INTRODUCTION TO DIFFERENTIAL GEOMETRY

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Contents

1. Fundamental Definitions and Results

1.1. Set Theory.

Definition 1.1.1. Let $\{A_i\}_{i\in I}$ be a collection of sets. The **disjoint union of** $\{A_i\}_{i\in I}$, denoted $\coprod_{i\in I} A_i$, is defined by

$$\coprod_{i\in I} A_i = \bigcup_{i\in I} \{i\} \times A_i$$

We define the **natural projection map**, denoted $\pi : \coprod_{i \in I} A_i \to I$, by $\pi(i, a) = i$.

Definition 1.1.2. Let Let $\{A_i\}_{i \in I}$ be a collection of sets and $\sigma : I \to \coprod_{i \in I} A_i$. Then σ is said to be a **section of** $\coprod_{i \in I} A_i$ if

$$\pi \circ \sigma = \mathrm{id}_I$$

Note 1.1.3. In these notes, we will identify $\{i\} \times A_i$ and A_i.

Exercise 1.1.4. Let $\{A_i\}_{i \in I}$ be a collection of sets and $\sigma : I \to \coprod_{i \in I} A_i$. Then σ is a section of $\coprod_{i \in I} A_i$ iff for each $i \in I$, $\sigma(i) \in A_i$

Proof. Clear. □

2. Calculus

2.1. Differentiation.

Definition 2.1.1. Let $n \geq 1$. For $i = 1, \cdots, n$, define $x^i : \mathbb{R}^n \to \mathbb{R}$ by $x^i(a^1, \cdots, a^n) = a^i$. The functions $(x^i)_{i=1}^n$ are called the **standard coordinate functions on** $\mathbb{R}^n$.

Definition 2.1.2. Let $U \subset \mathbb{R}^n$ be open, $f : U \to \mathbb{R}$ and $a \in U$. Then f is said to be **differentiable with respect to** x^i **at** a if

$$\lim_{h \to 0} \frac{f(a + he^i) - f(a)}{h}$$

exists. If f is differentiable with respect to x^i at a, we define the **partial derivative of** f **with respect to** x^i **at** a, denoted

$$\frac{\partial f}{\partial x^i}(a) \text{ or } \left.\frac{\partial}{\partial x^i}\right|_a f$$

to be the limit above.

Definition 2.1.3. Let $U \subset \mathbb{R}^n$ be open and $f : U \to \mathbb{R}$. Then f is said to be **differentiable with respect to** x^i if for each $a \in U$, f is differentiable with respect to x^i at a.

Exercise 2.1.4. Let $U \subset \mathbb{R}^n$ be open, $f : U \to \mathbb{R}$ and $a \in U$. Suppose that $\frac{\partial^2 f}{\partial x^i x^j}$ and $\frac{\partial^2 f}{\partial x^j x^i}$ exist and are continuous at a. Then

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

Proof. □

Definition 2.1.5. Let $U \subset \mathbb{R}^n$ be open and $f : U \to \mathbb{R}$. Then f is said to be **smooth** if for each $i_1, \cdots, i_k \in \{1, \cdots, n\}$, $\frac{\partial^k f}{\partial i_1 \cdots i_k}$ exists and is continuous on U.

Definition 2.1.6. Let $U \subset \mathbb{R}^n$, $f : U \to \mathbb{R}$. Then f is said to be **smooth** if there exists $U' \subset \mathbb{R}^n$ and $f' : U' \to \mathbb{R}$ such that $U \subset U'$, U' is open, $f'|_U = f$ and f' is smooth. The set of smooth functions on U is denoted $C^\infty(U)$.

Definition 2.1.7. Let $U \subset \mathbb{R}^n$ and $p \in U$. Then U is said to be **star-shaped** if for each $q \in U$, $\{p + t(q - p) : 0 \leq t \leq 1\} \subset U$.

Exercise 2.1.8. Taylor's Theorem:
Let $U \subset \mathbb{R}^n$ be open, $p \in U$ and $f \in C^\infty(U)$. Suppose that U is star-shaped with respect to p. Then there exist $g_1, \cdots, g_n \in C^\infty(U)$ such that for each $x \in U$,

$$f(x) = f(p) + \sum_{i=1}^{n} (x^i - p^i) g_i(x)$$

and for each $i \in \{1, \cdots, n\}$,

$$g_i(p) = \frac{\partial f}{\partial x^i}(p)$$

Proof. Let $x \in U$. Since U is star-shaped with respect to p, $\{p + t(x-p) : 0 \leq t \leq 1\} \subset U$. By the chain rule,

$$\frac{\mathrm{d}}{\mathrm{d}t}\Big[f(p + t(x-p))\Big] = \sum_{i=1}^{n} \frac{\partial f}{\partial x^i}(p + t(x-p))(x^i - p^i)$$

Integrating both sides with respect to t from 0 to 1, we obtain

$$f(x) - f(p) = \sum_{i=1}^{n} (x^i - p^i) \int_0^1 \frac{\partial f}{\partial x^i}(p + t(x-p))dt$$

For $i \in \{1, \cdots, n\}$, define $g_i \in C^\infty(U)$ by

$$g_i(x) = \int_0^1 \frac{\partial f}{\partial x^i}(p + t(x-p))dt$$

Then for each $i \in \{1, \cdots, n\}$,

$$g_i(p) = \frac{\partial f}{\partial x^i}(p))$$

□

2.2. **Smooth Maps.**

Definition 2.2.1. Let $U \subset \mathbb{R}^n$ and $F : U \to \mathbb{R}^m$. Let $x^1, \cdots, x^n$ be the standard coordinate functions on $\mathbb{R}^n$ and $y_1, \cdots, y_m$ be the standard coordinate functions on $\mathbb{R}^m$. For $i \in \{1, \cdots, m\}$, we define the i**th component of** F, denoted $F^i : U \to \mathbb{R}$, by

$$F^i = y^i \circ F$$

Thus $F = (F_1, \cdots, F_m)$

Definition 2.2.2. Let $U \subset \mathbb{R}^n$ and $F : U \to \mathbb{R}^m$. Then F is said to be **smooth** if for each $i \in \{1, \cdots, m\}$, the ith component of F, $F^i : U \to \mathbb{R}$, is smooth.

Definition 2.2.3. Let $U \subset \mathbb{R}^n$ and $V \subset \mathbb{R}^m$ and $F : U \to V$. Then F is said to be a **diffeomorphism** if F is a bijection and F, F^{-1} are smooth.

Exercise 2.2.4. Let $U \subset \mathbb{R}^n$ and $V \subset \mathbb{R}^m$ and $F : U \to V$. If F is a diffeomorphism, then F is a homeomorphism.

Proof. Suppose that F is a diffeomorphism. By definition, F is a bijection and F and F^{-1} are smooth. Thus, F and F^{-1} are continuous and F is a homeomorphism. □

Definition 2.2.5. Let $U \subset \mathbb{R}^n$ be open, $p \in U$ and $F : U \to \mathbb{R}^m$. We define the **Jacobian of** F **at** p, denoted $\frac{\partial F}{\partial x}(p) \in \mathbb{R}^{m \times n}$, by

$$\left(\frac{\partial F}{\partial x}(p)\right)_{i,j} = \frac{\partial F^i}{\partial x^j}(p)$$

Exercise 2.2.6. Inverse Function Theorem:
Let $U, V \subset \mathbb{R}^n$ be open and $F : U \to V$.

Exercise 2.2.7. Let $U, V \subset \mathbb{R}^n$ and $F : U \to V$. Then F is a diffeomorphism iff for each $p \in U$, there exists a relatively open neighborhood $N \subset U$ of p such that $F|_N : N \to F(N)$ is a diffeomorphism

Proof. content... □

2.3. Topology.

Definition 2.3.1. Let $(X, \mathbb{T}_X), (Y, \mathcal{T}_Y)$ be topological spaces and $f : X \to Y$. Then f is said to be **continuous** if for each $U \in \mathcal{T}$, $f^{-1}(U) \in \mathcal{T}_X$.

Definition 2.3.2. Let $(X, \mathcal{T}_X), (Y, \mathcal{T}_Y)$ be topological spaces and $f : X \to Y$. Then f is said to be a homeomorphism if f is a bijection and f, f^{-1} are continuous.

Definition 2.3.3. Let X, Y be topological spaces. Then X and Y are said to be **homeomorphic** if there exists $f : X \to Y$ such that f is a homeomorphism. If X and Y are homeomorphic, we write $X \cong Y$.

Theorem 2.3.4. Let $m, n \in \mathbb{N}$. If $m \neq n$, then $\mathbb{R}^m \ncong \mathbb{R}^n$

3. Multilinear Algebra

3.1. (r, s)-Tensors.

Definition 3.1.1. Let $V_1, \dots, V_k, W$ be vector spaces and $\alpha : \prod_{i=1}^n V_i \to W$. Then α is said to be **multilinear** if for each $i \in \{1, \cdots, k\}$, $v \in V$, $c \in \mathbb{R}$ and $v_1, \cdots, v_k \in V$,

$$\alpha(v_1, \cdots, v_i + cv, \cdots, v_k) = \alpha(v_1, \cdots, v_i, \cdots, v_k) + c\alpha(v_1, \cdots, v, \cdots, v_k)$$

We define

$$L(V_1, \dots, V_k; W) = \left\{\alpha : \prod_{i=1}^n V_i \to W : \alpha \text{ is multilinear}\right\}$$

Note 3.1.2. For the remainder of this section we let V denote an n-dimensional vector space with basis $\{e^1, \cdots, e^n\}$ with dual space V^* and dual basis $\{\epsilon_1, \cdots, \epsilon_n\}$ defined by $\epsilon^i(e^j) = \delta_{i,j}$. We identify V with V^{**} by the isomorphism $V \to V^{**}$ defined by $v \mapsto \hat{v}$ where $\hat{v}(\alpha) = \alpha(v)$ for each $\alpha \in V^*$.

Definition 3.1.3. Let $\alpha : (V^*)^r \times V^s \to \mathbb{R}$. Then α is said to be an (r, s)-tensor on V if $\alpha \in L(\underbrace{V^*, \dots, V^*}_{r}, \underbrace{V, \dots, V}_{s}; \mathbb{R})$. The set of all (r, s)-tensors on V is denoted $T^r_s(V)$.
When $r = s = 0$, we set $T^r_s = \mathbb{R}$.

Exercise 3.1.4. We have that $T^r_s(V)$ is a vector space.

Proof. Clear. □

Exercise 3.1.5. Under the identification of V with V^{**} as noted above, we have that $V = T^1_0(V)$.

Proof. By definition,

$$\begin{aligned} V &= V^{**} \\ &= L(V^*; \mathbb{R}) \\ &= T^1_0(V) \end{aligned}$$

□

Definition 3.1.6. Let $\alpha \in T^{r_1}_{s_1}(V)$ and $\beta \in T^{r_2}_{s_2}(V)$. We define the **tensor product of** α **with** β, denoted $\alpha \otimes \beta \in T^{r_1+r_2}_{s_1+s_2}(V)$, by

$$\alpha \otimes \beta(v^*, w^*, v, w) = \alpha(v^*, v)\beta(w^*, w)$$

for each $v^* \in (V^*)^{r_1}$, $w^* \in (V^*)^{r_2}$, $v \in V^{s_1}$ and $w \in V^{s_2}$.
When $r_1 = s_1 = r_2 = s_2 = 0$ (so that $\alpha, \beta \in \mathbb{R}$), we set $\alpha \otimes \beta = \alpha\beta$.

Definition 3.1.7. We define the **tensor product**, denoted $\otimes : T^{r_1}_{s_1}(V) \times T^{r_2}_{s_2}(V) \to T^{r_1+r_2}_{s_1+s_2}(V)$ by

$$(\alpha, \beta) \mapsto \alpha \otimes \beta$$

Exercise 3.1.8. The tensor product $\otimes : T^{r_1}_{s_1}(V) \times T^{r_2}_{s_2}(V) \to T^{r_1+r_2}_{s_1+s_2}(V)$ is well defined.

Proof. Tedious but straightforward. □

Exercise 3.1.9. The tensor product $\otimes : T^{r_1}_{s_1}(V) \times T^{r_2}_{s_2}(V) \to T^{r_1+r_2}_{s_1+s_2}(V)$ is associative.

Proof. Let $\alpha \in T^{r_1}_{s_1}(V)$, $\beta \in T^{r_2}_{s_2}(V)$ and $\gamma \in T^{r_3}_{s_3}(V)$. Then for each $u^* \in (V^*)^{r_1}, v^* \in (V^*)^{r_2}, w^* \in (V^*)^{r_3}, u \in V^{s_1}, v \in V^{s_2}, w \in V^{s_3}$,

$$\begin{aligned}(\alpha \otimes \beta) \otimes \gamma(u^*, v^*, w^*, u, v, w) &= (\alpha \otimes \beta)(u^*, v^*, u, v)\gamma(w^*, w) \\ &= [\alpha(u^*, u)\beta(v^*, v)]\gamma(w^*, w) \\ &= \alpha(u^*, u)[\beta(v^*, v)\gamma(w^*, w)] \\ &= \alpha(u^*, u)(\beta \otimes \gamma)(v^*, w^*, v, w) \\ &= \alpha \otimes (\beta \otimes \gamma)(u^*, v^*, w^*, u, v, w)\end{aligned}$$

So that

$$(\alpha \otimes \beta) \otimes \gamma = \alpha \otimes (\beta \otimes \gamma)$$

□

Exercise 3.1.10. The tensor product $\otimes : T^{r_1}_{s_1}(V) \times T^{r_2}_{s_2}(V) \to T^{r_1+r_2}_{s_1+s_2}(V)$ is bilinear.

Proof.

(1) Linearity in the first argument:
Let $\alpha, \beta \in T^{r_1}_{s_1}(V)$, $\gamma \in T^{r_2}_{s_2}(V)$, $\lambda \in \mathbb{R}$, $v^* \in (V^*)^{r_1}$, $w^* \in (V^*)^{r_2}$, $vinV^{s_1}$ and $w \in V^{s_2}$. To see that the tensor product is linear in the first argument, we note that

$$\begin{aligned}[(\alpha + \lambda\beta) \otimes \gamma](v^*, w^*, v, w) &= (\alpha + \lambda\beta)(v^*, v)\gamma(w^*, w) \\ &= [\alpha(v^*, v) + \lambda\beta(v^*, v)]\gamma(w^*, w) \\ &= \alpha(v^*, v)\gamma(w^*, w) + \lambda\beta(v^*, v)\gamma(w^*, w) \\ &= \alpha \otimes \gamma(v^*, w^*, v, w) + \lambda(\beta \otimes \gamma)(v^*, w^*, v, w) \\ &= [\alpha \otimes \gamma + \lambda(\beta \otimes \gamma)](v^*, w^*, v, w)\end{aligned}$$

So that

$$(\alpha + \lambda\beta) \otimes \gamma = \alpha \otimes \gamma + \lambda(\beta \otimes \gamma)$$

(2) Linearity in the second argument:
Similar to (1).

□

Definition 3.1.11.

(1) Define $\mathcal{I}_{\otimes k} = \{(i_1, i_2, \cdots, i_k) \in \mathbb{N}^k : i_1, \cdots, i_k \leq n\}$. Each element $I \in \mathcal{I}_k$ is called an **unordered multi-index of length** k. Recall that $\#\mathcal{I}_{\otimes k} = n^k$.

(2) Define $\mathcal{I}_{\wedge k} = \{(i_1, i_2, \cdots, i_k) \in \mathbb{N}^k : i_1 < i_2 < \cdots < i_k \leq n\}$. Each element $I \in \mathcal{I}_k$ is called an **ordered multi-index of length** k. Recall that $\#\mathcal{I}_{\wedge k} = \binom{n}{k}$.

Note 3.1.12. For the remainder of this section we will write $\mathcal{I}_k$ in place of $\mathcal{I}_{\otimes k}$.

Definition 3.1.13. Let $I = \{(i_1, i_2, \cdots, i_k) \in \mathcal{I}_k$.

(1) Define $\epsilon^I \in (V^*)^k$ and $e_I \in V^k$ by

$$\epsilon^I = (\epsilon^{i_1}, \cdots, \epsilon^{i_k})$$

and

$$e^I = (e^{i_1}, \cdots, e^{i_k})$$

(2) Define $e^{\otimes I} \in T^k_0(V)$ and $\epsilon^{\otimes I} \in T^0_k(V)$ by
$$e^{\otimes I} = e^{i_1} \otimes \cdots \otimes e^{i_k}$$
and
$$\epsilon^{\otimes I} = \epsilon^{i_1} \otimes \cdots \otimes \epsilon^{i_k}$$

Exercise 3.1.14. Let $\alpha, \beta \in T^r_s(V)$. If for each $I \in \mathcal{I}_r, J \in \mathcal{I}_s$, $\alpha(\epsilon^I, e^J) = \beta(\epsilon^I, e^J)$, then $\alpha = \beta$.

Proof. Suppose that for each $I \in \mathcal{I}_r, J \in \mathcal{I}_s$, $\alpha(\epsilon^I, e^J) = \beta(\epsilon^I, e^J)$. Let $v_1^*, \dots, v_r^* \in V^*$ and $v_1, \dots, v_s \in V$. For each $i \in \{1, \dots, r\}$ and $j \in \{1, \dots, s\}$, write
$$v_i^* = \sum_{k_i=1}^{n} a_{i,k_i} \epsilon^{k_i}$$
and
$$v_j = \sum_{l_j=1}^{n} b_{j,l_j} e^{l_j}$$
Then
$$\begin{aligned}
\alpha(v_1^*, \dots, v_r^*, v_1, \dots, v_s) &= \sum_{k_1,\dots,k_r=1}^{n} \sum_{l_1,\dots,l_s=1}^{n} \prod_{i=1}^{r} \prod_{j=1}^{s} a_{i,k_i} b_{j,l_j} \alpha(\epsilon^{k_1}, \dots, \epsilon^{k_r}, e^{l_1}, \cdots, e^{l_s}) \\
&= \sum_{k_1,\dots,k_r=1}^{n} \sum_{l_1,\dots,l_s=1}^{n} \prod_{i=1}^{r} \prod_{j=1}^{s} a_{i,k_i} b_{j,l_j} \beta(\epsilon^{k_1}, \dots, \epsilon^{k_r}, e^{l_1}, \cdots, e^{l_s}) \\
&= \beta(v_1^*, \dots, v_r^*, v_1, \dots, v_s)
\end{aligned}$$
So that $\alpha = \beta$. □

Exercise 3.1.15. Let $I, K \in \mathcal{I}_r$ and $J, L \in \mathcal{I}_s$. Then $e^{\otimes I} \otimes \epsilon^{\otimes J}(\epsilon^K, e^L) = \delta_{I,K}\delta_{J,L}$.

Proof. Write $I = (i_1, \dots, i_r), K = (k_1, \dots, k_r)$ and $J = (j_1, \dots, j_s), L = (l_1, \dots, l_s)$. Then
$$\begin{aligned}
e^{\otimes I} \otimes \epsilon^{\otimes J}(\epsilon^K, e^L) &= e^{\otimes I}(\epsilon^K)\epsilon^{\otimes J}(e^L) \\
&= e^{i_1} \otimes \cdots \otimes e^{i_r}(\epsilon^{k_1}, \dots, \epsilon^{k_r})\epsilon^{j_1} \otimes \cdots \otimes \epsilon^{j_s}(e^{l_1}, \dots, e^{l_s}) \\
&= \left[\prod_{m=1}^{r} e^{i_m}(\epsilon^{k_m})\right]\left[\prod_{n=1}^{s} \epsilon^{j_n}(e^{l_n})\right] \\
&= \left[\prod_{m=1}^{r} \delta_{i_m,k_m}\right]\left[\prod_{n=1}^{s} \delta_{j_n,l_n}\right] \\
&= \delta_{I,K}\delta_{J,L}
\end{aligned}$$
□

Exercise 3.1.16. The set $\{e^{\otimes I} \otimes \epsilon^{\otimes J} : I \in \mathcal{I}_r, J \in \mathcal{I}_s\}$ is a basis for $T^r_s(V)$ and $\dim T^r_s(V) = n^{r+s}$.

Proof. Let $(a^I_J)_{I \in \mathcal{I}_r, J \in \mathcal{I}_s} \subset \mathbb{R}$. Let $\alpha = \sum_{(I,J) \in \mathcal{I}_r \times \mathcal{I}_s} a^I_J e^{\otimes I} \otimes \epsilon^{\otimes J}$. Suppose that $\alpha = 0$. Then for each $(I, J) \in \mathcal{I}_r \times \mathcal{I}_s$, $\alpha(\epsilon^I, e^J) = a^I_J = 0$. Thus $\{e^{\otimes I} \otimes \epsilon^{\otimes J} : I \in \mathcal{I}_r, J \in \mathcal{I}_s\}$ is linearly independent. Let $\beta \in T^r_s(V)$. For $(I, J) \in \mathcal{I}_r \times \mathcal{I}_s$, put $b^I_J = \beta(\epsilon^J, e^I)$. Define

$\mu = \sum_{(I,J)\in\mathcal{I}_r\times\mathcal{I}_s} b^I_J e^{\otimes I} \otimes \epsilon^{\otimes J} \in T^r_s(V)$. Then for each $(I,J) \in \mathcal{I}_r \times \mathcal{I}_s$, $\mu(\epsilon^I, e^J) = b^I_J = \beta(\epsilon^I, e^J)$. Hence $\mu = \beta$ and therefore $\beta \in \operatorname{span}\{e^{\otimes I} \otimes \epsilon^{\otimes J}\}$. $\square$

3.2. k-Tensors.

Definition 3.2.1. Let $\alpha : V^k \to \mathbb{R}$. Then α is said to be a **k-tensor on V** if $\alpha \in T^0_k(V)$. We will write $T_k(V)$ in place of $T^0_k(V)$.

Definition 3.2.2. For $\sigma \in S_k$ and $\alpha \in T_k(V)$, define the $\sigma\alpha : V^k \to \mathbb{R}$ by

$$\sigma\alpha(v_1, \cdots, v_k) = \alpha(v_{\sigma(1)}, \cdots, v_{\sigma(k)})$$

The map $\alpha \mapsto \sigma\alpha$ is called the **permutation action** of S_k on $T_k(V)$

Exercise 3.2.3. The permutation action of S_k on $T_k(V)$ is a group action.

Proof.

(1) Clearly for each $\sigma \in S_k$ and $\alpha \in T_k(V), \sigma\alpha \in T_k(V)$.
(2) Clearly for each $\alpha \in T_k(V)$, $e\alpha = \alpha$.
(3) Let $\tau, \sigma \in S_k$ and $\alpha \in T_k(V)$. Then for each $v_1, \cdots, v_k \in V$,

$$\begin{aligned}(\tau\sigma)\alpha(v_1, \cdots, v_k) &= \alpha(v_{\tau\sigma(1)}, \cdots, v_{\tau\sigma(k)}) \\ &= \tau\alpha(v_{\sigma(1)}, \cdots, v_{\sigma(k)}) \\ &= \tau(\sigma\alpha)(v_1, \cdots, v_k)\end{aligned}$$

□

Exercise 3.2.4. Let $\sigma \in S_k$. Then $L_\sigma : T_k(V) \to T_k(V)$ given by $L_\sigma(\alpha) = \sigma\alpha$ is a linear transformation.

Proof. Let $\alpha, \beta \in T_k(V)$, $c \in \mathbb{R}$ and $v_1, \cdots, v_k \in V$. Then

$$\begin{aligned}\sigma(c\alpha + \beta)(v_1, \cdots, v_k) &= (c\alpha + \beta)(v_{\sigma(1)}, \cdots, v_{\sigma(k)}) \\ &= c\alpha(v_{\sigma(1)}, \cdots, v_{\sigma(k)}) + \beta(v_{\sigma(1)}, \cdots, v_{\sigma(k)}) \\ &= c\sigma\alpha(v_1, \cdots, v_k) + \sigma\beta(v_1, \cdots, v_k)\end{aligned}$$

So $\sigma(c\alpha + \beta) = c\sigma\alpha + \sigma\beta$. □

Definition 3.2.5. Let $\alpha \in T_k(V)$. Then α is said to be **symmetric** if for each $\sigma \in S_k$, $\sigma\alpha = \alpha$. and α is said to be **alternating** if for each $\sigma \in S_k$, $\sigma\alpha = \operatorname{sgn}(\sigma)\alpha$. The set of symmetric k-tensors on V is denoted $\Xi_k(V)$ and the set of alternating k-tensors on V is denoted $\Lambda_k(V)$.

Definition 3.2.6. Define the **symmetric operator** $S : T_k(V) \to \Xi_k(V)$ by

$$S(\alpha) = \frac{1}{k!}\sum_{\sigma \in S_k} \sigma\alpha$$

Define the **alternating operator** $A : T_k(V) \to \Lambda_k(V)$ by

$$A(\alpha) = \frac{1}{k!}\sum_{\sigma \in S_k} \operatorname{sgn}(\sigma)\sigma\alpha$$

Exercise 3.2.7.

(1) For $\alpha \in T_k(V)$, $S(\alpha)$ is symmetric.
(2) For $\alpha \in T_k(V)$, $A(\alpha)$ is alternating.

Proof.

(1) Let $\alpha \in T_k(V)$ and $\sigma \in S_k$. Then

$$\begin{aligned}
\sigma S(\alpha) &= \sigma\left[\frac{1}{k!}\sum_{\tau \in S_k} \tau\alpha\right] \\
&= \frac{1}{k!}\sum_{\tau \in S_k} \sigma\tau\alpha \\
&= \frac{1}{k!}\sum_{\tau \in S_k} \tau\alpha \\
&= S(\alpha)
\end{aligned}$$

(2) Let $\alpha \in T_k(V)$ and $\sigma \in S_k$. Then

$$\begin{aligned}
\sigma A(\alpha) &= \sigma\left[\frac{1}{k!}\sum_{\tau \in S_k} \operatorname{sgn}(\tau)\tau\alpha\right] \\
&= \frac{1}{k!}\sum_{\tau \in S_k} \operatorname{sgn}(\tau)\sigma\tau\alpha \\
&= \frac{1}{k!}\sum_{\tau \in S_k} \operatorname{sgn}(\sigma)\operatorname{sgn}(\sigma\tau)\sigma\tau\alpha \\
&= \operatorname{sgn}(\sigma)\frac{1}{k!}\sum_{\tau \in S_k} \operatorname{sgn}(\sigma\tau)\sigma\tau\alpha \\
&= \operatorname{sgn}(\sigma)\frac{1}{k!}\sum_{\tau \in S_k} \operatorname{sgn}(\tau)\tau\alpha \\
&= \operatorname{sgn}(\sigma)A(\alpha)
\end{aligned}$$

□

Exercise 3.2.8.

(1) For $\alpha \in \Xi_k(V)$, $S(\alpha) = \alpha$.
(2) For $\alpha \in \Lambda_k(V)$, $A(\alpha) = \alpha$.

Proof.

(1) Let $\alpha \in \Xi_k(V)$. Then

$$\begin{aligned}
S(\alpha) &= \frac{1}{k!}\sum_{\sigma \in S_k} \sigma\alpha \\
&= \frac{1}{k!}\sum_{\sigma \in S_k} \alpha \\
&= \alpha
\end{aligned}$$

(2) Let $\alpha \in \Lambda_k(V)$. Then

$$\begin{aligned} A(\alpha) &= \frac{1}{k!} \sum_{\sigma \in S_k} \operatorname{sgn}(\sigma)\sigma\alpha \\ &= \frac{1}{k!} \sum_{\sigma \in S_k} \operatorname{sgn}(\sigma)^2\alpha \\ &= \alpha \end{aligned}$$

□

Exercise 3.2.9. The symmetric operator $S : T_k(V) \to \Xi_k(V)$ and the alternating operator $A : T_k(V) \to \Lambda_k(V)$ are linear.

Proof. Clear. □

Definition 3.2.10. Let $\alpha \in \Lambda_k(V)$ and $\beta \in \Lambda_l(V)$. The **exterior product** of α and β is defined to be the map $\alpha \wedge \beta \in \Lambda_{k+l}(V)$ given by

$$\alpha \wedge \beta = \frac{(k+l)!}{k!l!} A(\alpha \otimes \beta)$$

Thus $\wedge : \Lambda_k(V) \times \Lambda_l(V) \to \Lambda_{k+l}(V)$.

Exercise 3.2.11. The exterior product $\wedge : \Lambda_k(V) \times \Lambda_l(V) \to T_{k+l}(V)$ is bilinear.

Proof. Clear. □

Exercise 3.2.12. Let $\alpha \in T_k(V)$ and $\beta \in T_l(V)$. Then

(1) $A(A(\alpha) \otimes \beta) = A(\alpha \otimes \beta)$
(2) $A(\alpha \otimes A(\beta)) = A(\alpha \otimes \beta)$

Proof. First note that if we fix $\mu \in S_{k+1}$, then for each $\tau \in S_k$, choosing $\sigma = \mu\tau^{-1}$ yields $\sigma\tau = \mu$. For each $\mu \in S_{k+l}$, the map $\phi_\mu : S_k \to S_{k+l}$ given by $\phi_\mu(\tau) = \mu\tau^{-1}$ is injective. Thus for each $\mu \in S_{k+l}$, we have that $\#\{(\sigma, \tau) \in S_{k+l} \times S_k : \mu = \sigma\tau\} = k!$

(1) Then

$$
\begin{aligned}
A(A(\alpha)\otimes\beta) &= \frac{1}{(k+l)!}\sum_{\sigma\in S_{k+l}}\operatorname{sgn}(\sigma)\sigma\left[A(\alpha)\otimes\beta\right]\\
&= \frac{1}{(k+l)!}\sum_{\sigma\in S_{k+l}}\operatorname{sgn}(\sigma)\sigma\left[\left(\frac{1}{k!}\sum_{\tau\in S_k}\operatorname{sgn}(\tau)\tau\alpha\right)\otimes\beta\right]\\
&= \frac{1}{(k+l)!}\sum_{\sigma\in S_{k+l}}\operatorname{sgn}(\sigma)\sigma\left[\frac{1}{k!}\sum_{\tau\in S_k}\operatorname{sgn}(\tau)(\tau\alpha)\otimes\beta\right]\\
&= \frac{1}{(k+l)!}\sum_{\sigma\in S_{k+l}}\operatorname{sgn}(\sigma)\sigma\left[\frac{1}{k!}\sum_{\tau\in S_k}\operatorname{sgn}(\tau)\tau(\alpha\otimes\beta)\right]\\
&= \frac{1}{k!(k+l)!}\sum_{\sigma\in S_{k+l}}\sum_{\tau\in S_k}\operatorname{sgn}(\sigma\tau)\sigma\tau(\alpha\otimes\beta)\\
&= \frac{k!}{k!(k+l)!}\sum_{\mu\in S_{k+l}}\operatorname{sgn}(\mu)\mu(\alpha\otimes\beta)\\
&= \frac{1}{(k+l)!}\sum_{\mu\in S_{k+l}}\operatorname{sgn}(\mu)\mu(\alpha\otimes\beta)\\
&= A(\alpha\otimes\beta)
\end{aligned}
$$

(2) Similar to (1).

$\square$

Exercise 3.2.13. The exterior product $\wedge : \Lambda_k(V)\times\Lambda_l(V)\to\Lambda_{k+l}(V)$ is associative.

Proof. Let $\alpha \in \Lambda_k(V)$, $\beta \in \Lambda_l(V)$ and $\gamma \in \Lambda_m(V)$. Then

$$\begin{aligned}
(\alpha \wedge \beta) \wedge \gamma &= \left[\frac{(k+l)!}{k!l!} A(\alpha \otimes \beta)\right] \wedge \gamma \\
&= \frac{(k+l+m)!}{(k+l)!m!} A\left(\left[\frac{(k+l)!}{k!l!} A(\alpha \otimes \beta)\right] \otimes \gamma\right) \\
&= \frac{(k+l+m)!}{(k+l)!m!} \frac{(k+l)!}{k!l!} A(A(\alpha \otimes \beta) \otimes \gamma) \\
&= \frac{(k+l+m)!}{m!} \frac{1}{k!l!} A((\alpha \otimes \beta) \otimes \gamma) \\
&= \frac{(k+l+m)!}{k!(l+m)!} \frac{(l+m)!}{l!m!} A(\alpha \otimes (\beta \otimes \gamma)) \\
&= \frac{(k+l+m)!}{k!(l+m)!} \frac{(l+m)!}{l!m!} A(\alpha \otimes A(\beta \otimes \gamma)) \\
&= \frac{(k+l+m)!}{k!(l+m)!} A(\alpha \otimes \frac{(l+m)!}{l!m!} A(\beta \otimes \gamma)) \\
&= \frac{(k+l+m)!}{k!(l+m)!} A(\alpha \otimes (\beta \wedge \gamma)) \\
&= \alpha \wedge (\beta \wedge \gamma))
\end{aligned}$$

□

Exercise 3.2.14. Let $\alpha_i \in \Lambda_{k_i}(V)$ for $i = 1, \cdots, m$. Then

$$\bigwedge_{i=1}^{m} \alpha_i = \frac{(\sum_{i=1}^{m} k_i)!}{\prod_{i=1}^{m} k_i!} A\left(\bigotimes_{i=1}^{m} \alpha_i\right)$$

Proof. To see that the statment is true in the case $m = 3$, the proof of the previous exercise tells us that indeed

$$\alpha_1 \wedge \alpha_2 \wedge \alpha_3 = \frac{(k_1+k_2+k_3)!}{k_1!k_2!k_3!} A(\alpha_1 \otimes \alpha_2 \otimes \alpha_3)$$

Now, suppose that the statement is true for each $3 \leq m \leq m_0$. Then the proof of the previous exercise tells us the

$$\begin{aligned}
\bigwedge_{i=1}^{m_0+1} \alpha_i &= \left(\bigwedge_{i=1}^{m_0-1} \alpha_i\right) \wedge \alpha_{m_0} \wedge \alpha_{m_0+1} \\
&= \frac{(\sum_{i=1}^{m_0-1} k_i + k_{m_0} + k_{m_0+1})!}{(\sum_{i=1}^{m_0-1} k_i)! k_{m_0}! k_{m_0+1}!} A\left(\left[\bigwedge_{i=1}^{m_0-1} \alpha_i\right] \otimes \alpha_{m_0} \otimes \alpha_{m_0+1}\right) \\
&= \frac{(\sum_{i=1}^{m_0-1} k_i + k_{m_0} + k_{m_0+1})!}{(\sum_{i=1}^{m_0-1} k_i)! k_{m_0}! k_{m_0+1}!} A\left(\left[\frac{(\sum_{i=1}^{m_0-1} k_i)!}{\prod_{i=1}^{m_0-1} k_i!} A\left(\bigotimes_{i=1}^{m_0-1} \alpha_i\right)\right] \otimes \alpha_{m_0} \otimes \alpha_{m_0+1}\right) \\
&= \frac{(\sum_{i=1}^{m_0+1} k_i)!}{\prod_{i=1}^{m_0+1} k_i!} A\left(A\left[\bigotimes_{i=1}^{m_0-1} \alpha_i\right] \otimes \alpha_{m_0} \otimes \alpha_{m_0+1}\right) \\
&= \frac{(\sum_{i=1}^{m_0+1} k_i)!}{\prod_{i=1}^{m_0+1} k_i!} A\left(\left[\bigotimes_{i=1}^{m_0-1} \alpha_i\right] \otimes \alpha_{m_0} \otimes \alpha_{m_0+1}\right) \\
&= \frac{(\sum_{i=1}^{m_0+1} k_i)!}{\prod_{i=1}^{m_0+1} k_i!} A\left(\bigotimes_{i=1}^{m_0+1} \alpha_i\right)
\end{aligned}$$

□

Exercise 3.2.15. Define $\tau \in S_{k+l}$ by

$$\tau = \begin{pmatrix} 1 & 2 & \cdots & l & l+1 & l+2 & \cdots & l+k \\ 1+k & 2+k & \cdots & l+k & 1 & 2 & \cdots & k \end{pmatrix}$$

Then the inversion number of τ is kl. (Hint: inversion number)

Proof.

$$\begin{aligned}
N(\tau) &= \sum_{i=1}^{l} k \\
&= kl
\end{aligned}$$

Since $\operatorname{sgn}(\tau) = (-1)^{N(\tau)}$ we know that $\operatorname{sgn}(\tau) = (-1)^{kl}$. □

Exercise 3.2.16. Let $\alpha \in \Lambda_k(V)$, $\beta \in \Lambda_l(V)$. Then

$$\alpha \wedge \beta = (-1)^{kl} \beta \wedge \alpha$$

Proof. Define $\tau \in S_{k+l}$ as in the previous exercise. Note that For $\sigma \in S_{k+l}$ and $v_1, \cdots, v_{k+l} \in V$, we have that

$$\begin{aligned}
\sigma\tau(\beta \otimes \alpha)(v_1, \cdots, v_l, v_{l+1}, \cdots v_{l+k}) &= \beta \otimes \alpha(v_{\sigma\tau(1)}, \cdots, v_{\sigma\tau(l)}, v_{\sigma\tau(l+1)}, \cdots v_{\sigma\tau(l+k)}) \\
&= \beta(v_{\sigma\tau(1)}, \cdots, v_{\sigma\tau(l)}) \alpha(v_{\sigma\tau(l+1)}, \cdots v_{\sigma\tau(l+k)}) \\
&= \beta(v_{\sigma(1+k)}, \cdots, v_{\sigma(l+k)}) \alpha(v_{\sigma(1)}, \cdots v_{\sigma(k)}) \\
&= \alpha(v_{\sigma(1)}, \cdots v_{\sigma(k)}) \beta(v_{\sigma(1+k)}, \cdots, v_{\sigma(l+k)}) \\
&= \alpha \otimes \beta(v_{\sigma(1)}, \cdots v_{\sigma(k)}, v_{\sigma(1+k)}, \cdots, v_{\sigma(l+k)}) \\
&= \sigma(\alpha \otimes \beta)(v_1, \cdots, v_k, v_{1+k}, \cdots v_{l+k})
\end{aligned}$$

Thus $\sigma\tau(\beta\otimes\alpha)=\sigma(\alpha\otimes\beta)$. Then

$$\begin{aligned}\beta\wedge\alpha &= \frac{(k+l)!}{k!l!}A(\beta\otimes\alpha)\\ &= \frac{(k+l)!}{k!l!}\frac{1}{(k+l)!}\sum_{\sigma\in S_{k+l}}\operatorname{sgn}(\sigma)\sigma(\beta\otimes\alpha)\\ &= \frac{(k+l)!}{k!l!}\frac{1}{(k+l)!}\sum_{\sigma\in S_{k+l}}\operatorname{sgn}(\sigma\tau)\sigma\tau(\beta\otimes\alpha)\\ &= \operatorname{sgn}(\tau)\frac{(k+l)!}{k!l!}\frac{1}{(k+l)!}\sum_{\sigma\in S_{k+l}}\operatorname{sgn}(\sigma)\sigma(\alpha\otimes\beta)\\ &= \operatorname{sgn}(\tau)\frac{(k+l)!}{k!l!}A(\alpha\otimes\beta)\\ &= \operatorname{sgn}(\tau)\alpha\wedge\beta\\ &= (-1)^{kl}\alpha\wedge\beta\end{aligned}$$

□

Exercise 3.2.17. Let $\alpha\in\Lambda_k(V)$. If k is odd, then $\alpha\wedge\alpha=0$.

Proof. Suppose that k is odd. The previous exercise tells us that

$$\begin{aligned}\alpha\wedge\alpha &= (-1)^{k^2}\alpha\wedge\alpha\\ &= -\alpha\wedge\alpha\end{aligned}$$

Thus $\alpha\wedge\alpha=0$. □

Exercise 3.2.18. Fundamental Example:
Let $\alpha_1,\cdots,\alpha_m\in\Lambda_1(V)$ and $v_1,\cdots,v_m\in V$. Then

$$\left(\bigwedge_{i=1}^m\alpha_i\right)(v_1,\cdots,v_m)=\det(\alpha_i(v_j))$$

Proof. The previous exercises tell us that

$$\begin{aligned}\left(\bigwedge_{i=1}^m\alpha_i\right)(v_1,\cdots,v_m) &= m!A\left(\bigotimes_{i=1}^m\alpha_i\right)(v_1,\cdots,v_m)\\ &= m!\left[\frac{1}{m!}\sum_{\sigma\in S_m}\operatorname{sgn}(\sigma)\sigma\left(\bigotimes_{i=1}^m\alpha_i\right)\right](v_1,\cdots,v_m)\\ &= \sum_{\sigma\in S_m}\operatorname{sgn}(\sigma)\left(\bigotimes_{i=1}^m\alpha_i\right)(v_{\sigma(1)},\cdots,v_{\sigma(m)})\\ &= \sum_{\sigma\in S_m}\operatorname{sgn}(\sigma)\prod_{i=1}^m\alpha_i(v_{\sigma(i)})\\ &= \det(\alpha_i(v_j))\end{aligned}$$

□

Note 3.2.19. Recall that $\mathcal{I}_{\wedge k} = \{(i_1, i_2, \cdots, i_k) \in \mathbb{N}^k : i_1 < i_2 < \cdots < i_k \leq n\}$ and that $\#\mathcal{I}_{\wedge k} = \binom{n}{k}$. For the remainder of this section, we will write $\mathcal{I}_k$ in place of $\mathcal{I}_{\wedge k}$.

Definition 3.2.20. Let $I = \{(i_1, i_2, \cdots, i_k) \in \mathcal{I}_k$.
Define $\epsilon^{\wedge I} \in \Lambda_k(V)$ by

$$\epsilon^{\wedge I} = \epsilon^{i_1} \wedge \cdots \wedge \epsilon^{i_k}$$

Exercise 3.2.21. Let $I = (i_1, \cdots, i_k)$ and $J = (j_1, \cdots, j_k) \in \mathcal{I}_k$. Then $\epsilon^{\wedge I}(e^J) = \delta_{I,J}$.

Proof. Put $A = \begin{pmatrix} \epsilon^{i_1}(e^{j_1}) & \cdots & \epsilon^{i_1}(e^{j_k}) \\ & \vdots & \\ \epsilon^{i_k}(e^{j_1}) & \cdots & \epsilon^{i_k}(e^{j_k}) \end{pmatrix}$. A previous exercise tells us that $\epsilon^{\wedge I}(e^J) = \det A$. If $I = J$, then $A = I_{k \times k}$ and therefore $\epsilon^I(e^J) = 1$. Suppose that $I \neq J$. Put $l_0 = \min\{l : 1 \leq l \leq k, i_l \neq j_l\}$. If $i_{l_0} < j_{l_0}$, then all entries on the $l_0 th$ row of A are 0. If $i_{l_0} > j_{l_0}$, then all entries on the $l_0 th$ column of A are 0. $\square$

Exercise 3.2.22. Let $\alpha, \beta \in \Lambda_k(V)$. If for each $I \in \mathcal{I}_k$, $\alpha(e^I) = \beta(e^I)$, then $\alpha = \beta$.

Proof. Suppose that for each $I \in \mathcal{I}_k$, $\alpha(e^I) = \beta(e^I)$. Let $v_1, \cdots, v_k \in V$. For $i = 1, \cdots, k$, write $v_i = \sum_{j_i=1}^n a_{i,j_i} e^{j_i}$. Then

$$\begin{aligned}
\alpha(v_1, \cdots, v_k) &= \sum_{j_1, \cdots, j_k=1}^{n} \left(\prod_{i=1}^{k} a_{i,j_i}\right) \alpha(e^{j_1}, \cdots, e^{j_k}) \\
&= \sum_{j_1 \neq \cdots \neq j_k}^{n} \left(\prod_{i=1}^{k} a_{i,j_i}\right) \alpha(e^{j_1}, \cdots, e^{j_k}) \\
&= \sum_{J \in \mathcal{I}_k} \left[\sum_{\sigma \in S_J} \operatorname{sgn}(\sigma) \left(\prod_{i=1}^{k} a_{i,\sigma(j_i)}\right)\right] \alpha(e^J) \\
&= \sum_{J \in \mathcal{I}_k} \left[\sum_{\sigma \in S_J} \operatorname{sgn}(\sigma) \left(\prod_{i=1}^{k} a_{i,\sigma(j_i)}\right)\right] \beta(e^J) \\
&= \sum_{j_1, \cdots, j_k=1}^{n} \left(\prod_{i=1}^{k} a_{i,j_i}\right) \beta(e^{j_1}, \cdots, e^{j_k}) \\
&= \beta(v_1, \cdots, v_k)
\end{aligned}$$

$\square$

Exercise 3.2.23. The set $\{\epsilon^{\wedge I} : I \in \mathcal{I}_k\}$ is a basis for $\Lambda_k(V)$ and $\dim \Lambda_k(V) = \binom{n}{k}$.

Proof. Let $(a_I)_{I \in \mathcal{I}_k} \subset \mathbb{R}$. Let $\alpha = \sum_{I \in \mathcal{I}_k} a_I \epsilon^{\wedge I}$. Suppose that $\alpha = 0$. Then for each $J \in \mathcal{I}_k$, $\alpha(e^J) = a_J = 0$. Thus $\{\epsilon^{\wedge I} : I \in \mathcal{I}_k\}$ is linearly independent. Let $\beta \in \Lambda_k(V)$. For $I \in \mathcal{I}_k$, put $b_I = \beta(e^I)$. Define $\mu = \sum_{I \in \mathcal{I}_k} b_I \epsilon^{\wedge I} \in \Lambda_k(V)$. Then for each $J \in \mathcal{I}_k$, $\mu(e^J) = b_J = \beta(e^J)$. Hence $\mu = \beta$ and therefore $\beta \in \operatorname{span}\{\epsilon^{\wedge I} : I \in \mathcal{I}_k\}$. $\square$

4. Manifolds

4.1. Smooth Manifolds.

Definition 4.1.1. Define the **upper half space** of $\mathbb{R}^n$, denoted $\mathbb{H}_n$, by

$$\mathbb{H}_n = \{(x_1, x_2, \cdots, x_n) \in \mathbb{R}^n : x_n \geq 0\}$$

and define

$$\partial\mathbb{H}_n = \{(x_1, x_2, \cdots, x_n) \in \mathbb{R}^n : x_n = 0\}$$
$$(\mathbb{H}^n)^\circ = \{(x_1, x_2, \cdots, x_n) \in \mathbb{R}^n : x_n > 0\}$$

Definition 4.1.2. Let M be a topological space and $n \geq 1$.

(1) Let $U \subset M$ and $V \subset \mathbb{H}^n$ be open and $\phi : U \to V$. Then (U, ϕ) is said to be a **coordinate chart** on M if ϕ is a homeomorphism.
(2) Let $\mathcal{A}$ be a collection of coordinate charts on M. Then $\mathcal{A}$ is said to be an **atlas** on M if $\bigcup_{(U,\phi)\in\mathcal{A}} U = M$.
(3) The space M is said to be **locally half Euclidean of dimension** n if there exists an atlas $\mathcal{A}$ on M such that for each $(U, \phi) \in \mathcal{A}$, $\phi(U) \subset \mathbb{H}^n$.
(4) The space M is said to be an **n-dimensional manifold** if M is Hausdorff, second countable and locally half Euclidean of dimension n.

Note 4.1.3. For the remainder of this section, we assume M is an n-dimensional manifold.

Definition 4.1.4.

(1) Define the **boundary** of M, denoted ∂M, by
$$\partial M = \{p \in M : \text{ there exists a chart } (U, \phi) \text{ on } M \text{ such that } p \in U \text{ and } \phi(p) \in \partial\mathbb{H}^n\}$$
(2) Define the **interior** of M, denoted M°, by
$$M^\circ = M \setminus \partial M$$

Exercise 4.1.5. Let $p \in M$. Then $p \in \partial M$ iff for each chart (U, ϕ) on M, $p \in U$ implies that $\phi(p) \in \partial\mathbb{H}^n$. (Hint: simply connected)

Proof. Suppose that $p \in \partial M$. Then there exists a coordinate chart (V, ψ) on M such that $\psi(p) \in \partial\mathbb{H}^n$. Let (U, ϕ) be a coordinate chart on M. Suppose that $p \in U$. Note that $\phi \circ \psi^{-1} : \psi(V \cap U) \to \phi(V \cap U)$ is a homeomorphism. Choose open n-balls B_ϕ, $B_\psi \subset \mathbb{H}^n$ such that $B_\phi \subset \phi(V \cap U)$, $B_\psi \subset \psi(V \cap U)$, $\phi(p) \in B_\phi$ and $\psi(p) \in B_\psi$. For the sake of contradiction, suppose that $\phi(p) \notin \partial\mathbb{H}^n$. Put $U' = B_\phi \setminus \{\phi(p)\}$ and $V' = B_\psi \setminus \{\psi(p)\}$. Define $\lambda : V' \to U'$ by $\lambda = \phi \circ \psi|_{B_\psi}$. Then λ is a homeomorphism. Note that V' is simply connected and U' is not. This is a contradiction. □

Exercise 4.1.6. If $\partial M \neq \varnothing$, then

(1) ∂M is an $n-1$-dimensional manifold
(2) $\partial(\partial M) = \varnothing$.

Proof.

(1) Since subspaces of Hausdorff, second countable spaces are Hausdorff and second countable, we need only show that ∂M is locally half euclidean of dimension $n-1$. Let $p \in \partial M$. Then there exists a coordinate chart (U, ϕ) on M such that $p \in U$ and $\phi(p) \in \partial\mathbb{H}^n$.

Put $U' = U \cap \partial M$. Note that U' is open in ∂M and $\phi(U) \cap \partial \mathbb{H}^n$ is open in $\partial \mathbb{H}^n$.
Define $\phi' : U' \to \phi(U) \cap \partial \mathbb{H}^n$ by $\phi' = \phi|_{U'}$. Then ϕ' is a homeomorphism.
Since $\partial \mathbb{H}^n$ is homeomorphic to $\mathbb{R}^{n-1}$ which is homeomorphic to $(\mathbb{H}^{n-1})^\circ$ there exists $\psi : \partial \mathbb{H}^n \to (\mathbb{H}^{n-1})^\circ$ such that ψ is a homeomorphism.
Define $V' = \psi(\phi(U) \cap \partial \mathbb{H}^n)$ and $\psi' : \phi(U) \cap \partial \mathbb{H}^n \to V'$ by and $\psi' = \psi|_{\phi(U) \cap \partial \mathbb{H}^n}$. Then V' is open in $(\mathbb{H}^{n-1})^\circ$ and ψ' is a homeomrophism.
Define $\lambda : U' \to V'$ by $\lambda = \psi' \circ \phi'$. Then λ is a homeomorhism and (U', λ) is a cooridnate chart on ∂M. So ∂M is locally Euclidean of dimension $n-1$.

(2) Let $p \in \partial M$. Define $(U \cap \partial M, \lambda \circ \psi)$ as in (1). Since $\lambda \circ \psi(p) \in (\mathbb{H}^{n-1})^\circ$, we have that $p \in M^\circ$. Thus $\partial M = (\partial M)^\circ$ and $\partial(\partial M) = \varnothing$.

□

Theorem 4.1.7. Let $(M, \mathcal{A})$ be an m-dimensional manifold, $(N, \mathcal{B})$ a n-dimensional manifold and $F : M \to N$. If F is a homeomorphism, then $m = n$.

Definition 4.1.8.

(1) Let $(U, \phi), (V, \psi)$ be coordinate charts on M. Then (U, ϕ) and (V, ψ) are said to be **smoothly compatible** if
$$\phi \circ \psi^{-1} : \psi(U \cap V) \to \phi(U \cap V) \text{ is a diffeomorphism}$$
(2) Let $\mathcal{A} = ((U_a, \phi_a))_{a \in A}$ be an atlas on M. Then $\mathcal{A}$ is said to be **smooth** if for each $a, b \in A$, (U_a, ϕ_a) and (U_b, ϕ_b) are smoothly compatible.
(3) Let $\mathcal{A}$ be a smooth atlas on M. Then $\mathcal{A}$ is said to be **maximal** if for each smooth atlas $\mathcal{B}$ on M, $\mathcal{A} \subset \mathcal{B}$ implies that $\mathcal{A} = \mathcal{B}$. A maximal smooth atlas on M is called a **smooth structure on** M.
(4) Let $\mathcal{A}$ be a smooth structure on M. Then $(M, \mathcal{A})$ is said to be a **smooth** n**-dimensional manifold**.

Exercise 4.1.9. Let $\mathcal{B}$ be a smooth atlas on M. Then there exists a unique smooth structure $\mathcal{A}$ on M such that $\mathcal{B} \subset \mathcal{A}$.

Proof. Define $\mathcal{A}$ to be the set of all coordinate charts (U, ϕ) on M such that for each coordinate chart $(V, \psi) \in \mathcal{B}$, (U, ϕ) and (V, ψ) are smoothly compatible.
Clearly $\mathcal{B} \subset \mathcal{A}$.
Let $(U, \phi), (V, \psi) \in \mathcal{A}$ and $p \in U \cap V$. Then there exists $(W, \chi) \in \mathcal{B}$ such that $p \in W$. By assumption, $\phi \circ \chi^{-1} : \chi(U \cap W) \to \phi(U \cap W)$ and $\chi \circ \psi^{-1} : \psi(W \cap V) \to \chi(W \cap V)$ are diffeomorphisms. Then $(\phi \circ \chi^{-1}) \circ (\chi \circ \psi^{-1}) = \phi \circ \psi^{-1} : \psi(U \cap W \cap V) \to \phi(U \cap W \cap V)$ is a diffeomorphism. Since for each $q \in \psi(U \cap V)$, there exits an open neighborhood $N \subset \psi(U \cap V)$ of q on which $\phi \circ \psi^{-1}$ are diffeomorphic, we have that $\phi \circ \psi^{-1}$ is a diffeomorphism on $\psi(U \cap V)$ and therefore (U, ϕ) and (V, ψ) are smoothly compatible. Hence $\mathcal{A}$ is a smooth atlas.
To see that $\mathcal{A}$ is maximal, let $\mathcal{B}'$ be a smooth atlas on M. Suppose that $\mathcal{A} \subset \mathcal{B}'$ and let $(U, \phi) \in \mathcal{B}'$. By definition, for each chart $(V, \psi) \in \mathcal{B}'$, (U, ϕ) and (V, ψ) are smoothly compatible. Since $\mathcal{B} \subset \mathcal{A} \subset \mathcal{B}'$, we have that $(U, \phi) \in \mathcal{A}$. So $\mathcal{A} = \mathcal{B}'$ and $\mathcal{A}$ is a maximal smooth atlas on M. □

Exercise 4.1.10. Let $\mathcal{A}$ be a smooth atlas on M. Define $\lambda : \partial \mathbb{H}^n \to \mathbb{R}^{n-1}$ by $\lambda(x_1, \cdots, x_{n-1}, 0) = (x_1, \cdots, x_{n-1})$. Put $\mathcal{A}|_{\partial M} = \{(U \cap \partial M, \lambda \circ \phi_{U \cap \partial M}) : (U, \phi) \in \mathcal{A}\}$. Then

(1) $\mathcal{A}|_{\partial M}$ is a smooth atlas on ∂M.
(2) if $\mathcal{A}$ is maximal, then $\mathcal{A}|_{\partial M}$ is maximal.

Proof. □

Note 4.1.11. For the rest of this section, we assume that $(M, \mathcal{A})$ is a smooth n-dimensional manifold and we denote the standard coordinate functions on $\mathbb{R}^n$ by $u^1, \cdots, u^n$. For a coordinate chart $(U, \phi) \in \mathcal{A}$ and $i \in \{1, \cdots, n\}$, we will typically denote the ith coordinate of ϕ by x^i, that is, $x^i = u^i(\phi)$.

4.2. **Smooth Maps.**

Definition 4.2.1. Let $f : M \to \mathbb{R}$. Then f is said to be smooth if for each coordinate chart $(U, \phi) \in \mathcal{A}$, $f \circ \phi^{-1}$ is smooth. The set of all smooth functions on M is denoted $C^\infty(M)$.

Exercise 4.2.2. We have that $C^\infty(M)$ is a vector space.

Proof. Clear. $\square$

Definition 4.2.3. Let $(N, \mathcal{B})$ be a smooth manifold and $F : M \to N$. Then F is said to be

- **smooth** if for each $(U, \phi) \in \mathcal{A}$ and $(V, \psi) \in \mathcal{B}$,
$$\psi \circ F \circ \phi^{-1} : \phi(U \cap F^{-1}(V)) \to \psi(F(U) \cap V)$$
is smooth
- a **diffeomorphism** if F is a bijection and F, F^{-1} are smooth.

Exercise 4.2.4. Let $(M, \mathcal{A})$ and $(N, \mathcal{B})$ be smooth manifold and $F : M \to N$. If F is smooth, then F is continuous.

Proof. Suppose that F is smooth. Let $p \in M$. Choose $(U, \phi) \in \mathcal{A}$ and $(V, \psi) \in \mathcal{B}$ such that $p \in U$ and $F(p) \in V$. Put $\tilde{U} = U \cap F^{-1}(V)$ and $\tilde{V} = F(U) \cap V$.
Define $\tilde{\phi} : \tilde{U} \to \phi(\tilde{U})$ and $\tilde{\psi} : \tilde{V} \to \psi(\tilde{V})$ by
$$\tilde{\phi} = \phi|_{\tilde{U}}, \ \ \tilde{\phi} = \psi|_{\tilde{V}}$$
Then $\tilde{\phi}$ and $\tilde{\psi}$ are homeomorphisms, $p \in \tilde{U}$ and $F(\tilde{U}) \subset \tilde{V}$. Define $\tilde{F} : \phi(\tilde{U}) \to \psi(\tilde{V})$ by
$$\tilde{F} = \tilde{\psi} \circ F \circ \tilde{\phi}^{-1}$$
By definition, $\tilde{F}$ is smooth and therefore continuous. Since ϕ and ψ are homeomorphisms and $F|_{\tilde{U}} = \tilde{\psi}^{-1} \circ \tilde{F} \circ \tilde{\phi}$, we have that $F|_{\tilde{U}}$ is continuous. In particular, F is continuous at p and since $p \in M$ is arbitrary, F is continuous. $\square$

Exercise 4.2.5. Let $(M, \mathcal{A})$ and $(N, \mathcal{B})$ be smooth manifold and $F : M \to N$. If F is a diffeomorphism, then F is a homeomorphism.

Proof. Suppose that F is a diffeomorphism. By definition, F and F^{-1} are smooth. The previous exercise implies that F and F^{-1} are continuous. Hence F is a homeomorphism. $\square$

Exercise 4.2.6. Let $(N, \mathcal{B})$ be a smooth manifold and $F : M \to N$ a diffeomorphism. Then for each $(U, \phi) \in \mathcal{A}$, $(F(U), \phi \circ F^{-1}) \in \mathcal{B}$.

Proof. Let $(V, \psi) \in \mathcal{B}$.

(1) Since ϕ and F^{-1} are homeomorphisms, $\phi \circ F^{-1} : F(U) \cap V \to \phi(U \cap F^{-1}(V))$ is a homeomorphism
(2) Since F is a diffeomorphism,
$$\phi \circ F^{-1} \circ \psi^{-1} : \psi(F(U) \cap V) \to \phi(U \cap F^{-1}(V))$$
and
$$\psi \circ F \circ \phi^{-1} : \phi(F^{-1}(V) \cap U) \to \psi(V \cap F(U))$$
are smooth.

Therefore $(F(U), \phi \circ F^{-1})$ and (V, ψ) are smoothly compatible. Since $\mathcal{B}$ is maximal, $(F(U), \phi \circ F^{-1}) \in \mathcal{B}$. $\square$

Definition 4.2.7. Let $(N, \mathcal{B})$ be a smooth n-dimensional manifold, $F : M \to N$ smooth and $(V, \psi) \in \mathcal{B}$ with $\psi = (y^1, \dots, y^n)$. For $i \in \{1, \dots, n\}$, We define the ***i*-th component of F with respect to** (V, ψ), denoted $F^i : V \to \mathbb{R}$, by

$$F^i = y^i \circ F$$

4.3. Partitions of Unity.

Definition 4.3.1. Let $p \in M$, $U \in \mathcal{N}_a$ open and $\rho \in C_c^\infty(M)$. Then ρ is said to be a **bump function at p supported in** U if

(1) $\rho \geq 0$
(2) there exists $V \in \mathcal{N}_p$ such that V is open and $\rho|_V = 1$
(3) $\operatorname{supp} \rho \subset U$

Exercise 4.3.2. Define $f : \mathbb{R} \to \mathbb{R}$ by

$$f(t) = \begin{cases} e^{-\frac{1}{1-t^2}} & t \in (-1,1) \\ 0 & t \notin (-1,1) \end{cases}$$

Then $f \in C_c^\infty(\mathbb{R})$.

Proof. □

4.4. **The Tangent Space.**

Definition 4.4.1. Let $p \in M$. Define the relation $\sim_p$ on $C^\infty(M)$ by $f \sim_p g$ iff there exists $U \in \mathcal{N}_p$ such that U is open and $f|_U = g|_U$. Clearly $\sim_p$ is an equivalence relation on $C^\infty(M)$. We denote $C^\infty(M)/\sim_p$ by $C^\infty_p(M)$. For $f \in C^\infty(M)$, we define the **germ of f at** p to be the equivalence class of f under $\sim_p$.

Exercise 4.4.2. Let $p \in$We have that $C^\infty_p(M)$ is a vector space.

Proof. Clear. □

Definition 4.4.3. Let $(U, \phi) \in \mathcal{A}$ with $\phi = (x^1, \cdots, x^n)$, $p \in U$ and $f \in C^\infty_p(M)$. For $i \in \{1, \cdots, n\}$, define the partial derivative of f with respect to x^i at p, denoted

$$\frac{\partial f}{\partial x^i}(p), \ \ \frac{\partial}{\partial x^i}\bigg|_p f, \ \partial_{x^i} f(p) \text{ or } \partial_{x^i}|_p f$$

by

$$\frac{\partial}{\partial x^i}\bigg|_p f = \frac{\partial}{\partial u^i}\bigg|_{\phi(p)} f \circ \phi^{-1}$$

Exercise 4.4.4. Let $(U, \phi) \in \mathcal{A}$ with $\phi = (x^1, \cdots, x^n)$ and $p \in U$. Then for each $i, j \in \{1, \cdots, n\}$, we have that

$$\frac{\partial x^i}{\partial x^j}(p) = \delta_{i,j}$$

Proof. Let $i, j \in \{1, \cdots, n\}$. Then

$$\begin{aligned}
\frac{\partial}{\partial x^j}\bigg|_p x^i &= \frac{\partial}{\partial u^j}\bigg|_{\phi(p)} x^i \circ \phi^{-1} \\
&= \frac{\partial}{\partial u^j}\bigg|_{\phi(p)} u^i \circ \phi \circ \phi^{-1} \\
&= \frac{\partial}{\partial u^j}\bigg|_{\phi(p)} u^i \\
&= \delta_{i,j}
\end{aligned}$$

□

Exercise 4.4.5. Change of Coordinates:
Let $(U, \phi), (V, \psi) \in \mathcal{A}$ with $\phi = (x^1, \cdots, x^n)$ and $\psi = (y^1, \cdots, y^n)$, $p \in U \cap V$ and $f \in C^\infty_p(M)$. Then for each $i \in \{1, \cdots, n\}$, we have

$$\frac{\partial f}{\partial y^i}(p) = \sum_{j=1}^n \frac{\partial f}{\partial x^j}(p) \frac{\partial x^j}{\partial y^i}(p)$$

Proof. Put $h = \phi \circ \psi^{-1}$ and write $h = (h_1, \cdots, h_n)$. Then $\phi = h \circ \psi$ and $\psi^{-1} = \phi^{-1} \circ h$. By definition and the chain rule, we have that

$$\begin{aligned}
\frac{\partial}{\partial y^i}\bigg|_p f &= \frac{\partial}{\partial u^i}\bigg|_{\psi(p)} f \circ \psi^{-1} \\
&= \frac{\partial}{\partial u^i}\bigg|_{\psi(p)} f \circ \phi^{-1} \circ h \\
&= \sum_{j=1}^n \left(\frac{\partial}{\partial u^j}\bigg|_{h\circ\psi(p)} f \circ \phi^{-1} \right) \left(\frac{\partial}{\partial u^i}\bigg|_{\psi(p)} h_j \right) \\
&= \sum_{j=1}^n \left(\frac{\partial}{\partial u^j}\bigg|_{\phi(p)} f \circ \phi^{-1} \right) \left(\frac{\partial}{\partial u^i}\bigg|_{\psi(p)} x^j \circ \psi^{-1} \right) \\
&= \sum_{j=1}^n \left(\frac{\partial}{\partial x^j}\bigg|_p f \right) \left(\frac{\partial}{\partial y^i}\bigg|_p x^j \right)
\end{aligned}$$

□

Exercise 4.4.6. Taylor's Theorem:
Let $(U, \phi) \in \mathcal{A}$ with $\phi = (x^1, \cdots, x^n)$, $p \in U$ and $f \in C_p^\infty(M)$. Then there exist $g_1, \cdots g_n \in C_p^\infty(M)$ such that

$$f = f(p) + \sum_{i=1}^n (x^i - x^i(p)) g_i$$

and for each $i \in \{1, \cdots, n\}$,

$$g_i(p) = \frac{\partial}{\partial x^i}\bigg|_p f$$

Proof. Since we are interested in the germ of f at p, we may assume that $\phi(U)$ is star-shaped with respect to $\phi(p)$. Let $q \in U$. From Taylor's theorem in section 1, we know that there exist $\tilde{g}_1, \cdots, \tilde{g}_n \in C^\infty(\phi(U))$ such that for each $q \in U$,

$$f \circ \phi^{-1}(\phi(q)) = f \circ \phi^{-1}(\phi(p)) + \sum_{i=1}^n [u^i \circ \phi(q) - u^i \circ \phi(p)] \tilde{g}_i(\phi(q))$$

and for each $i \in \{1, \cdots, n\}$,

$$\tilde{g}_i(\phi(p)) = \frac{\partial}{\partial u^i}\bigg|_{\phi(p)} f \circ \phi^{-1}$$

For each $i \in \{1, \cdots, n\}$, define $g_i = \tilde{g}_i \circ \phi$. Then for each $q \in U$,

$$f(q) = f(p) + \sum_{i=1}^n [x^i(q) - x^i(p)] g_i(q)$$

and for each $i \in \{1, \cdots, n\}$,

$$g_i(p) = \frac{\partial}{\partial x^i}\bigg|_p f$$

□

Definition 4.4.7. Let $p \in M$ and $v : C_p^\infty(M) \to \mathbb{R}$. Then v is said to be **Leibnizian** if for each $f, g \in C_p^\infty(M)$,

$$v(fg) = v(f)g(p) + f(p)v(g)$$

and v is said to be a **derivation at** p if for each $f, g \in C_p^\infty(M)$ and $a \in \mathbb{R}$,

(1) v is linear
(2) v is Leibnizian

We define the **tangent space of** M **at** p, denoted T_pM, by

$$T_pM = \{v : C_p^\infty(M) \to \mathbb{R} : v \text{ is a derivation at } p\}$$

Exercise 4.4.8. Let $f \in C_p^\infty(M)$ and $v \in T_pM$. If f is constant, then $vf = 0$.

Proof. Suppose that $f = 1$. Then $f^2 = f$ and $v(f^2) = 2v(f)$. So $v(f) = 2v(f)$ which implies that $v(f) = 0$. If $f \neq 1$, then there exists $c \in \mathbb{R}$ such that $f = c$. Since v is linear, $v(f) = cv(1) = 0$. □

Exercise 4.4.9. Let $(U, \phi) \in \mathcal{A}$ with $\phi = (x^1, \cdots, x^n)$ and $p \in U$. Then

$$\left\{ \frac{\partial}{\partial x^1}\bigg|_p, \cdots, \frac{\partial}{\partial x^n}\bigg|_p \right\}$$

is a basis for T_pM and $\dim T_pM = n$.

Proof. Clearly $\frac{\partial}{\partial x^1}\big|_p, \cdots, \frac{\partial}{\partial x^n}\big|_p \in T_pM$. Let $a_1, \cdots, a_n \in \mathbb{R}$. Suppose that

$$v = \sum_{i=1}^n a_i \frac{\partial}{\partial x^i}\bigg|_p = 0$$

Then

$$\begin{aligned} 0 &= vx^j \\ &= \sum_{i=1}^n a_i \frac{\partial}{\partial x^i}\bigg|_p x^j \\ &= a_j \end{aligned}$$

Hence $\left\{ \frac{\partial}{\partial x^1}\big|_p, \cdots, \frac{\partial}{\partial x^n}\big|_p \right\}$ is independent.
Now, let $v \in T_pM$ and $f \in \mathbb{C}_p^\infty(M)$. By Taylor's theorem, there exist $g_1, \cdots g_n \in C_p^\infty(M)$ such that

$$f = f(p) + \sum_{i=1}^n (x^i - x^i(p))g_i$$

and for each $i \in \{1, \cdots, n\}$,

$$g_i(p) = \frac{\partial}{\partial x^i}\bigg|_p f$$

Then

$$\begin{aligned} v(f) &= \sum_{i=1}^{n} v(x^i - x^i(p))g_i(p) + \sum_{i=1}^{n}(x^i(p) - x^i(p))v(g_i) \\ &= \sum_{i=1}^{n} v(x^i)g_i(p) \\ &= \sum_{i=1}^{n} v(x^i) \left.\frac{\partial}{\partial x^i}\right|_p f \\ &= \left[\sum_{i=1}^{n} v(x^i) \left.\frac{\partial}{\partial x^i}\right|_p\right] f \end{aligned}$$

So

$$v = \sum_{i=1}^{n} v(x^i) \left.\frac{\partial}{\partial x^i}\right|_p$$

and

$$v \in \operatorname{span}\left\{ \left.\frac{\partial}{\partial x^1}\right|_p, \cdots, \left.\frac{\partial}{\partial x^n}\right|_p \right\}$$

□

Definition 4.4.10. Let $(N, \mathcal{B})$ be a smooth manifold, $F : M \to N$ smooth and $p \in M$. We define the **differential of** F **at** p, denoted $dF_p : T_pM \to T_{F(p)}N$, by

$$\Big[dF_p(v)\Big](f) = v(f \circ F)$$

for $v \in T_pM$ and $f \in C^\infty_{F(p)}(N)$.

Exercise 4.4.11. Let $(N, \mathcal{B})$ be a smooth manifold, $F : M \to N$ smooth and $p \in M$. Then dF_p is well defined.

Proof. Let $v \in T_pM$, $f, g \in C^\infty_{F(p)}(N)$ and $c \in \mathbb{R}$. Then

(1)

$$\begin{aligned} dF_p(v)(f + cg) &= v((f + cg) \circ F) \\ &= v(f \circ F + cg \circ F) \\ &= v(f \circ F) + cv(g \circ F) \\ &= dF_p(v)(f) + cdF_p(v)(g) \end{aligned}$$

So $dF_p(v)$ is linear.

(2)

$$\begin{aligned} dF_p(v)(fg) &= v(fg \circ F) \\ &= v((f \circ F) * (g \circ F)) \\ &= v(f \circ F) * (g \circ F)(p) + (f \circ F)(p) * v(g \circ F) \\ &= dF_p(v)(f) * g(F(p)) + f(F(p)) * dF_p(v)(g) \end{aligned}$$

So $dF_p(v)$ is Leibnizian and hence $dF_p(v) \in T_{F(p)}N$ $\square$

Exercise 4.4.12. Let $(N, \mathcal{B})$ be a smooth manifold, $F : M \to N$ smooth and $p \in M$. If F is a diffeomorphism, then dF_p is an isomorphism.

Proof. Suppose that F is a diffeomorphism. Since F is a homeomorphism, $\dim N = n$. Choose $(U, \phi) \in \mathcal{A}$ such that $p \in U$. A previous exercise tells us that $(F(U), \phi \circ F^{-1}) \in \mathcal{B}$. Write $\phi = (x^1, \cdots, x^n)$ and $\phi \circ F^{-1} = (y^1, \cdots, y^n)$. Let $f \in C^\infty_{F(p)}(N)$ Then

$$\begin{aligned} \frac{\partial}{\partial y^i}\bigg|_{F(p)} f &= \frac{\partial}{\partial u^i}\bigg|_{\phi\circ F^{-1}(F(p))} f \circ (\phi \circ F^{-1})^{-1} \\ &= \frac{\partial}{\partial u^i}\bigg|_{\phi(p)} f \circ F \circ \phi^{-1} \\ &= \frac{\partial}{\partial x^i}\bigg|_{p} f \circ F \end{aligned}$$

Therefore

$$\begin{aligned} \left[dF_p\left(\frac{\partial}{\partial x^i}\bigg|_p\right)\right](f) &= \frac{\partial}{\partial x^i}\bigg|_{p} f \circ F \\ &= \frac{\partial}{\partial y^i}\bigg|_{F(p)} f \end{aligned}$$

Hence

$$dF_p\left(\frac{\partial}{\partial x^i}\bigg|_p\right) = \frac{\partial}{\partial y^i}\bigg|_{F(p)}$$

Since $\left\{ \frac{\partial}{\partial x^1}\Big|_p, \cdots, \frac{\partial}{\partial x^n}\Big|_p \right\}$ is a basis for T_pM and $\left\{ \frac{\partial}{\partial y^1}\Big|_{F(p)}, \cdots, \frac{\partial}{\partial y^n}\Big|_{F(p)} \right\}$ is a basis for $T_{F(p)}N$, dF_p is an isomorphism. $\square$

Exercise 4.4.13. Let $(N, \mathcal{B})$ be a smooth manifold, $F : M \to N$ smooth, $(U, \phi) \in \mathcal{A}$ with $\phi = (x^1, \ldots, x^m)$, $(V, \psi) \in \mathcal{B}$ with $\psi = (y^1, \ldots, y^n)$ and $p \in U$. Define the ordered bases $B_\phi = \left\{ \frac{\partial}{\partial x^1}\Big|_p, \cdots, \frac{\partial}{\partial x^m}\Big|_p \right\}$ and $B_\psi = \left\{ \frac{\partial}{\partial y^1}\Big|_{F(p)}, \cdots, \frac{\partial}{\partial y^n}\Big|_{F(p)} \right\}$. Then the matrix representation of dF_p with respect to the bases B_ϕ and B_ψ is

$$dF_p^{i,j} = \frac{\partial F^i}{\partial x^j}(p)$$

Proof. Let $(dF_p)_{B_\phi, B_\psi} = (a_{i,j})_{i,j} \in \mathbb{R}^{m\times n}$. Then for each $j \in \{1, \ldots, m\}$,

$$dF_p\left(\frac{\partial}{\partial x^j}\bigg|_p\right) = \sum_{i=1}^{n} a_{i,j} \frac{\partial}{\partial y^i}\bigg|_{F(p)}$$

This implies that

$$\begin{aligned} dF_p\left(\frac{\partial}{\partial x^j}\bigg|_p \right)(y^k) &= \sum_{i=1}^{n} a_{i,j} \; \frac{\partial}{\partial y^i}\bigg|_{F(p)} (y^k) \\ &= \sum_{i=1}^{n} a_{i,j}\delta_{i,k} \\ &= a_{k,j} \end{aligned}$$

By definition,

$$\begin{aligned} dF_p\left(\frac{\partial}{\partial x^j}\bigg|_p \right)(y^k) &= \frac{\partial}{\partial x^j}\bigg|_p y^k \circ F \\ &= \frac{\partial}{\partial x^j}\bigg|_p F^k \\ &= \frac{\partial F^k}{\partial x^j}(p) \end{aligned}$$

$\square$

Definition 4.4.14. Let $(N, \mathcal{B})$ be a smooth manifold, $F : M \to N$ a diffeomorphism. Define the **push forward of** F, denoted

$$F_* : M \to \coprod_{p \in M} \text{Iso}(T_p M, T_{F(p)} N)$$

by

$$p \mapsto dF_p$$

4.5. **The Cotangent Space.**

Definition 4.5.1. Let $p \in M$. We define the **cotangent space of** M **at** p, denoted T_p^*M, by

$$T_p^*M = (T_pM)^*$$

Definition 4.5.2. Let $f \in C^\infty(M)$. We define the **differential of** f **at** p, denoted $df_p : T_pM \to \mathbb{R}$, by

$$df_p(v) = vf$$

Exercise 4.5.3. Let $f \in C^\infty(M)$ and $p \in M$. Then $df_p \in T_p^*M$.

Proof. Let $v_1, v_2 \in T_pM$ and $\lambda \in \mathbb{R}$. Then

$$\begin{aligned} df_p(v_1 + \lambda v_2) &= (v_1 + \lambda v_2)f \\ &= v_1 f + \lambda v_2 f \\ &= df_p(v_1) + \lambda df_p(v_2) \end{aligned}$$

So that df_p is linear and hence $df_p \in T_p^*M$. □

Exercise 4.5.4. Let $(U, \phi) \in \mathcal{A}$ with $\phi = (x^1, \cdots, x^n)$ and $p \in U$. Then for each $i, j \in \{1, \cdots, n\}$,

$$dx^i_p\bigg(\frac{\partial}{\partial x^j}\bigg|_p\bigg) = \delta_{i,j}$$

In particular, $\{dx^1_p, \cdots, dx^n_p\}$ is the dual basis to $\left\{ \frac{\partial}{\partial x^1}\big|_p, \cdots, \frac{\partial}{\partial x^n}\big|_p \right\}$ and $T_p^*M = \operatorname{span}\{dx^1_p, \cdots, dx^n_p\}$.

Proof. Let $i, j \in \{1, \cdots, n\}$. Then by defintion,

$$\begin{aligned} \left[dx^i_p\bigg(\frac{\partial}{\partial x^j}\bigg|_p\bigg)\right]_p &= \frac{\partial}{\partial x^j}\bigg|_p x^i \\ &= \delta_{i,j} \end{aligned}$$

□

Exercise 4.5.5. Let $f \in C^\infty(M)$, (U, ϕ) a chart on M with $\phi = (x^1, \cdots, x^n)$ and $p \in U$. Then

$$df_p = \sum_{i=1}^n \frac{\partial f}{\partial x^i}(p) d{x^i}_p$$

Proof. Since $\{dx^1_p, \cdots, dx^n_p\}$ is a basis for T_p^*M, for each there exist $a_1(p), \cdots, a_n(p) \in \mathbb{R}$ such that $df_p = \sum\limits_{i=1}^n a_i(p) dx^i_p$. Therefore, we have that

$$\begin{aligned} df_p\bigg(\frac{\partial}{\partial x^j}\bigg|_p\bigg) &= \sum_{i=1}^n a_i(p) dx^i_p\bigg(\frac{\partial}{\partial x^j}\bigg|_p\bigg) \\ &= a_j(p) \end{aligned}$$

By definition, we have that

$$\begin{aligned} df_p\left(\frac{\partial}{\partial x^j}\bigg|_p \right) &= \frac{\partial}{\partial x^j}\bigg|_p f \\ &= \frac{\partial f}{\partial x^j}(p) \end{aligned}$$

So $a_j(p) = \frac{\partial f}{\partial x^j}(p)$ and

$$df_p = \sum_{i=1}^{n} \frac{\partial f}{\partial x^j}(p) dx_p^i$$

$\square$

4.6. **Maps of Full Rank.**

Definition 4.6.1. Let $(M, \mathcal{A})$ and $(N, \mathcal{B})$ be smooth manifolds, $F : M \to N$ a smooth map and $p \in M$. We define the **rank of F at** p, denoted $\operatorname{rank}_p F$, by $\operatorname{rank}_p F = \operatorname{rank} dF_p$. We say that F has **constant rank** if for each $p, q \in M$, $\operatorname{rank}_p F = \operatorname{rank}_q F$. If F has constant rank, we define the **rank of** F, denoted $\operatorname{rank} F$, by $\operatorname{rank} F = \operatorname{rank}_p F$.

Definition 4.6.2. Let $(M, \mathcal{A})$ and $(N, \mathcal{B})$ be smooth manifolds, $F : M \to N$ a smooth map. Then F is said to be

- an **immersion** if for each $p \in M$, $dF_p : T_pM \to T_{F(p)}N$ is injective
- a **submersion** if for each $p \in M$, $dF_p : T_pM \to T_{F(p)}N$ is surjective

Definition 4.6.3. Let $(M, \mathcal{A})$ and $(N, \mathcal{B})$ be smooth manifolds and $F : M \to N$ smooth. Then F is said to be an **embedding** if

(1) F is an immersion
(2) $F : M \to F(M)$.

Note 4.6.4. Here the topology on $F(M)$ is the subspace topology.

4.7. **Submanifolds.**

Definition 4.7.1. Let $(M, \mathcal{A})$ and $(N, \mathcal{B})$ be smooth manifolds. Suppose that $M \subset N$. Then $(M, \mathcal{A})$ is said to be

(1) an **immersed submanifold** of $(N, \mathcal{B})$ if $\mathrm{id} : M \to N$ is a smooth immersion
(2) an **embedded submanifold** of $(N, \mathcal{B})$ if $\mathrm{id} : M \to N$ is a smooth embedding

Note 4.7.2. Essentially, embedded submanifolds are immersed submanifolds with the subspace topology.

Note 4.7.3. For the remainder of this section, we assume that $k \leq n$.

Definition 4.7.4. Let $U \subset \mathbb{R}^n$ and $S \subset U$. Then S is said to be a k**-slice** of U if $S = \{u \in U : u^{k+1}, \dots, u^n = 0\}$.

Exercise 4.7.5. Let $U \subset \mathbb{R}^n$ and $S \subset U$. Suppose that S is a k-slice of U. Define $\pi : \mathbb{R}^n \to \mathbb{R}^k$ by

$$\pi(u^1, \dots, u^k, \dots, u^n) = (u^1, \dots, u^k)$$

Then $\pi|_S \to \pi(S)$ is a diffeomorphism.

Proof. Clear. $\square$

Definition 4.7.6. Let $(M, \mathcal{A})$ be a smooth manifold, $(U, \phi) \in \mathcal{A}$ and $S \subset U$. Then S is said to be a k**-slice** of U if $\phi(S)$ is a k-slice of $\phi(U)$.

Definition 4.7.7. Let $(M, \mathcal{A})$ be a smooth manifold, $S \subset M$ and $(U, \phi) \in \mathcal{A}$. Then (U, ϕ) is said to be a k**-slice chart for** S if $U \cap S$ is a k-slice of U.

Exercise 4.7.8. Let $(M, \mathcal{A})$ be a smooth manifold, $S \subset M$ and $(U, \phi) \in \mathcal{A}$ with $\phi = (x^1, \dots, x^n)$. If (U, ϕ) is a k-slice chart for S, then $\phi|_S = (x^1|_S, \dots, x^k|_S, 0, \dots, 0)$.

Proof. Clear. $\square$

Definition 4.7.9. Let $(M, \mathcal{A})$ be a smooth manifold and $S \subset M$. Then S is said to satisfy the **local** k**-slice condition** if for each $p \in S$, there exists $(U, \phi) \in \mathcal{A}$ such that $p \in U$ and (U, ϕ) is a k-slice chart of S.

Exercise 4.7.10. Let $(M, \mathcal{A})$ be a smooth n-dimensional manifold and $S \subset M$ a subspace. If S satisfies the local k-slice condition, then there exists a smooth structure $\tilde{\mathcal{A}}$ on S such that $(S, \tilde{\mathcal{A}})$ is an embedded submanifold of M.

Proof. Suppose that S satisfies the local k-slice condition. Define $\pi : \mathbb{R}^n \to \mathbb{R}^k$ as above Let $(U, \phi) \in \mathcal{A}$. Suppose that (U, ϕ) is a k-slice chart for S. Define $\tilde{U} = U \cap S$ and $\tilde{\phi} : \tilde{U} \to \pi \circ \phi(\tilde{U})$ by

$$\tilde{\phi} = \pi \circ \phi|_{\tilde{U}}$$

By definition, $\phi(\tilde{U})$ is a k-slice of $\phi(U)$. A previous exercise implies that $\pi|_{\phi(\tilde{U})} \to \pi \circ \phi(\tilde{U})$ is a diffeomorphism and hence a homeomorphism. Thus $\tilde{\phi}$ is a homeomorphism.
Define

$$\tilde{\mathcal{B}} = \{(\tilde{U}, \tilde{\phi}) : (U, \phi) \text{ is a } k\text{-slice for } S\}$$

Let $p \in S$. By assumption, there exists $(U, \phi) \in \mathcal{A}$ such that $p \in U$ and (U, ϕ) is a k-slice chart of S. Then $(\tilde{U}, \tilde{\phi}) \in \tilde{\mathcal{B}}$ and $\mathcal{A}$ is an atlas on S. By construction of $\tilde{\mathcal{B}}$, S is locally half

Euclidean of dimension k. Since M is second countable Hausdorff, so is S in the subspace topology. Thus $(S, \tilde{\mathcal{B}})$ is a k-dimensional manifold. Let $(\tilde{U}, \tilde{\phi})$, $(\tilde{V}, \tilde{\psi}) \in \tilde{\mathcal{B}}$. Then

$$\tilde{\phi} \circ \tilde{\psi}^{-1}|_{\tilde{U} \cap \tilde{V}} = \pi|_{\phi(\tilde{U} \cap \tilde{V})} \circ \phi|_{\tilde{U} \cap \tilde{V}} \circ \psi|^{-1}_{\tilde{U} \cap \tilde{V}} \circ \pi|^{-1}_{\psi(\tilde{U} \cap \tilde{V})}$$

which is a diffeomorphism. So $(\tilde{U}, \tilde{\phi})$ and $(\tilde{V}, \tilde{\psi})$ smoothly compatible. Hence $\tilde{\mathcal{B}}$ is smooth. An exercise in section 4.1 implies that there exists a unique smooth structure $\tilde{\mathcal{A}}$ on S such that $\tilde{\mathcal{B}} \subset \tilde{\mathcal{A}}$. So $(S, \tilde{\mathcal{A}})$ is a smooth k-dimensional manifold.
Clearly $\mathrm{id} : S \to S$ is a homeomorphism. Let $(V, \psi) \in \mathcal{A}$ and $(\tilde{U}, \tilde{\phi}) \in \tilde{\mathcal{A}}$.

Finish!! □

Definition 4.7.11.

Exercise 4.7.12.

5. Vector Bundles and Tensor Fields

5.1. The Vector Bundle.

Definition 5.1.1. Let E, M and F be smooth manifolds and $\pi : E \to M$ a smooth surjection, $U \subset M$ open and $\Phi : \pi^{-1}(U) \to U \times F$. Then (U, Φ) is said to be a **smooth local trivialization of** E **over** U if

(1) Φ is a diffeomorphism
(2) $\pi_U \circ \Phi = \pi|_{\pi^{-1}(U)}$ (where $\pi_U : U \times F \to U$ denotes projection onto U)

Exercise 5.1.2. Let E, M and F be topological spaces and $\pi : E \to M$ a continuous surjection and (U, Φ) a local trivialization of E over U. Then for each $A \subset U$,

$$\Phi(\pi^{-1}(A)) = A \times F$$

Hint: show that $\pi^{-1}(A) = (\pi_U \circ \Phi)^{-1}(A)$

Proof. Let $A \subset U$. Since $\pi^{-1}(A) \subset \pi^{-1}(U)$, property (2) implies that $\pi^{-1}(A) = (\pi_U \circ \Phi)^{-1}(A)$. Since Φ is a bijection,

$$\begin{aligned}
\Phi(\pi^{-1}(A)) &= \Phi \circ (\pi_U \circ \Phi)^{-1}(A)] \\
&= \Phi \circ \Phi^{-1}(\pi_U^{-1}(A)) \\
&= \pi_U^{-1}(A) \\
&= A \times F
\end{aligned}$$

□

Definition 5.1.3. Let E and M be topological spaces and $\pi : E \to M$ a continuous surjection. Then (E, M, π) is said to be a **smooth vector bundle of rank** n if

(1) for each $p \in M$, $\pi^{-1}(\{p\})$ is a n-dimensional real vector space.
(2) for each $p \in M$, there exist open $U \in \mathcal{N}_p$ and $\Phi : \pi^{-1}(U) \to U \times \mathbb{R}^n$ such that (U, Φ) is a smooth local trivialization of E over U.
(3) for each $p \in M$,
$$\Phi|_{\pi^{-1}(\{p\})} : \pi^{-1}(\{p\}) \to \{p\} \times \mathbb{R}^n$$
is an isomorphism.

Exercise 5.1.4. Let M be a smooth n-dimensional manifold. Set $E = M \times \mathbb{R}^n$ and define $\pi : E \to M$ by $\pi(p, x) = p$. Then (E, M, π) is a smooth vector bundle of rank n.

Proof.

(1) For each $p \in M$, $\pi_1^{-1}(\{p\}) = \{p\} \times \mathbb{R}^n$ which may be given the obvious vector space structure.
(2) Let $p \in M$. Set $U = M$. Then $\pi^{-1}(U) = E$. Define $\Phi : \pi^{-1}(U) \to U \times \mathbb{R}^n$ by $\Phi = \mathrm{id}_E$. Then (U, Φ) is a smooth local trivialization of E over U.
(3) Let $p \in M$. Then $\Phi|_{\pi^{-1}(\{p\})} : \pi^{-1}(\{p\}) \to \{p\} \times \mathbb{R}^n$ is clearly an isomorphism.

□

Theorem 5.1.5. Let E and M be smooth manifolds and $\pi : E \to M$ a smooth surjection.

Definition 5.1.6. We define the **tangent bundle of** M, denoted TM, by

$$TM = \coprod_{p \in M} T_p M$$

We denote the natrual projection map by $\pi : TM \to M$.

Definition 5.1.7. Let $(U, \phi) \in \mathcal{A}$ with $\phi = (x^1, \ldots, x^n)$. Define $\tilde{U} \subset TM$ and $\tilde{\phi} : \tilde{U} \to \phi(U) \times \mathbb{R}^n$ by

- $\tilde{U} = \pi^{-1}(U)$
-

$$\begin{aligned} \tilde{\phi}\bigg(\sum_{i=1}^n v^i \, \frac{\partial}{\partial x^i}\bigg|_p \bigg) &= (\phi(p), v) \\ &= (x^1(p), \ldots, x^n(p), v^1, \ldots, v^n) \end{aligned}$$

,

Exercise 5.1.8. Let $(U, \phi) \in \mathcal{A}$ with $\phi = (x^1, \ldots, x^n)$. Then $\tilde{\phi} : \tilde{U} \to \phi(U) \times \mathbb{R}$ is a bijection.

5.2. **The cotangent Bundle.**

Definition 5.2.1. We define the **cotangent bundle of** M, denoted T^*M, by

$$T^*M = \coprod_{p \in M} T_p^*M$$

5.3. **The (r,s)-Tensor Bundle.**

Definition 5.3.1.

(1) the **cotangent bundle of** M, denoted T^*M, by

$$T^*M = \coprod_{p \in M} T_p^*M$$

(2) the (r,s)**-tensor bundle of** M, denoted T_s^rM, by

$$T_s^rM = \coprod_{p \in M} T_s^r(T_pM)$$

(3) the k**-alternating tensor bundle of** M, denoted $\Lambda_k(M)$, by

$$\Lambda_kM = \coprod_{p \in M} \Lambda_k(T_pM)$$

5.4. **Vector Fields.**

Definition 5.4.1. Let $X : M \to TM$. Then X is said to be a **vector field on** M if for each $p \in M$, $X_p \in T_pM$.
For $f \in \mathbb{C}^\infty(M)$, we define $Xf : M \to \mathbb{R}$ by

$$(Xf)_p = X_p(f)$$

and X is said to be **smooth** if for each $f \in \mathbb{C}^\infty(M)$, Xf is smooth.
We denote the set of smooth vector fields on M by $\Gamma^1(M)$.

Definition 5.4.2. Let $f \in C^\infty(M)$ and $X, Y \in \Gamma^1(M)$. We define

- $fX \in \Gamma^1(M)$ by

$$(fX)_p = f(p)X_p$$

- $X + Y \in \Gamma^1(M)$ by

$$(X+Y)_p = X_p + Y_p$$

Exercise 5.4.3. The set $\Gamma^1(M)$ is a $C^\infty(M)$-module.

Proof. Clear. □

Exercise 5.4.4. Let $X \in \Gamma^1(M)$ and $(U, \phi) \in \mathcal{A}$ with $\phi = (x^1, \cdots, x^n)$. Then

$$X|_U = \sum_{i=1}^n (Xx^i)\frac{\partial}{\partial x^i}$$

Proof. Let $p \in M$. Then $X_p \in T_pM$ and $\left\{ \frac{\partial}{\partial x^1}\Big|_p, \cdots, \frac{\partial}{\partial x^n}\Big|_p \right\}$ is a basis of T_pM. So there exist $f_1(p), \cdots, f_n(p) \in \mathbb{R}$ such that $X_p = \sum\limits_{i=1}^n f^i(p) \frac{\partial}{\partial x^i}\Big|_p$. Let $j \in \{1, \cdots, n\}$. Then,

$$\begin{aligned} X_p(x^j) &= \sum_{i=1}^n f^i(p)\frac{\partial x^j}{\partial x^i}(p) \\ &= f_j(p) \end{aligned}$$

Hence $Xx^j = f_j$ and $X|_U = \sum\limits_{i=1}^n (Xx^i)\frac{\partial}{\partial x^i}$. □

Exercise 5.4.5. Let $(U, \phi) \in \mathcal{A}$ with $\phi = (x^1, \cdots, x^n)$. Then for each $i \in \{1, \cdots, n\}$,

$$\frac{\partial}{\partial x^i} \in \Gamma(U)$$

Proof. Let $i \in \{1, \cdots, n\}$ and $f \in C^\infty(M)$. Define $g : M \to \mathbb{R}$ by $g = \frac{\partial}{\partial x^i} f$. Let $(V, \psi) \in \mathcal{A}$. Then for each $x \in \psi(U \cap V)$,

$$\begin{aligned} g \circ \psi^{-1}(x) &= \frac{\partial}{\partial x^i}\bigg|_{\psi^{-1}(x)} f \\ &= \frac{\partial}{\partial u^i}\bigg|_{\phi \circ \psi^{-1}(x)} f \circ \phi^{-1} \\ &= \frac{\partial}{\partial u^i}[f \circ \phi^{-1}](\phi \circ \psi^{-1}(x)) \end{aligned}$$

Since $f \circ \phi^{-1}$ and $\phi \circ \psi^{-1}$ are smooth, $g \circ \psi^{-1}$ is smooth and hence g is smooth. Since $f \in C^\infty(M)$ was arbitrary, by definition, $\frac{\partial}{\partial x^i}$ is smooth. $\square$

5.5. 1-Forms.

Definition 5.5.1. Let $\omega : M \to T^*M$. Then ω is said to be a **1-form on** M if for each $p \in M$, $\omega_p \in T_p^*M$.
For each $X \in \Gamma^1(M)$, we define $\omega(X) : M \to \mathbb{R}$ by

$$\omega(X)_p = \omega_p(X_p)$$

and ω is said to be **smooth** if for each $X \in \Gamma^1(M)$, $\omega(X)$ is smooth.
The set of smooth 1-forms on M is denoted $\Gamma_1(M)$.

Definition 5.5.2. Let $f \in C^\infty(M)$ and $\alpha, \beta \in \Gamma^1(M)$. We define

- $f\alpha \in \Gamma_1(M)$ by
$$(f\omega)_p = f(p)\omega_p$$
- $\alpha + \beta \in \Gamma^1(M)$ by
$$(\alpha + \beta)_p = \alpha_p + \beta_p$$

Exercise 5.5.3. The set $\Gamma_1(M)$ is a $C^\infty(M)$-module.

Proof. Clear. □

Exercise 5.5.4.

5.6. (r, s)-Tensor Fields.

Definition 5.6.1. Let $\alpha : M \to T^r_s M$. Then α is said to be a (r, s)**-tensor field on** M if for each $p \in M$, $\alpha_p \in T^r_s(T_p M)$.
For each $\omega \in \Gamma_1(M)^r$ and $X \in \Gamma^1(M)^s$, we define $\alpha(\omega, X) : M \to \mathbb{R}$ by

$$\alpha(\omega, X)_p = \alpha_p(\omega_p, X_p)$$

and α is said to be **smooth** if for each $\omega \in \Gamma_1(M)^r$ and $X \in \Gamma^1(M)^s$, $\alpha(\omega, X)$ is smooth. The set of smooth (r, s)-tensor fields on M is denoted $\Gamma^r_s(M)$.

Definition 5.6.2. Let $f \in C^\infty(M)$ and $\alpha, \beta \in \Gamma^r_s(M)$. We define

- $f\alpha : M \to T^r_s M$ by
$$(f\omega)_p = f(p)\omega_p$$
- $\alpha + \beta : M \to T^r_s M$ by
$$(\alpha + \beta)_p = \alpha_p + \beta_p$$

Exercise 5.6.3. Let $f \in C^\infty(M)$ and $\alpha, \beta \in \Gamma^r_s(M)$. Then

(1) $f\alpha \in \Gamma^r_s(M)$ by
$$(f\omega)_p = f(p)\omega_p$$
(2) $\alpha + \beta \in \Gamma^r_s(M)$ by
$$(\alpha + \beta)_p = \alpha_p + \beta_p$$

Proof. Clear. □

Exercise 5.6.4. The set $\Gamma^r_s(M)$ is a $C^\infty(M)$-module.

Proof. Clear. □

Definition 5.6.5. Let $\alpha_1 \in \Gamma^{r_1}_{s_1}(M)$ and $\alpha_2 \in \Gamma^{r_2}_{s_2}(M)$. We define the **tensor product of** α **with** β, denoted $\alpha \otimes \beta : M \to T^{r_1+r_2}_{s_1+s_2} M$, by

$$(\alpha \otimes \beta)_p = \alpha_p \otimes \beta_p$$

Exercise 5.6.6. Let $\alpha_1 \in \Gamma^{r_1}_{s_1}(M)$ and $\alpha_2 \in \Gamma^{r_2}_{s_2}(M)$. Then $\alpha_1 \otimes \alpha_2 \in \Gamma^{r_1+r_2}_{s_1+s_2}(M)$

Proof. Let $\omega_1 \in \Gamma_1(M)^{r_1}$, $\omega_2 \in \Gamma_1(M)^{r_2}$, $X_1 \in \Gamma^1(M)^{s_1}$ and $X_2 \in \Gamma^1(M)^{s_2}$. By definition,

$$\alpha_1 \otimes \alpha_2(\omega_1, \omega_2, X_1, X_2) = \alpha_1(\omega_1, X_1)\alpha_2(\omega_2, X_2)$$

This implies that $\alpha_1 \otimes \alpha_2$ is smooth since α_1 and α_2 are smooth by assumption. □

Definition 5.6.7. We define the **tensor product**, denoted $\otimes : \Gamma^{r_1}_{s_1}(M) \times \Gamma^{r_2}_{s_2}(M) \to \Gamma^{r_1+r_2}_{s_1+s_2}(M)$ by

$$(\alpha_1, \alpha_2) \mapsto \alpha_1 \otimes \alpha_2$$

Exercise 5.6.8. The tensor product $\otimes : \Gamma^{r_1}_{s_1}(M) \times \Gamma^{r_2}_{s_2}(M) \to \Gamma^{r_1+r_2}_{s_1+s_2}(M)$ is associative.

Proof. Clear. □

Exercise 5.6.9. The tensor product $\otimes : \Gamma^{r_1}_{s_1}(M) \times \Gamma^{r_2}_{s_2}(M) \to \Gamma^{r_1+r_2}_{s_1+s_2}(M)$ is $C^\infty(M)$-bilinear.

Proof. Clear. □

Definition 5.6.10. Let $(N,\mathcal{B})$ be a smooth manifold, $F:M\to N$ a smooth map and $\alpha\in\Gamma^0_k(N)$. We define the **pullback of α by F**, denoted $F^*\alpha\in\Gamma^0_k(M)$, by

$$(F^*\alpha)_p(v_1,\dots,v_k)=\alpha_{F(p)}(dF_p(v_1),\dots,dF_p(v_k))$$

for $p\in M$ and $v_1,\dots,v_k\in T_pM$

Exercise 5.6.11. Let $(M,\mathcal{A})$, $(N,\mathcal{B})$ and $(L,\mathcal{C})$ be smooth manifolds, $F:M\to N$ and $G:N\to L$ smooth maps, $\alpha\in\Gamma^0_k(N)$, $\beta\in\Gamma^0_l(N)$, $\gamma\in\Gamma^0_k(L)$ and $f\in C^\infty(N)$. Then

(1) $F^*(f\alpha)=(f\circ F)F^*\alpha$
(2) $F^*(\alpha\otimes\beta)=F^*\alpha\otimes F^*\beta$
(3) $F^*(\alpha+\beta)=F^*\alpha+F^*\beta$
(4) $(G\circ F)^*\gamma=F^*(G^*\gamma)$
(5) $id_N^*\alpha=\alpha$

Proof.

(1)

$$\begin{aligned}[F^*(f\alpha)]_p(v_1,\dots,v_k)&=(f\alpha)_{F(p)}(dF_p(v_1),\dots,dF_p(v_k))\\&=f(F(p))\alpha_{F(p)}(dF_p(v_1),\dots,dF_p(v_k))\\&=(f\circ F)(p)(F^*\alpha)_p(v_1,\dots,v_k)\end{aligned}$$

So that $F^*(f\alpha)=(f\circ F)F^*\alpha$

(2)

$$F^*$$

□

Definition 5.6.12.

Exercise 5.6.13.

Proof. □

Exercise 5.6.14. Let $\alpha\in\Gamma^r_s(M)$ and $(U,\phi)\in\mathcal{A}$ with $\phi=(x^1,\cdots,x^n)$. Then there exist $(f^I_J)_{I\in\mathcal{I}_r,J\in\mathcal{I}_s}\subset C^\infty(M)$ such that

$$\alpha|_U=\sum_{(I,J)\in\mathcal{I}_r\times\mathcal{I}_s}f^I_J\partial_{x^{\otimes I}}\otimes dx^{\otimes J}$$

Proof. Let $p\in M$. Then $\omega_p\in T^r_s(T_pM)$ and $\left\{\partial_{x^{\otimes I}}|_p\otimes dx^{\otimes J}_p\right\}$ is a basis of $T^r_s(T_pM)$. So there exist $(f^I_J(p))_{I\in\mathcal{I}_r,J\in\mathcal{I}_s}\subset\mathbb{R}$ such that

$$\omega_p=\sum_{(I,J)\in\mathcal{I}_r\times\mathcal{I}_s}f^I_J(p)\partial_{x^{\otimes I}}|_p\otimes dx^{\otimes J}_p$$

Let $(K,L)\in\mathcal{I}_r\times\mathcal{I}_s$. Then

$$\begin{aligned}\alpha_p(dx^K_p,\partial_{x^L}|_p)&=\sum_{(I,J)\in\mathcal{I}_r\times\mathcal{I}_s}f^I_J(p)\partial_{x^{\otimes I}}|_p\otimes dx^{\otimes J}_p(dx^K_p,\partial_{x^L}|_p)\\&=\sum_{(I,J)\in\mathcal{I}_r\times\mathcal{I}_s}f^I_J(p)\partial_{x^{\otimes I}}|_p(dx^K_p)dx^{\otimes J}_p(\partial_{x^L}|_p)\\&=f^K_L(p)\end{aligned}$$

By assumption, the map $p \mapsto \alpha(dx^K, \partial_{x^L})_p$ is smooth, so that $f^K_L \in C^\infty(U)$.

$\square$

Definition 5.6.15.

5.7. **Differential Forms.**

Definition 5.7.1. We define

$$\Lambda_k(TM) = \coprod_{p \in M} \Lambda_k(T_pM)$$

Definition 5.7.2. Let $\omega : M \to \Lambda_k(TM)$. Then ω is said to be a k**-form on** M if for each $p \in M$, $\omega_p \in \Lambda_k(T_pM)$.
For each $X \in \Gamma^1(M)^k$, we define $\omega(X) : M \to \mathbb{R}$ by

$$\omega(X)_p = \omega_p(X_p)$$

and ω is said to be **smooth** if for each $X \in \Gamma^1(M)^k$, $\omega(X)$ is smooth.
The set of smooth k-forms on M is denoted $\Omega_k(M)$.

Note 5.7.3. Observe that
(1) $\Omega_k(M) \subset \Gamma^0_k(M)$
(2) $\Omega_0(M) = C^\infty(M)$

Exercise 5.7.4. The set $\Omega_k(M)$ is a $C^\infty(M)$-submodule of $\Gamma^0_k(M)$.

Proof. Clear. □

Definition 5.7.5. Define the **exterior product**

$$\wedge : \Omega_k(M) \times \Omega_l(M) \to \Omega_{k+l}(M)$$

by

$$(\alpha \wedge \beta)_p = (\alpha)_p \wedge (\beta)_p$$

Note 5.7.6. For $f \in \Omega_0(M)$ and $\alpha \in \Omega_k(M)$, we have that $f \wedge \alpha = f\alpha$.

Exercise 5.7.7. The exterior product $\wedge : \Omega_k(M) \times \Omega_l(M) \to \Omega_{k+l}(M)$ is well defined.

Proof. Let $\alpha \in \Omega_k(M)$, $\beta \in \Omega_l(M)$, $(x^i)_{i=1}^k \subset \Gamma^1(M)$, $(y^j)_{i=1}^l \subset \Gamma^1(M)$ and $p \in M$. Then

$$\begin{aligned}
\alpha \wedge \beta(X_1, \dots, X_{k+l})_p &= (\alpha \wedge \beta)_p(X_1(p), \cdots, X_{k+l}(p)) \\
&= \frac{(k+l)!}{k!l!} A(\alpha_p \otimes \beta_p)(X_1(p), \cdots, X_{k+l}(p)) \\
&= \frac{1}{k!l!} \sum_{\sigma \in S_{k+l}} \operatorname{sgn}(\sigma)\sigma(\alpha_p \otimes \beta_p)(X_1(p), \cdots, X_{k+l}(p)) \\
&= \frac{1}{k!l!} \sum_{\sigma \in S_{k+l}} \operatorname{sgn}(\sigma)(\alpha_p \otimes \beta_p)(X_{\sigma(1)}(p), \cdots, X_{\sigma(k+l)}(p)) \\
&= \frac{1}{k!l!} \sum_{\sigma \in S_{k+l}} \operatorname{sgn}(\sigma)\alpha_p(X_{\sigma(1)}(p), \dots, X_{\sigma(k)}(p))\beta(X_{\sigma(k+1)(p)}, \dots X_{\sigma(k+l)}(p)) \\
&= \frac{1}{k!l!} \sum_{\sigma \in S_{k+l}} \operatorname{sgn}(\sigma)\alpha_p(X_{\sigma(1)}(p), \dots, X_{\sigma(k)}(p))\beta(X_{\sigma(k+1)(p)}, \dots X_{\sigma(k+l)}(p))
\end{aligned}$$

□

Exercise 5.7.8. The exterior product $\wedge : \Omega_k(M) \times \Omega_l(M) \to \Omega_{k+l}(M)$ is $C^\infty(M)$-bilinear.

Proof.

(1) $C^\infty(M)$-linearity in the first argument:
Let $\alpha \in \Omega_k(M)$, $\beta, \gamma \in \Omega_l(M)$, $f \in C^\infty(M)$ and $p \in M$. Bilinearity of $\wedge : \Lambda_k(T_pM) \times \Lambda_l(T_pM) \to \Lambda_{k+l}(T_pM)$ implies that

$$\begin{aligned} [(\beta + f\gamma) \wedge \alpha]_p &= (\beta + f\gamma)_p \wedge \alpha_p \\ &= (\beta_p + f(p)\gamma_p) \wedge \alpha_p \\ &= \beta_p \wedge \alpha_p + f(p)(\gamma_p \wedge \alpha_p) \\ &= [\beta \wedge \alpha + f(\gamma \wedge \alpha)]_p \end{aligned}$$

So that

$$(\beta + f\gamma) \wedge \alpha = \beta \wedge \alpha + f(\gamma \wedge \alpha)$$

and $\wedge : \Omega_k(M) \times \Omega_l(M) \to \Omega_{k+l}(M)$ is $C^\infty(M)$-linear in the first argument.

(2) $C^\infty(M)$-linearity in the second argument:
Similar to (1).

□

Note 5.7.9. All of the results from multilinear algebra apply here.

Definition 5.7.10. We define the **exterior derivative** $d : \Omega_k(M) \to \Omega_{k+1}(M)$ inductively by

(1) $d(d\alpha) = 0$ for $\alpha \in \Omega_p(M)$
(2) $df(X) = Xf$ for $f \in \Omega_0(M)$
(3) $d(\alpha \wedge \beta) = d\alpha \wedge \beta + (-1)^p \alpha \wedge d\beta$ for $\alpha \in \Omega_p(M)$ and $\beta \in \Omega_q(M)$
(4) extending linearly

Exercise 5.7.11. Let (U, ϕ) be a chart on M with $\phi = (x^1, \cdots, x^n)$. Then on U, for each $i, j \in \{1, \cdots, n\}$,

$$dx^i\left(\frac{\partial}{\partial x^j}\right) = \delta_{i,j}$$

In particular, for each $p \in U$, $\{dx^1_p, \cdots, dx^n_p\}$ is the dual basis to $\left\{ \frac{\partial}{\partial x^1}\Big|_p, \cdots, \frac{\partial}{\partial x^n}\Big|_p \right\}$ and $T^*_pM = \text{span}\{dx^1_p, \cdots, dx^n_p\}$.

Proof. Let $p \in U$ and $i, j \in \{1, \cdots, n\}$. Then by defintion,

$$\begin{aligned} \left[dx^i\left(\frac{\partial}{\partial x^j}\right)\right]_p &= \left(\frac{\partial}{\partial x^j}x^i\right)_p \\ &= \frac{\partial}{\partial x^j}\bigg|_p x^i \\ &= \delta_{i,j} \end{aligned}$$

□

Exercise 5.7.12. Let $f \in C^\infty(M)$ and (U, ϕ) be a chart on M with $\phi = (x^1, \cdots, x^n)$. Then

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

Proof. Let $p \in U$. Since $\{dx^1, \cdots, dx^n\}$ is a basis for $\Lambda(T_pM)$, for each there exist $a_1(p), \cdots, a_n(p) \in \mathbb{R}$ such that $df_p = \sum\limits_{i=1}^n a^i(p) dx^i_p$. Therefore, we have that

$$\begin{aligned} df_p\bigg(\frac{\partial}{\partial x^j}\bigg|_p \bigg) &= \sum_{i=1}^n a^i(p) dx^i_p \bigg(\frac{\partial}{\partial x^j}\bigg|_p \bigg) \\ &= a_j(p) \end{aligned}$$

By definition, we have that

$$\begin{aligned} df_p\bigg(\frac{\partial}{\partial x^j}\bigg|_p \bigg) &= \frac{\partial}{\partial x^j}\bigg|_p f \\ &= \frac{\partial f}{\partial x^j}(p) \end{aligned}$$

So $a_j(p) = \frac{\partial f}{\partial x^j}(p)$ and

$$df_p = \sum_{i=1}^n \frac{\partial f}{\partial x^j}(p) dx^i_p$$

Therefore

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

□

Exercise 5.7.13. Let $f \in \Omega_0(M)$. If f is constant, then $df = 0$.

Proof. Suppose that f is constant. Let $p \in M$. Choose $(U, \phi) \in \mathcal{A}$ such that $p \in U$. Write $\phi = (x_1, \ldots, x_n)$. Then for each $i \in \{1, \ldots, n\}$,

$$\frac{\partial}{\partial x^i}\bigg|_p f = 0$$

This implies that

$$\begin{aligned} df_p &= \sum_{i=1}^n \frac{\partial f}{\partial x^j}(p) dx^i_p \\ &= 0 \end{aligned}$$

□

Exercise 5.7.14.

Definition 5.7.15. Let $(U, \phi) \in \mathcal{A}$ with $\phi = (x^1, \cdots, x^n)$ and $I = (i_1, \cdots, i_k) \in \mathcal{I}_k$. We define

$$dx^i = dx_{i_1} \wedge \cdots \wedge dx_{i_k} \in \Omega_k(M)$$

and we define

$$\frac{\partial}{\partial x^i} = \left(\frac{\partial}{\partial x_{i_1}}, \cdots, \frac{\partial}{\partial x_{i_k}}\right)$$

Note 5.7.16. We have that

(1)

$$dx^i\left(\frac{\partial}{\partial x^j}\right) = \delta_{I,J}$$

(2) Since $\frac{\partial}{\partial x^i} \in \Gamma(U)^k$, by definition, for each $\omega \in \Omega_k(U)$,

$$\omega\left(\frac{\partial}{\partial x^i}\right) \in C^\infty(U)$$

Exercise 5.7.17. Let $\omega \in \Omega_k(M)$ and (U, ϕ) be a chart on M with $\phi = (x^1, \cdots, x^n)$. Then

$$\omega = \sum_{I \in \mathcal{I}_k} \omega\left(\frac{\partial}{\partial x^i}\right) dx^i$$

Proof. Let $p \in U$. Since $\{dx^i_p : I \in \mathcal{I}_k\}$ is a basis for $\Lambda_k(T_pM)$, there exists $(f_I(p))_{I\in\mathcal{I}} \subset \mathbb{R}$ such that $\omega_p = \sum_{I\in\mathcal{I}_k} f_I(p) dx^i_p$. So for each $J \in \mathcal{I}_k$,

$$\begin{aligned}\omega\left(\frac{\partial}{\partial x^j}\right) &= \sum_{I\in\mathcal{I}_k} f_I dx^i\left(\frac{\partial}{\partial x^j}\right) \\ &= f_J\end{aligned}$$

□

Exercise 5.7.18. Let $\omega \in \Omega_k(M)$ and (U, ϕ) be a chart on M with $\phi = (x^1, \cdots, x^n)$. If $\omega = \sum_{I\in\mathcal{I}_k} f_I dx^i$, then

$$d\omega = \sum_{I\in\mathcal{I}_k}\sum_{i=1}^n \frac{\partial f_I}{\partial x^i} dx^i \wedge dx^i$$

.

Proof. First we note that

$$\begin{aligned}d(f_I dx^i) &= df_I \wedge dx^i + (-1)^0 f d(dx^i) \\ &= df_I \wedge dx^i \\ &= \left(\sum_{i=1}^n \frac{\partial f_I}{\partial x^i} dx^i\right) \wedge dx^i \\ &= \sum_{i=1}^n \frac{\partial f_I}{\partial x^i} dx^i \wedge dx^i\end{aligned}$$

Then we extend linearly. □

Definition 5.7.19. Let $(N, \mathcal{B})$ be a smooth manifold and $F : M \to N$ be a diffeomorphism. Define the **pullback of** F, denoted $F^* : \Omega_k(N) \to \Omega_k(M)$ by

$$(F^*\omega)_p(v_1, \cdots, v_k) = \omega_{F(p)}(dF_p(v_1), \cdots, dF_p(v_k))$$

for $\omega \in \Omega_k(N)$, $p \in M$ and $v_1, \cdots, v_k \in T_pM$

6. Extra

Definition 6.0.1. When working in $\mathbb{R}^n$, we introduce the formal objects $dx^1, dx_2, \cdots, dx^n$. Let $I = (i_1, i_2, \cdots, i_k) \in \mathcal{I}_{k,n}$ and $\phi : \mathbb{R}^k \to \mathbb{R}^n$. Write $\phi = (\phi_1, \phi_2, \cdots, \phi_n)$. We formally define $dx^i = dx_{i_1} \wedge dx_{i_2} \wedge \cdots \wedge dx_{i_k}$ and $\phi_I = (\phi_{i_1}, \phi_{i_2}, \cdots, \phi_{i_k})$.

Definition 6.0.2. Let $k \in \{0, 1, \cdots, n\}$. We define a $C^\infty(\mathbb{R}^n)$-module of dimension $\binom{n}{k}$, denoted $\Gamma^k(\mathbb{R}^n)$ to be

$$\Phi_k(\mathbb{R}^n) = \begin{cases} C^\infty(\mathbb{R}^n) & k = 0 \\ \operatorname{span}\{dx^i : I \in \mathcal{I}_{k,n}\} & k \geq 1 \end{cases}$$

For each $\omega \in \Phi_k(\mathbb{R}^n)$ and $\chi \in \Gamma^l(\mathbb{R}^n)$, we may form their **exterior product**, denoted by $\omega \wedge \chi \in \Gamma^{k+l}(\mathbb{R}^n)$. Thus the exterior product is a map $\wedge : \Phi_k(\mathbb{R}^n) \times \Gamma^l(\mathbb{R}^n) \to \Gamma^{k+l}(\mathbb{R}^n)$. The exterior product is characterized by the following properties:

(1) the exterior product is bilinear
(2) for each $\omega \in \Phi_k(\mathbb{R}^n)$ and $\chi \in \Gamma^l(\mathbb{R}^n)$, $\omega \wedge \chi = -\chi \wedge \omega$
(3) for each $\omega \in \Phi_k(\mathbb{R}^n)$, $\omega \wedge \omega = 0$
(4) for each $f \in C^\infty(\mathbb{R}^n)$ and $\omega \in \Phi_k(\mathbb{R}^n)$, $f \wedge \omega = f\omega$

We call $\Phi_k(\mathbb{R}^n)$ the differential k-forms on $\mathbb{R}^n$. Let ω be a k-form on $\mathbb{R}^n$. If $k \geq 1$, then for each $I \in \mathcal{I}_{k,n}$, there exists $f_I \in C^\infty(\mathbb{R}^n)$ such that $\omega = \sum\limits_{I \in \mathcal{I}_{k,n}} f_I dx^i$

Note 6.0.3. The terms $dx^1, dx_2, \cdots, dx^n$ are are a sort of place holder for the coordinates of a point $x = (x_1, x_2, \cdots, x_n) \in \mathbb{R}^n$. When we work with functions $\phi : \mathbb{R}^k \to \mathbb{R}^n$, we will have different coordinates and to avoid confusion, we will write $\{du^1, du_2, \cdots, du_k\}$ when referencing the coordinates on $\mathbb{R}^k$ and $\{dx^1, dx_2, \cdots, dx^n\}$ when referencing the coordinates on $\mathbb{R}^n$.

Exercise 6.0.4. Let $B_{n\times n} = (b_{i,j}) \in [C^\infty(M)]^{n\times n}$ be an $n \times n$ matrix. Then

$$\bigwedge_{i=1}^n \left(\sum_{j=1}^n b_{i,j} dx^j \right) = (\det B) dx^1 \wedge dx_2 \wedge \cdots \wedge dx^n$$

Proof. Bilinearity of the exterior product implies that

$$\begin{aligned}
\bigwedge_{i=1}^n \left(\sum_{j=1}^n b_{i,j} dx^j \right) &= \left(\sum_{j=1}^n b_{1,j} dx^j \right) \wedge \left(\sum_{j=1}^n b_{2,j} dx^j \right) \wedge \cdots \wedge \left(\sum_{j=1}^n b_{n,j} dx^j \right) \\
&= \sum_{j_1, \cdots, j_n = 1}^n \left(\prod_{i=1}^n b_{i,j_i} \right) dx_{j_1} \wedge dx_{j_2} \wedge \cdots \wedge dx_{j_n} \\
&= \sum_{j_1 \neq \cdots \neq j_n} \left(\prod_{i=1}^n b_{i,j_i} \right) dx_{j_1} \wedge dx_{j_2} \wedge \cdots \wedge dx_{j_n} \\
&= \left[\sum_{\sigma \in S_n} \operatorname{sgn}(\sigma) \left(\prod_{i=1}^n b_{i,\sigma(i)} \right) \right] dx_1 \wedge dx_2 \wedge \cdots \wedge dx_n \\
&= (\det B) dx_1 \wedge dx_2 \wedge \cdots \wedge dx_n
\end{aligned}$$

□

Definition 6.0.5. Let $f : \mathbb{R}^n \to \mathbb{R}$ be a 0-form on $\mathbb{R}^n$. We define a 1-form, denoted df, on $\mathbb{R}^n$ by

$$df = \sum_{i=1}^{n} \frac{\partial f}{\partial x^i} dx^i$$

Let $\omega = \sum\limits_{I \in \mathcal{I}_{k,n}} f_I dx^i$ be a k-form on $\mathbb{R}^n$. We can define a differential $k+1$-form, denoted $d\omega$, on $\mathbb{R}^n$ by

$$d\omega = \sum_{I \in \mathcal{I}_{k,n}} df_I \wedge dx^i$$

Exercise 6.0.6. On $\mathbb{R}^3$, put

(1) $\omega_0 = f_0$,
(2) $\omega_1 = f_1 dx^1 + f2 dx_2 + f_2 dx_3$,
(3) $\omega_2 = f_1 dx_2 \wedge dx_3 - f_2 dx^1 \wedge dx_3 + f_3 dx^1 \wedge dx_2$

Show that

(1) $d\omega_0 = \frac{\partial f_0}{\partial x_1} dx^1 + \frac{\partial f_0}{\partial x_2} dx_2 + \frac{\partial f_0}{\partial x_3} dx_3$
(2) $d\omega_1 = \left(\frac{\partial f_3}{\partial x_2} - \frac{\partial f_2}{\partial x_3}\right) dx_2 \wedge dx_3 + \left(\frac{\partial f_3}{\partial x_1} - \frac{\partial f_1}{\partial x_3}\right) dx^1 \wedge dx_3 + \left(\frac{\partial f_2}{\partial x_1} - \frac{\partial f_1}{\partial x_2}\right) dx^1 \wedge dx_2$
(3) $d\omega_2 = \left(\frac{\partial f_1}{\partial x_1} + \frac{\partial f_2}{\partial x_2} + \frac{\partial f_3}{\partial x_3}\right) dx^1 \wedge dx_2 \wedge dx_3$

Proof. Straightforward. □

Exercise 6.0.7. Let $I \in \mathcal{I}_{k,n}$. Then there is a unique $I_* \in \mathcal{I}_{n-k,n}$ such that $dx^i \wedge dx_{I_*} = dx^1 \wedge dx_2 \wedge \cdots \wedge dx^n$.

Definition 6.0.8. We define a linear map $* : \Phi_k(\mathbb{R}^n) \to \Gamma^{n-k}(\mathbb{R}^n)$ called the **Hodge $*$-operator** by

$$* \sum_{I \in \mathcal{I}_{k,n}} f_I dx^i = \sum_{I \in \mathcal{I}_{k,n}} f_I dx_{I_*}$$

Definition 6.0.9. Let $\phi : \mathbb{R}^k \to \mathbb{R}^n$ be smooth. Write $\phi = (\phi_1, \phi_2, \cdots, \phi_n)$. We define $\phi^* : \Phi_k(\mathbb{R}^n) \to \Phi_k(\mathbb{R}^k)$ via the following properties:

(1) for each 0-form f on $\mathbb{R}^n$, $\phi^* f = f \circ \phi$
(2) for $i = 1, \cdots, n$, $\phi^* dx^i = d\phi_i$
(3) for an s-form ω, and a t-form χ on $\mathbb{R}^n$, $\phi^*(\omega \wedge \chi) = (\phi^*\omega) \wedge (\phi^*\chi)$
(4) for l-forms ω, χ on $\mathbb{R}^n$, $\phi^*(\omega + \chi) = \phi^*\omega + \phi^*\chi$

Exercise 6.0.10. Let $M \subset \mathbb{R}^n$ be a k-dimensional smooth submanifold of $\mathbb{R}^n$, $\phi : U \to V$ a smooth parametrization of M, $\omega = \sum_{I \in \mathcal{I}_{k,n}} f_I dx^i$ an k-form on $\mathbb{R}^n$. Then

$$\phi^*\omega = \left(\sum_{I \in \mathcal{I}_{k,n}} (f_I \circ \phi)(\det v\phi_I)\right) du^1 \wedge du_2 \wedge \cdots \wedge du_k$$

Proof. By definition,

$$\begin{aligned}
\phi^*\omega &= \phi^* \sum_{I \in \mathcal{I}_{k,n}} f_I dx^i \\
&= \sum_{I \in \mathcal{I}_{k,n}} (\phi^* f_I) \phi^* dx^i \\
&= \sum_{I \in \mathcal{I}_{k,n}} (f_I \circ \phi) d\phi_I
\end{aligned}$$

A previous exercise tells us that for each $I \in \mathcal{I}_{k,n}$,

$$\begin{aligned}
d\phi_I &= d\phi_{i_1} \wedge d\phi_{i_2} \wedge \cdots \wedge d\phi_{i_n} \\
&= (\sum_{j=1}^n \frac{\partial \phi_{i_1}}{\partial u^j} du^j) \wedge (\sum_{j=1}^n \frac{\partial \phi_{i_2}}{\partial u^j} du^j) \wedge \cdots \wedge (\sum_{j=1}^n \frac{\partial \phi_{i_k}}{\partial u^j} du^j) \\
&= (\det v\phi_I) du^1 \wedge du_2 \wedge \cdots \wedge du_k
\end{aligned}$$

Therefore

$$\begin{aligned}
\phi^*\omega &= \sum_{I \in \mathcal{I}_{k,n}} (f_I \circ \phi) d\phi_I \\
&= \sum_{I \in \mathcal{I}_{k,n}} (f_I \circ \phi)(\det v\phi_I) du^1 \wedge du_2 \wedge \cdots \wedge du_k \\
&= \left(\sum_{I \in \mathcal{I}_{k,n}} (f_I \circ \phi)(\det v\phi_I) \right) du^1 \wedge du_2 \wedge \cdots \wedge du_k
\end{aligned}$$

□

6.1. **Integration of Differential Forms.**

Definition 6.1.1. Let $U \subset \mathbb{R}^k$ be open and $\omega = f dx^1 \wedge dx_2 \wedge \cdots \wedge dx_k$ a k-form on $\mathbb{R}^k$. Define

$$\int_U \omega = \int_U f dx$$

Definition 6.1.2. Let $M \subset \mathbb{R}^n$ be a k-dimensional oriented smooth submanifold of $\mathbb{R}^n$, ω a k-form on $\mathbb{R}^n$ and $\phi : U \to V$ a local smooth, orientation-preserving parametrization of M. Define

$$\int_V \omega = \int_U \phi^*\omega$$

Exercise 6.1.3.

Theorem 6.1.4. Stokes Theorem:
Let $M \subset \mathbb{R}^n$ be a k-dimensional oriented smooth submanifold of $\mathbb{R}^n$ and ω a $k-1$-form on $\mathbb{R}^n$. Then

$$\int_{\partial M} \omega = \int_M d\omega$$