

ALTERNATING MULTILINEAR FORMS

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1. PERMUTATIONS

We follow Cartan [2] and Abraham and Marsden [1].

Let E be a real vector space. Let $\mathcal{L}_p(E; \mathbb{R})$ be the set of multilinear maps $E^p \rightarrow \mathbb{R}$.

Definition 1. A map $f \in \mathcal{L}_p(E; \mathbb{R})$ is called **alternating** if $(x_1, \dots, x_p) \in E^p$ with $x_i = x_{i+1}$ for some $1 \leq i < p$ implies $f(x_1, \dots, x_p) = 0$. Let $\mathcal{A}_p(E; \mathbb{R})$ be the set of alternating elements of $\mathcal{L}_p(E; \mathbb{R})$.

For a set X , let S_X be the group of bijections $X \rightarrow X$, and let $S_p = S_{\{1, \dots, p\}}$. For $\sigma, \tau \in S_X$, write $\sigma\tau = \sigma \circ \tau$.

Definition 2. For a function $f : E^p \rightarrow \mathbb{R}$ and a permutation $\sigma \in S_p$, define the function $\sigma f : E^p \rightarrow \mathbb{R}$ by

$$(\sigma f)(x_1, \dots, x_p) = f(x_{\sigma(1)}, \dots, x_{\sigma(p)}), \quad (x_1, \dots, x_p) \in E^p.$$

Theorem 3. For a function $f : E^p \rightarrow \mathbb{R}$ and for $\sigma, \tau \in S_p$,

$$\tau(\sigma f) = (\tau\sigma)f.$$

Proof. Define $g = \sigma f$. For $(x_1, \dots, x_p) \in E^p$ and for $y_i = x_{\tau(i)}$, we have

$$\begin{aligned} \tau(\sigma f)(x_1, \dots, x_p) &= \tau(g)(x_1, \dots, x_p) \\ &= g(x_{\tau(1)}, \dots, x_{\tau(p)}) \\ &= g(y_1, \dots, y_p) \\ &= (\sigma f)(y_1, \dots, y_p) \\ &= f(y_{\sigma(1)}, \dots, y_{\sigma(p)}) \\ &= f(x_{\tau(\sigma(1))}, \dots, x_{\tau(\sigma(p))}) \\ &= (\tau\sigma)(f)(x_1, \dots, x_p). \end{aligned}$$

Thus

$$\tau(\sigma f) = (\tau\sigma)f.$$

□

For $1 \leq i, j \leq p$, define $(i, j) \in S_p$ by

$$(i, j)(k) = \begin{cases} j & k = i, \\ i & k = j, \\ k & k \neq i, j, \end{cases}$$

called a **transposition**. Define

$$\tau_i = (i, i+1),$$

called an **adjacent transposition**. We can write a transposition (i, j) , $i < j$, as a product of $2j - 2i - 1$ adjacent transpositions:

$$\begin{aligned} (i, j) &= (j-1, j)(j-2, j-1) \cdots (i+1, i+2)(i, i+1)(i+1, i+2) \cdots (j-1, j) \\ &= \tau_{j-1} \cdots \tau_{i+1} \tau_i \tau_{i+1} \cdots \tau_{j-1}. \end{aligned}$$

Theorem 4. For $\sigma, \tau \in S_p$,

$$\operatorname{sgn}(\sigma\tau) = \operatorname{sgn}(\sigma)\operatorname{sgn}(\tau).$$

Theorem 5. Let $f \in \mathcal{L}_p(E; \mathbb{R})$. $f \in \mathcal{A}_p(E; \mathbb{R})$ if and only if $\sigma f = (\operatorname{sgn} \sigma)f$ for all $\sigma \in S_p$.

Proof. (i) Suppose that $f \in \mathcal{A}_p(E; \mathbb{R})$ and let $\sigma \in S_p$; we have to show that $\sigma f = (\operatorname{sgn} \sigma)f$. Let $(x_1, \dots, x_p) \in E^p$ and for $1 \leq i < p$ define $g_i : E^2 \rightarrow \mathbb{R}$ by

$$g_i(y_1, y_2) = f(x_1, \dots, \underbrace{y_1}_i, \underbrace{y_2}_{i+1}, \dots, x_p), \quad (y_1, y_2) \in E^2.$$

Because f is multilinear and alternating, on the one hand

$$g_i(x_i + x_{i+1}, x_i + x_{i+1}) = 0,$$

and on the other hand

$$\begin{aligned} g_i(x_i + x_{i+1}, x_i + x_{i+1}) &= g_i(x_i, x_i) + g_i(x_i, x_{i+1}) + g_i(x_{i+1}, x_i) + g_i(x_{i+1}, x_{i+1}) \\ &= g_i(x_i, x_{i+1}) + g_i(x_{i+1}, x_i). \end{aligned}$$

Therefore

$$g_i(x_{i+1}, x_i) = -g_i(x_i, x_{i+1}),$$

that is,

$$f(x_1, \dots, x_p) = -f(x_1, \dots, x_p).$$

Thus, as $\operatorname{sgn} \tau_i = -1$,

$$\tau_i f = (\operatorname{sgn} \tau_i) f.$$

Because σ is equal to a product of adjacent transpositions, it then follows from Theorem 3 and Theorem 4 that $\sigma f = (\operatorname{sgn} \sigma)f$.

(ii) Suppose that $\sigma f = (\operatorname{sgn} \sigma)f$ for all $\sigma \in S_p$. Let $(x_1, \dots, x_p) \in E^p$ with $x_i = x_{i+1}$ for some $1 \leq i < p$; we have to show that $f(x_1, \dots, x_p) = 0$. On the one hand,

$$\tau_i f(x_1, \dots, x_p) = (\operatorname{sgn} \tau_i) f(x_1, \dots, x_p) = -f(x_1, \dots, x_p).$$

On the other hand, using that $x_i = x_{i+1}$,

$$\begin{aligned} \tau_i f(x_1, \dots, x_p) &= f(x_{\tau_i(1)}, \dots, x_{\tau_i(i)}, x_{\tau_i(i+1)}, \dots, x_{\tau_i(p)}) \\ &= f(x_1, \dots, x_{i+1}, x_i, \dots, x_p) \\ &= f(x_1, \dots, x_i, x_{i+1}, \dots, x_p). \end{aligned}$$

Hence

$$-f(x_1, \dots, x_p) = f(x_1, \dots, x_p),$$

which implies that $f(x_1, \dots, x_p) = 0$. This shows that $f \in \mathcal{A}_p(E; \mathbb{R})$. \square

Theorem 6. Let $f \in \mathcal{A}_p(E; \mathbb{R})$. If $(x_1, \dots, x_p) \in E^p$ with $x_i = x_j$ for some $i \neq j$, then $f(x_1, \dots, x_p) = 0$.

Proof. Check that there is some $\sigma \in S_p$ satisfying $\sigma(1) = i$ and $\sigma(2) = j$. For this σ ,

$$\begin{aligned} (\sigma f)(x_1, \dots, x_p) &= f(x_i, x_j, x_{\sigma(3)}, \dots, x_{\sigma(p)}) \\ &= f(x_i, x_i, x_{\sigma(3)}, \dots, x_{\sigma(p)}) \\ &= 0. \end{aligned}$$

But $(\sigma f) = (\text{sgn } \sigma)f$, so $(\text{sgn } \sigma)f(x_1, \dots, x_p) = 0$. Therefore $f(x_1, \dots, x_p) = 0$. \square

Definition 7. For $f \in \mathcal{L}_p(E; \mathbb{R})$, define

$$A_p f = \frac{1}{p!} \sum_{\sigma \in S_p} (\text{sgn } \sigma) \sigma f.$$

Lemma 8. A_p is a linear map $\mathcal{L}_p(E; \mathbb{R}) \rightarrow \mathcal{A}_p(E; \mathbb{R})$.

Proof. Let $f \in \mathcal{L}_p(E; \mathbb{R})$. For $\sigma \in S_p$, $\sigma f \in \mathcal{L}_p(E; \mathbb{R})$, hence $A_p f \in \mathcal{L}_p(E; \mathbb{R})$. Namely, $A_p f$ is multilinear. It remains to show that it is alternating.

For $\sigma \in S_p$, as $\tau \mapsto \sigma\tau$ is a bijection $S_p \rightarrow S_p$,

$$\begin{aligned} \sigma(A_p f) &= \frac{1}{p!} \sum_{\tau \in S_p} (\text{sgn } \tau) \sigma\tau f \\ &= (\text{sgn } \sigma) \frac{1}{p!} \sum_{\tau \in S_p} (\text{sgn } \tau) \tau f \\ &= (\text{sgn } \sigma) A_p f, \end{aligned}$$

showing that $A_p f$ is alternating by Theorem 5, so $A_p f \in \mathcal{A}_p(E; \mathbb{R})$. \square

Theorem 9. Let $f \in \mathcal{L}_p(E; \mathbb{R})$. $f \in \mathcal{A}_p(E; \mathbb{R})$ if and only if $A_p f = f$.

Proof. Suppose $f \in \mathcal{A}_p(E; \mathbb{R})$. Then $\sigma f = (\text{sgn } \sigma)f$ for each $\sigma \in S_p$, by Theorem 5. Then

$$A_p f = \frac{1}{p!} \sum_{\sigma \in S_p} \sigma f = \frac{1}{p!} \sum_{\sigma \in S_p} f = f.$$

Suppose $A_p f = f$. Lemma 8 tells us $A_p f \in \mathcal{A}_p(E; \mathbb{R})$, hence $f \in \mathcal{A}_p(E; \mathbb{R})$. \square

2. WEDGE PRODUCTS

A permutation $\sigma \in S_{p+q}$ is called a (p, q) -riffle shuffle if

$$\sigma(1) < \dots < \sigma(p), \quad \sigma(p+1) < \dots < \sigma(p+q).$$

Denote by $S_{p,q}$ those elements of S_{p+q} that are (p, q) -riffle shuffles.

Lemma 10. $|S_{p,q}| = \binom{p+q}{p} = \frac{(p+q)!}{p!q!}$.

Let $\mathcal{A}_{p,q}(E; \mathbb{R})$ be the set of those $h \in \mathcal{L}_{p+q}(E; \mathbb{R})$ such that (i) for each $(y_1, \dots, y_q) \in E^q$, the map

$$(x_1, \dots, x_p) \mapsto h(x_1, \dots, x_p, y_1, \dots, y_q), \quad E^p \rightarrow \mathbb{R},$$

belongs to $\mathcal{A}_p(E; \mathbb{R})$, and (ii) for $(x_1, \dots, x_p) \in E^p$, the map

$$(y_1, \dots, y_q) \mapsto h(x_1, \dots, x_p, y_1, \dots, y_q), \quad E^q \rightarrow \mathbb{R},$$

belongs to $\mathcal{A}_q(E; \mathbb{R})$.

Definition 11. For $h \in \mathcal{A}_{p,q}(E; \mathbb{R})$ define

$$\phi_{p,q}(h) = \sum_{\sigma \in S_{p,q}} (\text{sgn } \sigma)(\sigma h).$$

Theorem 12. $\phi_{p,q}$ is a linear map $\mathcal{A}_{p,q}(E; \mathbb{R}) \rightarrow \mathcal{A}_{p+q}(E; \mathbb{R})$.

Proof. Let $h \in \mathcal{A}_{p,q}(E; \mathbb{R})$, and say $(x_1, \dots, x_{p+q}) \in E^{p+q}$ with $x_k = x_{k+1}$ for some $1 \leq k < p$.

Let A_1 be those $\sigma \in S_{p,q}$ such that $i = \sigma^{-1}(k), j = \sigma^{-1}(k+1) \leq p$. For $\sigma \in A_1$, by Theorem 6,¹

$$(\sigma h)(x_1, \dots, x_{p+q}) = h(x_{\sigma(1)}, \dots, x_{\sigma(p)}, \dots, x_{\sigma(p+q)}) = 0.$$

Let A_2 be those $\sigma \in S_{p,q}$ such that $\sigma^{-1}(k), \sigma^{-1}(k+1) \geq p+1$. For $\sigma \in A_2$, by Theorem 6,

$$(\sigma h)(x_1, \dots, x_{p+q}) = h(x_{\sigma(1)}, \dots, x_{\sigma(p)}, \dots, x_{\sigma(p+q)}) = 0.$$

Thus

$$\sum_{\sigma \in A_1} (\text{sgn } \sigma)(\sigma h)(x_1, \dots, x_{p+q}) = 0$$

and

$$\sum_{\sigma \in A_2} (\text{sgn } \sigma)(\sigma h)(x_1, \dots, x_{p+q}) = 0.$$

Let A_3 be those $\sigma \in S_{p,q}$ for which $\sigma^{-1}(k) < p$ and $\sigma^{-1}(k+1) \geq p+1$ and let A_4 be those $\sigma \in S_{p,q}$ for which $\sigma^{-1}(k) \geq p+1$ and $\sigma^{-1}(k+1) \leq p$. If $\sigma \in A_3$ then

$$(\tau_k \sigma)^{-1}(k) = \sigma^{-1} \tau_k^{-1}(k) = \sigma^{-1}(k+1) \geq p+1$$

and

$$(\tau_k \sigma)^{-1}(k+1) = \sigma^{-1} \tau_k^{-1}(k+1) = \sigma^{-1}(k) < p,$$

so $\tau_k \sigma \in A_4$. Likewise, if $\sigma \in A_4$ then $\tau_k \sigma \in A_3$. Thus $A_4 = \tau_k A_3$. For $\sigma \in A_3$, let $i = \sigma^{-1}(k)$ and $j = \sigma^{-1}(k+1)$, for which $i < p$ and $j \geq p+1$. Then, as $x_k = x_{k+1}$,

$$\begin{aligned} & (\text{sgn } \sigma)(\sigma h)(x_1, \dots, x_{p+q}) + (\text{sgn } \tau_k \sigma)(\tau_k \sigma h)(x_1, \dots, x_{p+q}) \\ &= (\text{sgn } \sigma)h(x_{\sigma(1)}, \dots, x_{\sigma(p+q)}) - (\text{sgn } \sigma)h(x_{\tau_k \sigma(1)}, \dots, x_{\tau_k \sigma(p+q)}) \\ &= (\text{sgn } \sigma)(h(x_{\sigma(1)}, \dots, x_{\sigma(p+q)}) - h(x_{\tau_k \sigma(1)}, \dots, x_{\tau_k \sigma(i)}, \dots, x_{\tau_k \sigma(j)}, \dots, x_{\tau_k \sigma(p+q)})) \\ &= (\text{sgn } \sigma)(h(x_{\sigma(1)}, \dots, x_{\sigma(p+q)}) - h(x_{\tau_k \sigma(1)}, \dots, x_{\tau_k \sigma(k)}, \dots, x_{\tau_k \sigma(k+1)}, \dots, x_{\tau_k \sigma(p+q)})) \\ &= (\text{sgn } \sigma)(h(x_{\sigma(1)}, \dots, x_{\sigma(p+q)}) - h(x_{\sigma(1)}, \dots, x_{k+1}, \dots, x_k, \dots, x_{\sigma(p+q)})) \\ &= (\text{sgn } \sigma)(h(x_{\sigma(1)}, \dots, x_{\sigma(p+q)}) - h(x_{\sigma(1)}, \dots, x_k, \dots, x_{k+1}, \dots, x_{\sigma(p+q)})) \\ &= (\text{sgn } \sigma)(h(x_{\sigma(1)}, \dots, x_{\sigma(p+q)}) - h(x_{\sigma(1)}, \dots, x_{\sigma(p+q)})) \\ &= 0. \end{aligned}$$

Therefore

$$\sum_{\sigma \in A_3 \cup A_4} (\text{sgn } \sigma)(\sigma h)(x_1, \dots, x_{p+q}) = 0.$$

But $S_{p,q} = A_1 \cup A_2 \cup A_3 \cup A_4$, so

$$\phi_{p,q}(h)(x_1, \dots, x_{p+q}) = 0.$$

¹ i, j are distinct and $1 \leq i, j \leq p$; they need not be adjacent.

Thus $\phi_{p,q}(h) \in \mathcal{A}_{p+q}(E; \mathbb{R})$. \square

Definition 13. For $f \in \mathcal{L}_p(E; \mathbb{R})$ and $g \in \mathcal{L}_q(E; \mathbb{R})$, define the **tensor product** $f \otimes_{p,q} g \in \mathcal{L}_{p+q}(E; \mathbb{R})$ by

$$(f \otimes_{p,q} g)(x_1, \dots, x_{p+q}) = f(x_1, \dots, x_p)g(x_{p+1}, \dots, x_{p+q}).$$

It is apparent that

$$(f \otimes_{p,q} g) \otimes_{p+q,r} h = f \otimes_{p,q+r} (g \otimes_{q,r} h),$$

and thus it makes sense to write the tensor product without indices.

Definition 14. Define the **wedge product**

$$\wedge_{p,q} : \mathcal{A}_p(E; \mathbb{R}) \times \mathcal{A}_q(E; \mathbb{R}) \rightarrow \mathcal{A}_{p+q}(E; \mathbb{R})$$

by, for $f \in \mathcal{A}_p(E; \mathbb{R})$, $g \in \mathcal{A}_q(E; \mathbb{R})$,

$$f \wedge_{p,q} g = \phi_{p,q}(f \otimes g),$$

i.e., for $h = f \otimes g$,

$$\begin{aligned} (f \wedge_{p,q} g)(x_1, \dots, x_{p+q}) &= \sum_{\sigma \in S_{p,q}} (\text{sgn } \sigma)(\sigma h) \\ &= \sum_{\sigma \in S_{p,q}} (\text{sgn } \sigma) h(x_{\sigma(1)}, \dots, x_{\sigma(p+q)}) \\ &= \sum_{\sigma \in S_{p,q}} (\text{sgn } \sigma) f(x_{\sigma(1)}, \dots, x_{\sigma(p)}) g(x_{\sigma(p+1)}, \dots, x_{\sigma(p+q)}). \end{aligned}$$

Theorem 15. For $f \in \mathcal{A}_p(E; \mathbb{R})$ and $g \in \mathcal{A}_q(E; \mathbb{R})$,

$$f \wedge_{p,q} g = \frac{(p+q)!}{p!q!} A_{p+q}(f \otimes g).$$

Proof. For $\sigma \in S_{p,q}$,

$$\sigma(1) < \dots < \sigma(p), \quad \sigma(p+1) < \dots < \sigma(p+q).$$

Let $I_\sigma = \{\sigma(i) : 1 \leq i \leq p\}$ and $J_\sigma = \{\sigma(i) : p+1 \leq i \leq p+q\}$.

$$f \wedge_{p,q} g =$$

\square

Theorem 16. For $f \in \mathcal{A}_p(E; \mathbb{R})$ and $g \in \mathcal{A}_q(E; \mathbb{R})$,

$$g \wedge_{q,p} f = (-1)^{pq} f \wedge_{p,q} g.$$

Proof. Define $\alpha \in S_{p,q}$ by

$$\alpha(i) = q+i, \quad 1 \leq i \leq p, \quad \alpha(p+i) = i, \quad 1 \leq i \leq q.$$

Then²

$$\alpha = \prod_{1 \leq i \leq p} \prod_{1 \leq j \leq q} (i+q-j, i+q-j+1).$$

²For example, take $p = 3$ and $q = 2$. Then

$$\alpha(1) = 3, \alpha(2) = 4, \alpha(3) = 5, \alpha(4) = 1, \alpha(5) = 2.$$

Thus

$$\operatorname{sgn} \alpha = \prod_{1 \leq i \leq p} \prod_{1 \leq j \leq q} (-1) = (-1)^{pq}.$$

Let $\tau \in S_{q,p}$, then for $1 \leq i \leq p$,

$$(\tau\alpha)(i) = \tau(q+i)$$

and for $1 \leq i \leq q$,

$$(\tau\alpha)(p+i) = \tau(i),$$

But $\tau \in S_{q,p}$ so

$$\tau(1) < \cdots < \tau(q), \quad \tau(q+1) < \cdots < \tau(q+p),$$

thus

$$(\tau\alpha)(1) < \cdots < (\tau\alpha)(p), \quad (\tau\alpha)(p+1) < \cdots < (\tau\alpha)(p+q),$$

which means that $\tau\alpha \in S_{p,q}$. Likewise, if $\sigma \in S_{p,q}$ then

$$(\sigma\alpha^{-1})(1) = \sigma(q+1), \dots, (\sigma\alpha^{-1})(q) = \sigma(p+q)$$

and

$$(\sigma\alpha^{-1})(q+1) = \sigma(1), \dots, (\sigma\alpha^{-1})(q+p) = \sigma(p),$$

and because $\sigma \in S_{p,q}$ it follows that $\sigma\alpha^{-1} \in S_{q,p}$.

Hence for $(x_1, \dots, x_{p+q}) \in E^{p+q}$,

$$\begin{aligned} & (g \wedge_{q,p} f)(x_1, \dots, x_{p+q}) \\ &= \sum_{\tau \in S_{q,p}} (\operatorname{sgn} \tau) g(x_{\tau(1)}, \dots, x_{\tau(q)}) f(x_{\tau(q+1)}, \dots, x_{\tau(q+p)}) \\ &= \sum_{\sigma \in S_{p,q}} (\operatorname{sgn} \sigma\alpha^{-1}) g(x_{(\sigma\alpha^{-1})(1)}, \dots, x_{(\sigma\alpha^{-1})(q)}) f(x_{(\sigma\alpha^{-1})(q+1)}, \dots, x_{(\sigma\alpha^{-1})(q+p)}) \\ &= (\operatorname{sgn} \alpha^{-1}) \sum_{\sigma \in S_{p,q}} (\operatorname{sgn} \sigma) g(x_{\sigma(p+1)}, \dots, x_{\sigma(p+q)}) f(x_{\sigma(1)}, \dots, x_{\sigma(p)}) \\ &= (-1)^{pq} \sum_{\sigma \in S_{p,q}} (\operatorname{sgn} \sigma) f(x_{\sigma(1)}, \dots, x_{\sigma(p)}) g(x_{\sigma(p+1)}, \dots, x_{\sigma(p+q)}) \\ &= (-1)^{pq} (f \wedge_{p,q} g)(x_1, \dots, x_{p+q}). \end{aligned}$$

Thus

$$g \wedge_{q,p} f = (-1)^{pq} f \wedge_{p,q} g.$$

□

Here

$$\begin{aligned} \prod_{1 \leq i \leq p} \prod_{1 \leq j \leq q} (i+q-j, i+q-j+1) &= \prod_{1 \leq i \leq 3} \prod_{1 \leq j \leq 2} (i-j+2, i-j+3) \\ &= \prod_{1 \leq i \leq 3} (i+1, i+2)(i, i+1) \\ &= (2, 3)(1, 2)(3, 4)(2, 3)(4, 5)(3, 4) \\ &= \alpha. \end{aligned}$$

Let $\mathcal{A}_{p,q,r}(E; \mathbb{R})$ be the set of those $u \in \mathcal{L}_{p+q+r}(E; \mathbb{R})$ such that (i) for each $(y_1, \dots, y_q, z_1, \dots, z_r) \in E^{q+r}$, the map

$$(x_1, \dots, x_p) \mapsto u(x_1, \dots, x_p, y_1, \dots, y_q, z_1, \dots, z_r), \quad E^p \rightarrow \mathbb{R},$$

belongs to $\mathcal{A}_p(E; \mathbb{R})$, (ii) for $(x_1, \dots, x_p, z_1, \dots, z_r) \in E^{p+r}$, the map

$$(y_1, \dots, y_q) \mapsto u(x_1, \dots, x_p, y_1, \dots, y_q, z_1, \dots, z_r), \quad E^q \rightarrow \mathbb{R},$$

belongs to $\mathcal{A}_q(E; \mathbb{R})$, and (iii) for $(x_1, \dots, x_p, y_1, \dots, y_q) \in E^{p+q}$, the map

$$(z_1, \dots, z_r) \mapsto u(x_1, \dots, x_p, y_1, \dots, y_q, z_1, \dots, z_r), \quad E^r \rightarrow \mathbb{R},$$

belongs to $\mathcal{A}_r(E; \mathbb{R})$.

Let $S_{p,q,\bar{r}}$ be those $\sigma \in S_{p+q+r}$ such that

$$\sigma(1) < \dots < \sigma(p), \quad \sigma(p+1) < \dots < \sigma(p+q), \quad \sigma(p+q+i) = p+q+i, 1 \leq i \leq r.$$

Let $S_{\bar{p},q,r}$ be those $\sigma \in S_{p+q+r}$ such that

$$\sigma(i) = i, 1 \leq i \leq p, \quad \sigma(p+1) < \dots < \sigma(p+q), \quad \sigma(p+q+1) < \dots < \sigma(p+q+r).$$

Let $S_{p,q,r}$ be those $\sigma \in S_{p+q+r}$ such that

$$\sigma(1) < \dots < \sigma(p), \quad \sigma(p+1) < \dots < \sigma(p+q), \quad \sigma(p+q+1) < \dots < \sigma(p+q+r).$$

Lemma 17.

$$S_{p+q,r} S_{p,q,\bar{r}} = S_{p,q,r}$$

and

$$S_{p,q+r} S_{\bar{p},q,r} = S_{p,q,r}.$$

Proof. Let $\sigma \in S_{p+q,r}$ and $\tau \in S_{p,q,\bar{r}}$. Then

$$\sigma(1) < \dots < \sigma(p+q), \quad \sigma(p+q+1) < \dots < \sigma(p+q+r)$$

and

$$\tau(1) < \dots < \tau(p), \quad \tau(p+1) < \dots < \tau(p+q), \quad \tau(p+q+i) = p+q+i, 1 \leq i \leq r.$$

It follows that

$$(\sigma\tau)(1) < \dots < (\sigma\tau)(p)$$

and

$$(\sigma\tau)(p+1) < \dots < (\sigma\tau)(p+q)$$

and for $1 \leq i \leq r$, $(\sigma\tau)(p+q+i) = \sigma(p+q+i)$, so

$$(\sigma\tau)(p+q+1) < \dots < \sigma(p+q+r).$$

Thus $\sigma\tau \in S_{p,q,r}$. □

Define $\phi_{p,q,\bar{r}} : \mathcal{A}_{p,q,r}(E; \mathbb{R}) \rightarrow \mathcal{A}_{p+q,r}(E; \mathbb{R})$ by

$$\phi_{p,q,\bar{r}}(u) = \sum_{\sigma \in S_{p,q,\bar{r}}} (\text{sgn } \sigma)(\sigma u), \quad u \in \mathcal{A}_{p,q,r}(E; \mathbb{R})$$

and define $\phi_{\bar{p},q,r} : \mathcal{A}_{p,q,r}(E; \mathbb{R}) \rightarrow \mathcal{A}_{p,q+r}(E; \mathbb{R})$ by

$$\phi_{\bar{p},q,r}(u) = \sum_{\sigma \in S_{\bar{p},q,r}} (\text{sgn } \sigma)(\sigma u), \quad u \in \mathcal{A}_{p,q,r}(E; \mathbb{R})$$

Lemma 18. For $u \in \mathcal{A}_{p,q,r}(E; \mathbb{R})$,

$$(\phi_{p+q,r} \circ \phi_{p,q,\bar{r}})u = \sum_{\rho \in S_{p,q,r}} (\text{sgn } \rho) \rho u$$

and

$$(\phi_{p,q+r} \circ \phi_{\bar{p},q,r})u = \sum_{\rho \in S_{p,q,r}} (\text{sgn } \rho) \rho u,$$

and so

$$\phi_{p+q,r} \circ \phi_{p,q,\bar{r}} = \phi_{p,q+r} \circ \phi_{\bar{p},q,r}.$$

Proof. Applying Lemma 17 we get

$$\begin{aligned} (\phi_{p+q,r} \circ \phi_{p,q,\bar{r}})u &= \sum_{\sigma \in S_{p+q,r}} (\text{sgn } \sigma) \sigma \phi_{p,q,\bar{r}}(u) \\ &= \sum_{\sigma \in S_{p+q,r}} (\text{sgn } \sigma) \sigma \sum_{\tau \in S_{p,q,\bar{r}}} (\text{sgn } \tau) (\tau u) \\ &= \sum_{\sigma \in S_{p+q,r}} (\text{sgn } \sigma \tau) \sum_{\tau \in S_{p,q,\bar{r}}} \sigma \tau u \\ &= \sum_{\rho \in S_{p,q,r}} (\text{sgn } \rho) \rho u \end{aligned}$$

and similarly

$$\begin{aligned} (\phi_{p,q+r} \circ \phi_{\bar{p},q,r})u &= \sum_{\sigma \in S_{p,q+r}} (\text{sgn } \sigma) \sigma \phi_{\bar{p},q,r}(u) \\ &= \sum_{\sigma \in S_{p,q+r}} (\text{sgn } \sigma) \sigma \sum_{\tau \in S_{\bar{p},q,r}} (\text{sgn } \tau) (\tau u) \\ &= \sum_{\sigma \in S_{p,q+r}} (\text{sgn } \sigma \tau) \sum_{\tau \in S_{\bar{p},q,r}} \sigma \tau u \\ &= \sum_{\rho \in S_{p,q,r}} (\text{sgn } \rho) \rho u. \end{aligned}$$

Thus

$$(\phi_{p+q,r} \circ \phi_{p,q,\bar{r}})u = (\phi_{p,q+r} \circ \phi_{\bar{p},q,r})u,$$

from which the claim follows. \square

Theorem 19. If $f \in \mathcal{A}_p(E; \mathbb{R})$, $g \in \mathcal{A}_q(E; \mathbb{R})$, and $h \in \mathcal{A}_r(E; \mathbb{R})$, then

$$(f \wedge_{p,q} g) \wedge_{p+q,r} h = f \wedge_{p,q+r} (g \wedge_{q,r} h).$$

Proof. On the one hand,

$$\begin{aligned} (\phi_{p+q,r} \circ \phi_{p,q,\bar{r}})(f \otimes g \otimes h) &= \phi_{p+q,r}(\phi_{p,q,\bar{r}}((f \otimes g) \otimes h)) \\ &= \phi_{p+q,r}((f \wedge_{p,q} g) \otimes h) \\ &= (f \wedge_{p,q} g) \wedge_{p+q,r} h. \end{aligned}$$

On the other hand,

$$\begin{aligned} (\phi_{p,q+r} \circ \phi_{\bar{p},q,r})(f \otimes g \otimes h) &= \phi_{p,q+r}(\phi_{\bar{p},q,r})(f \otimes (g \otimes h)) \\ &= \phi_{p,q+r}(f \otimes (g \wedge_{q,r} h)) \\ &= f \wedge_{p,q+r} (g \wedge_{q,r} h). \end{aligned}$$

But by Lemma 18,

$$\phi_{p+q,r} \circ \phi_{p,q,\bar{r}} = \phi_{p,q+r} \circ \phi_{\bar{p},q,r},$$

hence

$$(f \wedge_{p,q} g) \wedge_{p+q,r} h = f \wedge_{p,q+r} (g \wedge_{q,r} h).$$

□

3. LINEAR FORMS

Let $E^* = \mathcal{L}_1(E; \mathbb{R})$, the **dual space of E** , whose elements we call **linear forms**. It is immediate that $\mathcal{A}_1(E; \mathbb{R}) = \mathcal{L}_1(E; \mathbb{R}) = E^*$.

Theorem 20. *If $f_1, \dots, f_n \in E^*$ then for $(x_1, \dots, x_n) \in E^n$,*

$$(f_1 \wedge \dots \wedge f_n)(x_1, \dots, x_n) = \sum_{\sigma \in S_n} (\text{sgn } \sigma) f_1(x_{\sigma(1)}) \dots f_n(x_{\sigma(n)}).$$

Proof. For $n = 1$ the claim is immediate. For $n = 2$, on the one hand, using the definition of the wedge product,

$$(f_1 \wedge f_2)(x_1, x_2) = \sum_{\sigma \in S_{1,1}} (\text{sgn } \sigma) f_1(x_{\sigma(1)}) f_2(x_{\sigma(2)}),$$

and as $S_{1,1} = S_2$ the claim is true for $n = 2$. Suppose the claim is true for some $n \geq 2$ and let $(f_1, \dots, f_n, f_{n+1}) \in E^*$ and $(x_1, \dots, x_n, x_{n+1}) \in E^{n+1}$. Then, setting $u = f_1 \wedge \dots \wedge f_n \in \mathcal{A}_n(E; \mathbb{R})$, we have

$$\begin{aligned} & (f_1 \wedge \dots \wedge f_n \wedge f_{n+1})(x_1, \dots, x_n, x_{n+1}) \\ &= (u \wedge_{n,1} f_{n+1})(x_1, \dots, x_n, x_{n+1}) \\ &= \sum_{\sigma \in S_{n,1}} (\text{sgn } \sigma) u(x_{\sigma(1)}, \dots, x_{\sigma(n)}) f_{n+1}(x_{\sigma(n+1)}) \\ &= \sum_{\sigma \in S_{n,1}} (\text{sgn } \sigma) \left(\sum_{\tau \in S_n} (\text{sgn } \tau) f_1(x_{(\sigma\tau)(1)}) \dots f_n(x_{(\sigma\tau)(n)}) \right) f_{n+1}(x_{\sigma(n+1)}) \\ &= \sum_{\rho \in S_{n+1}} (\text{sgn } \rho) f_1(x_{\rho(1)}) \dots f_n(x_{\rho(n)}) f_{n+1}(x_{\rho(n+1)}), \end{aligned}$$

thus the claim is true for $n + 1$. □

Let $f_1, \dots, f_n \in E^*$ and $x_1, \dots, x_n \in E$ and put

$$a_{i,j} = f_i(x_j), \quad 1 \leq i, j \leq n;$$

$a \in \text{Mat}_n(\mathbb{R})$. The Leibniz formula for the determinant of an $n \times n$ matrix tells us

$$\det a = \sum_{\sigma \in S_n} (\text{sgn } \sigma) \prod_{i=1}^n a_{i,\sigma(i)} = \sum_{\sigma \in S_n} (\text{sgn } \sigma) \prod_{i=1}^n f_i(x_{\sigma(i)}).$$

Then Theorem 20 gives

$$\det(f_i(x_j))_{1 \leq i, j \leq n} = (f_1 \wedge \cdots \wedge f_n)(x_1, \dots, x_n).$$

Lemma 21. *If $f_1, \dots, f_n \in E^*$ are linearly independent then there are $x_1, \dots, x_n \in E$ such that*

$$f_i(x_j) = \delta_{i,j}, \quad 1 \leq i, j \leq n.$$

Theorem 22. *$f_1, \dots, f_n \in E^*$ are linearly dependent if and only if*

$$f_1 \wedge \cdots \wedge f_n = 0.$$

Proof. Suppose f_1, \dots, f_n are linearly dependent, say, for some $\lambda_i \in \mathbb{R}$, $i \neq k$,

$$f_k = \sum_{i \neq k} \lambda_i f_i.$$

Then, as $f_i \wedge f_i = 0$,

$$f_1 \wedge \cdots \wedge f_n = 0.$$

Suppose that $f_1, \dots, f_n \in E^*$ are linearly independent. By Lemma 21, there are $x_1, \dots, x_n \in E$ such that

$$f_i(x_j) = \delta_{i,j}, \quad 1 \leq i, j \leq n.$$

Then $\det(f_i(x_j)) = 1$, and hence

$$(f_1 \wedge \cdots \wedge f_n)(x_1, \dots, x_n) = 1,$$

so $f_1 \wedge \cdots \wedge f_n$ is not identically 0. □

4. $E = \mathbb{R}^k$

We now take $E = \mathbb{R}^k$. For $1 \leq i \leq k$ define $\xi_i \in (\mathbb{R}^k)^*$ by

$$\xi_i(x_1, \dots, x_k) = x_i, \quad (x_1, \dots, x_k) \in \mathbb{R}^k.$$

Let $e_i = (0, \dots, \underbrace{1}_i, \dots, 0) \in \mathbb{R}^k$ for $1 \leq i \leq k$, in other words,

$$\xi_i(e_j) = \delta_{i,j}, \quad 1 \leq i, j \leq k.$$

For $x \in \mathbb{R}^k$,

$$x = \sum_{1 \leq i \leq k} \xi_i(x) e_i.$$

Theorem 23. (i) *If $f \in \mathcal{L}_p(\mathbb{R}^k; \mathbb{R})$ then for $(x_1, \dots, x_k) \in (\mathbb{R}^k)^p$,*

$$f(x_1, \dots, x_p) = \sum_{1 \leq i_1, \dots, i_p \leq k} f(e_{i_1}, \dots, e_{i_p}) \xi_{i_1}(x_1) \cdots \xi_{i_p}(x_p).$$

(ii) *If $f \in \mathcal{A}_p(\mathbb{R}^k; \mathbb{R})$ then*

$$f = \sum_{1 \leq i_1 < \cdots < i_p \leq k} f(e_{i_1}, \dots, e_{i_p}) \xi_{i_1} \wedge \cdots \wedge \xi_{i_p}.$$

(iii)

$$\dim \mathcal{A}_p(\mathbb{R}^k; \mathbb{R}) = \binom{k}{p}.$$

(iv) If $f \in \mathcal{A}_k(\mathbb{R}^k; \mathbb{R})$ then

$$f = f(e_1, \dots, e_n) \xi_1 \wedge \dots \wedge \xi_k.$$

Proof. (i) Let $f \in \mathcal{L}_p(\mathbb{R}^k; \mathbb{R})$. For $(x_1, \dots, x_p) \in (\mathbb{R}^k)^p$, because $f : (\mathbb{R}^k)^p \rightarrow \mathbb{R}$ is multilinear,

$$\begin{aligned} f(x_1, \dots, x_p) &= f\left(\sum_{1 \leq i_1 \leq k} \xi_{i_1}(x_1) e_{i_1}, \dots, \sum_{1 \leq i_p \leq k} \xi_{i_p}(x_p) e_{i_p}\right) \\ &= \sum_{1 \leq i_1, \dots, i_p \leq k} \xi_{i_1}(x_1) \cdots \xi_{i_p}(x_p) f(e_{i_1}, \dots, e_{i_p}). \end{aligned}$$

(ii) Let $f \in \mathcal{A}_p(\mathbb{R}^k; \mathbb{R})$. Then $f = A_p f$ (Theorem 9),

$$f = \frac{1}{p!} \sum_{\sigma \in S_p} (\text{sgn } \sigma) \sigma f,$$

so for $(x_1, \dots, x_p) \in (\mathbb{R}^k)^p$, applying Theorem 20,

$$\begin{aligned} f(x_1, \dots, x_p) &= \frac{1}{p!} \sum_{\sigma \in S_p} (\text{sgn } \sigma) f(x_{\sigma(1)}, \dots, x_{\sigma(p)}) \\ &= \frac{1}{p!} \sum_{\sigma \in S_p} (\text{sgn } \sigma) \sum_{1 \leq i_1, \dots, i_p \leq k} \xi_{i_1}(x_{\sigma(1)}) \cdots \xi_{i_p}(x_{\sigma(p)}) f(e_{i_1}, \dots, e_{i_p}) \\ &= \frac{1}{p!} \sum_{1 \leq i_1, \dots, i_p \leq k} f(e_{i_1}, \dots, e_{i_p}) \sum_{\sigma \in S_p} (\text{sgn } \sigma) \xi_{i_1}(x_{\sigma(1)}) \cdots \xi_{i_p}(x_{\sigma(p)}) \\ &= \frac{1}{p!} \sum_{1 \leq i_1, \dots, i_p \leq k} f(e_{i_1}, \dots, e_{i_p}) (\xi_{i_1} \wedge \dots \wedge \xi_{i_p})(x_1, \dots, x_p). \end{aligned}$$

Since f is alternating, $i_r = i_s$ for $r \neq s$ implies $f(e_{i_1}, \dots, e_{i_p}) = 0$. Let

$$\mathcal{I}_{p,k} = \{I \subset \{1, \dots, k\} : |I| = p\};$$

For $I \in \mathcal{I}_{p,k}$, define I_1, \dots, I_p by $I = \{I_1, \dots, I_p\}$ and $I_1 < \dots < I_p$. Then, applying Theorem 16, as $|S_I| = p!$,

$$\begin{aligned} f &= \frac{1}{p!} \sum_{I \in \mathcal{I}_{p,k}} \sum_{\tau \in S_I} f(e_{\tau(I_1)}, \dots, e_{\tau(I_p)}) \xi_{\tau(I_1)} \wedge \dots \wedge \xi_{\tau(I_p)} \\ &= \frac{1}{p!} \sum_{I \in \mathcal{I}_{p,k}} \sum_{\tau \in S_I} (\text{sgn } \tau) f(e_{I_1}, \dots, e_{I_p}) (\text{sgn } \tau) \xi_{I_1} \wedge \dots \wedge \xi_{I_p} \\ &= \sum_{I \in \mathcal{I}_{p,k}} f(e_{I_1}, \dots, e_{I_p}) \xi_{I_1} \wedge \dots \wedge \xi_{I_p}. \end{aligned}$$

proving the claim.

(iii) $|\mathcal{I}_{p,k}| = \binom{k}{p}$.

(iv) This follows from (ii) and the fact that $|\mathcal{I}_{p,k}| = 1$ with $\mathcal{I}_{p,k} = \{\{1, \dots, k\}\}$. \square

5. DETERMINANTS

REFERENCES

1. Ralph Abraham and Jerrold E. Marsden, *Foundations of mechanics*, second ed., AMS Chelsea Publishing, Providence, RI, 2008.
2. Henri Cartan, *Differential forms*, Hermann, Paris, 1970.
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