T^kT^*N)$ be a k-covariant tensor field, the **pull-back** of A by a smooth map $F : M \to N$ is $F^*A \in \Lambda(T^kT^*M)$ defined by $(F^*A)_p := dF_p^*(A_{F(p)})$. This way we get a $F^* : \Lambda(T^kT^*N) \to \Lambda(T^kT^*M)$

Definition 77. Let $A \in \Omega^k(N)$ be an alternating k-covariant tensor field, the **pull-back** of A by a smooth map $F : M \to N$ is $F^*A \in \Omega^k(M)$ defined by $(F^*A)_p := dF_p^*(A_{F(p)})$. This way we get a $F^* : \Omega^k(N) \to \Omega^k(M)$

Proposition 1.76. *F^* is a linear map.*

Proposition 1.77. *Given any two alternating k-covariant tensor fields $A, B \in \Omega^k(N)$, we have $F^*(A\wedge B) = F^*(A) \wedge F^*(B)$*

Proposition 1.78. $F^*(\sum_{I increasing} A_I dy^{i_1} \wedge \dots \wedge dy^{i_k}) = \sum_{I increasing}(A_I \circ F)d(y^{i_1} \circ F) \wedge \dots \wedge d(y^{i_k} \circ F)$

Example 1.12.1. Consider $M = U = \mathbb{R}^2 \setminus \{(x,0)|x \leq 0\}$ be the open set of $\mathbb{R}^2$ minus the negative x axis, with a polar coordinate local map $\phi(r\cos(\theta), r\sin(\theta)) = (r,\theta)$ on U, let this be M. We then consider $N = U$ to be with a Cartesian coordinate $\psi = (x(a,b) = a, y(a,b) = b) : N \to \mathbb{R}^2$. Let $Id : U \to U$ be the identity map. We thus have $x \circ Id \circ \phi^{-1}, y \circ Id \circ \phi^{-1} : \mathbb{R}^2 \to \mathbb{R}^2, x \circ Id \circ \phi^{-1}(r,\theta) = r\cos(\theta), y \circ Id \circ \phi^{-1}(r,\theta) = r\sin(\theta)$.

$$\begin{aligned}
Id^*(dx \wedge dy) &= Id^*(\mathbf{1} dx \wedge dy), \text{ in which } \mathbf{1}(x,y) = 1 : N \to \mathbb{R} \\
&= (\mathbf{1} \circ Id) \cdot d(x \circ Id) \wedge d(y \circ Id), \text{ in which } x \circ Id, y \circ Id : U \to \mathbb{R}, \\
&= d(x \circ Id) \wedge d(x \circ Id) \\
&= \left(\frac{\partial x \circ Id \circ \phi^{-1}}{\partial \theta} d\theta + \frac{\partial y \circ Id \circ \phi^{-1}}{\partial r} dr\right) \wedge \left(\frac{\partial x \circ Id \circ \phi^{-1}}{\partial \theta} d\theta + \frac{\partial y \circ Id \circ \phi^{-1}}{\partial r} dr\right) \\
&= \left(\frac{\partial r\cos\theta}{\partial \theta} d\theta + \frac{\partial r\cos\theta}{\partial r} dr\right) \wedge \left(\frac{\partial r\sin\theta}{\partial \theta} d\theta + \frac{\partial r\sin\theta}{\partial r} dr\right) \\
&= (-r\sin\theta d\theta + \cos\theta dr) \wedge (r\cos\theta d\theta + \sin\theta dr) \\
&= -r\sin^2\theta d\theta \wedge dr + r\cos^2\theta dr \wedge d\theta, \text{ since } dr \wedge dr = d\theta \wedge d\theta = 0 \\
&= r\sin^2\theta dr \wedge d\theta + r\cos^2\theta dr \wedge d\theta \\
&= r dr \wedge d\theta
\end{aligned}$$

Thus there is a canonical mapping between $dx \wedge dy \in \Omega^2(M)$ and $rdr \wedge d\theta \in \Omega^2(N)$

1.13 Lie Derivative

Definition 78. Let $\mathbf{v}, \mathbf{w} \in \mathfrak{X}(M)$, the **Lie derivative** of $\mathbf{w}$ with respect to $\mathbf{v}$ is a map $\mathcal{L}_\mathbf{v}\mathbf{w} : M \to TM$ defined by $\mathcal{L}_\mathbf{v}\mathbf{w}_p = \frac{d}{dt}|_{t=0}(d(\Theta_{-t})_{\Theta_t(p)}\mathbf{w}_{\Theta_t(p)})$, where Θ is the flow generated by $\mathbf{v}$.

Lemma 1.79. *$\mathcal{L}_v w \in \mathfrak{X}(M)$ is a vector field.*

Theorem 1.80. *If $v, w \in \mathfrak{X}(M)$, then $\mathcal{L}_v w = [v, w]$*

1.14 Exterior derivative

Definition 79. Let $\omega|_U = \sum_{(i_1 < \cdots < i_k) \in [n]^k} \omega_{i_1,\ldots,i_k} dx^{i_1} \wedge \cdots \wedge dx^{i_k} \in \Omega^k(\mathbb{R})$, the **exterior derivative** of ω is $\nabla\omega := \sum_{(i_1 < \cdots < i_k) \in [n]^k} d(\omega_{i_1,\ldots,i_k}) \wedge dx^{i_1} \wedge \cdots \wedge dx^{i_k} = \frac{\partial \omega_{i_1,\ldots,i_k}}{\partial x^j} dx^j \wedge dx^{i_1} \wedge \cdots \wedge dx^{i_k} \in \Omega^{k+1}(\mathbb{R})$

Proposition 1.81. *If $f \in C^\infty(U) = \Omega^0(U)$, then we have $\nabla f = df \in \Omega^1(U)$*

Proposition 1.82. *$\nabla : \Omega^k(U) \to \Omega^{k+1}(U)$ is linear*

Proposition 1.83. *$\nabla \circ \nabla : \Omega^k(U) \to \Omega^{k+2}(U)$ is the zero map.*

Proposition 1.84. *$\forall \omega \in \Omega^k(U), \eta \in \Omega^l(U)$, we have $\nabla(\omega \wedge \eta) = \nabla\omega \wedge \eta + (-1)^k \omega \wedge \nabla\eta$*

Proposition 1.85. *For any smooth map $F : U \to V$, and any alternating k-form $\omega \in \Omega^k(V)$, we always have $\nabla(F^*\omega) = F^*(\nabla\omega)$*

Theorem 1.86. *For any smooth manifold M and $k \in \mathbb{N}$, there is a unique linear map $\nabla : \Omega^k(M) \to \Omega^{k+1}(M)$ such that*

1. *If $f \in C^\infty(M) = \Omega^0(M)$, then we have $\nabla f = df \in \Omega^1(M)$*
2. *$\nabla \circ \nabla : \Omega^k(M) \to \Omega^{k+2}(M)$ is the zero map.*
3. *$\forall \omega \in \Omega^k(M), \eta \in \Omega^l(M)$, we have $\nabla(\omega \wedge \eta) = \nabla\omega \wedge \eta + (-1)^k \omega \wedge \nabla\eta$*