

Integration on Manifolds

Hugo Ludemann

December 23, 2019

1 Definitions

1.1 Tensors

Definition 1. A k -tensor is a multilinear map from $V^k \rightarrow \mathbb{R}$ where V is a vector space. The set of all k -tensors is denoted $\mathfrak{T}^k(V)$. If $S \in \mathfrak{T}^k(V)$ and $T \in \mathfrak{T}^l(V)$ define a tensor-product:

$$S \otimes T(v_1, \dots, v_k, v_{k+1}, \dots, v_{k+l}) = S(v_1, \dots, v_k) \cdot T(v_{k+1}, \dots, v_{k+l}).$$

This product is left and right distributive and associative if addition is defined the obvious way.

Theorem 1. Let v_1, \dots, v_n be a basis for V , and let $\varphi_1, \dots, \varphi_n$ be the dual basis, $\varphi_i(v_j) = \delta_{ij}$. Then the set of all

$$\varphi_{i_1} \otimes \dots \otimes \varphi_{i_k}, \quad 1 \leq i_1 \leq \dots \leq i_k \leq n$$

is a basis for $\mathfrak{T}^k(V)$, which therefore has dimension n^k .

Definition 2. A k -tensor is alternating if

$$a(v_1, \dots, v_i, v_j, \dots, v_k) = -a(v_1, \dots, v_j, v_i, \dots, v_k)$$

i.e. two elements are swapped and the rest left alone.

Definition 3. If T is some k -tensor, then you can have an alternating tensor for free:

$$Alt(T) = \frac{1}{k!} \sum_{\sigma \in S_k} sign(\sigma) T(v_{\sigma 1}, \dots, v_{\sigma k})$$

where S_k is the group of permutations on k letters.

In general, the tensor product of two alternating tensors is not likely to be alternating. Enter the wedge:

Definition 4. Let $\omega \in \Omega^k(V)$ and $\nu \in \Omega^l(V)$. Then

$$\omega \wedge \nu = \frac{(k+l)!}{k!l!} Alt(\omega \otimes \nu)$$

is in $\Omega^{k+l}(V)$.

1.2 Fields and Forms

Definition 5. For $p \in \mathbb{R}^n$ the tangent space of \mathbb{R}^n at p is the set of all (p, v) , $v \in \mathbb{R}^n$. Write v_p and say ‘the vector v at p .’

Definition 6. The tangent space inherits the inner product from \mathbb{R}^n , by defining

$$\langle v_p, w_p \rangle_p = \langle v, w \rangle.$$

Definition 7. For the standard orientation in \mathbb{R}_p^n , the sensible choice is

$$[(e_1)_p, \dots, (e_n)_p].$$

Definition 8. A vector field F is a function such that

$$F(p) \in \mathbb{R}_p^n$$

for every $p \in \mathbb{R}^n$. The component functions of F are the functions $F_i : \mathbb{R}^n \rightarrow \mathbb{R}$ such that

$$F(p) = F_1(p) \cdot (e_1)_p + \dots + F_n(p) \cdot (e_n)_p.$$

Definition 9. A k –form or differential form is a function on \mathbb{R}^n such that

$$\omega(p) \in \Omega^k(\mathbb{R}_p^n).$$

A 0–form f takes a vector p and returns a tensor of rank 0, that is a number. Hence a f is considered a function from \mathbb{R}^n to \mathbb{R} . Forms inherit the operations

$$\begin{aligned} (\omega + \mu)(p) &= \omega(p) + \mu(p) \\ (f \cdot \omega)(p)(v_1, \dots, v_k) &= f(p) \cdot \omega(p)(v_1, \dots, v_k) \\ (\omega \wedge \mu)(p)(v_1, \dots, v_k) &= \omega(p)(v_1, \dots, v(k)) \wedge \mu(p)(v_1, \dots, v_k). \end{aligned}$$

If $\varphi_1(p), \dots, \varphi_n(p)$ is the dual basis to $(e_1)_p, \dots, (e_n)_p$ then any k –form can be written as

$$\omega(p) = \sum_{i_1 < \dots < i_k} \omega_{i_1, \dots, i_k}(p) \cdot [\varphi_{i_1}(p) \wedge \dots \wedge \varphi_{i_k}(p)]$$

for numbers ω_{i_1, \dots, i_k} . The form ω is said to be continuous if each of these functions is.

Definition 10. If f is a 0–form (a function $\mathbb{R}^n \rightarrow \mathbb{R}$) define a 1–form df , the ‘differential of f at p ’ by

$$df(p)(v_p) = Df(p)(v).$$

For example, writing x^i for the projection map π^i we have

$$dx^i(p)(v_p) = Df^i(p)(v) = v^i$$

and so $dx^1(p), \dots, dx^n(p)$ is the dual basis to $(e_1)_p, \dots, (e_n)_p$. In particular, df in this basis is

$$df(p)(v_p) = D_1 f(p) \cdot dx^1(p)(v_p) + \dots + D_n f(p) \cdot dx^n(p)(v_p)$$

or without arguments

$$df = D_1 f \cdot dx^1 + \dots + D_n f dx^n.$$

Definition 11. If $f : \mathbb{R}^n \rightarrow \mathbb{R}^m$ is differentiable define the transformation induced by f as

$$f_*(v_p) = (Df(p)(v))_{f(p)}.$$

Definition 12. For f as above we have $f_* : \mathbb{R}_p^n \rightarrow \mathbb{R}_{f(p)}^m$. Write f^* for the dual map¹, i.e. if $T \in \Omega^k(\mathbb{R}_{f(p)}^m)$ then

$$\begin{aligned} f^* : \Omega^k(\mathbb{R}_{f(p)}^m) &\rightarrow \Omega^k(\mathbb{R}_p^n) \\ f^*(T)(v_1, \dots, v_k) &= T(f_*(v_1), \dots, f_*(v_k)). \end{aligned}$$

If ω is a k -form on \mathbb{R}^m define the k -form $f^*\omega$ on \mathbb{R}^n by $f^*\omega(p) = f^*(\omega(f(p)))$. To be explicit,

$$f^*(\omega(p))(v_1, \dots, v_k) = \omega(f(p))(f_*(v_1), \dots, f_*(v_k)).$$

Definition 13. Let ω be a k -form:

$$\omega = \sum_{i_1 < \dots < i_k} \omega_{i_1, \dots, i_k} dx^{i_1} \wedge \dots \wedge dx^{i_k}.$$

Define the ‘differential of ω ’ by

$$d\omega = \sum_{i_1 < \dots < i_k} d\omega_{i_1, \dots, i_k} dx^{i_1} \wedge \dots \wedge dx^{i_k} = \sum_{i_1 < \dots < i_k} \sum_{\alpha=1}^n D_\alpha \omega_{i_1, \dots, i_k} \cdot dx^\alpha \wedge dx^{i_1} \wedge \dots \wedge dx^{i_k}.$$

Definition 14. A form ω is called closed if $d\omega = 0$ and exact if $\omega = d\mu$ for some μ .

2 Comments

There’s a theme of ‘economy’ in the presentation of the theorems. For example, Fubini’s Theorem is given in pretty intense generality, but several more specific results follow trivially from it, such as Leibnitz’ Rule, equality of continuous mixed derivatives, volumes of solids of revolution, Cavalieri’s Principle and most importantly the volume of the image of a rectangle under a linear transformation.

3 Issues

These are incomplete/problematic:

- 3.10 Would like a proof using the notions developed here rather than topological facts.
- 3.11, 3.12, 3.19, 3.25, 3.28, 3.29, 3.31, 3.40, 3.41 Needs proof.
- Still not sure I understand what 3.21 is getting at. Is it asking for a partition which doesn’t contain any rectangles in $A - C$? If so its easy to draw JM sets with two connected components which seem to break this idea.

¹How can this be made precise?

- 3.33 (b) straight up makes no sense. f is defined on $[a, b] \times [c, d]$ and $G(x)$ is defined, nonsensically, as $\int_a^{g(x)} f(t, x) dt$.
- Be more clear on the hypothesis of Fubini's for switching order in 3.35.
- 3-37 (b) is reportedly broken. Still needs doing with an improved hypothesis.
- 4.4 might need a better comment on orientation.

It would be good to check whether an argument about absolute convergence should ever be made explicitly.

In other proofs Lemma 3.1 is used generously, in the sense that if (P') is a family of partitions subject to some condition which does not restrict the 'fine-ness' of P' then each P' is a refinement of some generic partition and so any result involving an infimum/supremum over all partitions holds equally well over the restricted set of partitions. Would be good to clear this up.

Personally I think the original statement 3.21 is pretty confusing. It could state explicitly that the partition contains no subrectangles contained in $A - C$.

4 Problems

Problem. 3.1 Let $f : [0, 1] \times [0, 1] \rightarrow \mathbb{R}$ be defined by

$$f(x, y) = \begin{cases} 0 & \text{if } 0 \leq x < \frac{1}{2} \\ 1 & \text{if } \frac{1}{2} \leq x \leq 1. \end{cases}$$

Then f is integrable and the value of the integral is $\frac{1}{2}$.

Proof. For $\varepsilon > 0$ let P_ε be the partition with subrectangles

$$\begin{aligned} S_1 &= [0, \frac{1}{2} - \frac{\varepsilon}{4}] \times [0, 1] \\ S_2 &= [\frac{1}{2} - \frac{\varepsilon}{4}, \frac{1}{2} + \frac{\varepsilon}{4}] \times [0, 1] \\ S_3 &= [\frac{1}{2} + \frac{\varepsilon}{4}, 1] \times [0, 1] \end{aligned}$$

Then $U(f, P_\varepsilon) - L(f, P_\varepsilon) = \frac{\varepsilon}{2} < \varepsilon$ i.e. f is integrable and $\int f = \inf U(f, P_\varepsilon) = \frac{1}{2}$. \square

Problem. 3.2 Let $f : A \rightarrow \mathbb{R}$ be integrable and $g = f$ except at finitely many points. Then g is integrable and $\int f = \int g$.

Proof. Suppose f and g differ except at a single point x . Let P be some partition fine enough that x lies in a single subrectangle S . Then

$$(U - L)(g, P) = (U - L)(f, P) + (M_S - m_S)(g - f) \cdot v(S)$$

can be made arbitrarily small, as the term $(U - L)(f, P)$ vanishes by integrability of f and the other term can be made as small as we like by insuring that the rectangle S is sufficiently small. Furthermore if $g(x) > f(x)$ then

$$\int g = \inf[U(g, P)] = \inf[U(f, P) + (M_S(g - f) \cdot v(S))] = \inf[U(f, P)] = \int f$$

with a similar argument for when $g(x) < f(x)$. Repetition of the argument proves the result for a finite collection of points. \square

Problem. 3.3 Linearity of the Integral. Let $f, g : A \rightarrow \mathbb{R}$ be integrable. Then $\int f + g = \int f + \int g$ and $\int cf = c \int f$.

Proof. Since

$$m_S(f) + m_S(g) \leq f(x) + g(x) \quad \forall x \in S$$

it follows that

$$m_S(f) + m_S(g) \leq \inf_S(f + g) = m_S(f + g).$$

Then $L(f, P) + L(g, P) \leq L(f + g, P)$ follows easily and by a similar argument $U(f + g, P) \leq U(f, P) + U(g, P)$. Hence the difference $(U - L)(f + g, P)$ is bounded from above by $(U - L)(f, P) + (U - L)(g, P)$ which vanishes by integrability of f and g .

To compute the value of the integral,

$$\begin{aligned}\int f + \int g &= \sup L(f, P) + \sup L(g, P) = \sup[L(f, P) + L(g, P)] \leq \sup L(f + g, P) = \int f + g \\ \int f + \int g &= \inf U(f, P) + \inf U(g, P) = \inf[U(f, P) + U(g, P)] \geq \inf U(f + g, P) = \int f + g\end{aligned}$$

and so $\int f + \int g = \int f + g$.

Finally for constants c ,

$$\inf U(cf, P) = c \inf U(f, P) = c \sup L(f, P) = \sup L(cf, P)$$

i.e cf is integrable with the value $\int cf = \inf U(cf, P) = c \inf U(f, P) = c \int f$. \square

Problem. 3.4 Let $f : A \rightarrow \mathbb{R}$ and let P be a partition of A . Then f is integrable if and only if the restriction of f to each subrectangle is integrable, and in this case $\int_A f = \sum_P \int_S f|_S$.

Proof. Let the n subrectangles of P be S_i and suppose that each $f|_{S_i}$ is integrable. Then for any $\varepsilon > 0$ and each i there is a partitions P_i of S_i such that $(U - L)(f|_{S_i}, P_i) < \varepsilon/n$. Then

$$\sum_{S_i \in P} \sum_{S_{ij} \in P_i} [(M_{S_{ij}} - m_{S_{ij}})(f|_{S_i}) \cdot v(S_{ij})] < \varepsilon \implies \sum_{S_i \in P} \sum_{S_{ij} \in P_i} [(M_{S_{ij}} - m_{S_{ij}})(f) \cdot v(S_{ij})] < \varepsilon$$

where the latter double sum is $(U - L)f$ over the partition formed by taking the union of all the P_i . Hence f is integrable.

On the other hand for any rectangle $S \in P$ we have

$$(U - L)(f|_S, S) = (U - L)(f, S) \leq (U - L)(f, P)$$

since $U - L$ is non-negative and S is contained in P . If f is integrable then the RHS can be made arbitrarily small by refining P , in which case S may need to be replaced by the part of that refinement which covers it, $S = \cup P'$. Then $(U - L)(f|_S, P')$ vanishes and so $f|_S$ is integrable.

To compute the integral we have, for partitions P_S of each S

$$\sum_P \int_S f|_S = \sum_P \sup [L(f|_S, P_S)] = \sup \left[\sum_P L(f|_S, P_S) \right] = \sup \left[\sum_P \sum_{P_i} m_{S_{ij}}(f) \cdot v(S_{ij}) \right].$$

The last term is the supremum over partitions P' which are generic partitions of A but for the refinement that each rectangle must be contained in one of the original $S \in P$. Hence the supremum over such partitions coincides with the supremum over generic ones and so $\sum \int f|_S = \int f$. \square

Problem. 3.5 Let $g, f : A \rightarrow \mathbb{R}$ be integrable and suppose $f \leq g$. Then $\int f \leq \int g$.

Proof.

$$\int f = \inf \sum M_S(f) \cdot v(S) \leq \inf \sum M_S(g) \cdot v(S) = \int g.$$

\square

Problem. If $f : A \rightarrow \mathbb{R}$ is integrable then $|f|$ is integrable and $|\int f| \leq \int |f|$.

Proof.

$$(U - L)(|f|, P) = \sum (M_S(|f|) - m_S(|f|)) \cdot v(S) \leq \sum (M_S(f) - m_S(f)) \cdot v(S)$$

which is as small as we like by integrability of f . The required comparison follows from taking infimums of

$$|\sum M_s(f) \cdot (S)| \leq \sum |M_s(f) \cdot (S)| = \sum M_s(|f|) \cdot (S).$$

□

Problem. 3.7 Let $f : [0, 1] \times [0, 1] \rightarrow \mathbb{R}$ be defined by

$$f(x, y) = \begin{cases} 0 & \text{if } x \text{ is irrational or } y \text{ is irrational} \\ 1/q & \text{if } x \text{ is rational and } y = p/q \text{ in lowest terms.} \end{cases}$$

Then f is integrable and the integral is 0.

Proof. ?

□

Problem. 3.8 The rectangle $A = \Pi[a_i, b_i] \subset \mathbb{R}^m$ does not have content zero if each $a_i < b_i$.

Proof. Let U_1, \dots, U_n be a finite cover of closed rectangles with each U_i contained in A and let $P_d = (a_d = t_{d0} < \dots < t_{dk(d)} = b_d)$ be the partition containing all the endpoints of U_i in the d th dimension, $d = 1, \dots, m$. Then each $v(U_i) = \prod_{d=1}^m \sum (t_{d,j} - t_{d,j-1})$ for a ‘certain number’ of summands. Moreover each $\prod_{d=1}^m (t_{d,j} - t_{d,j-1})$ lies in at least one U_i , so

$$\sum v(U_i) \geq \prod_{d=1}^m \sum_{j=1}^{k(d)} (t_{d,j} - t_{d,j-1}) = \prod (b_d - a_d) = v(A)$$

which is positive so long as each $a_i < b_i$.

□

Problem. 3.9 An unbounded set cannot have content zero, but can have measure zero.

Proof. If A has content zero then there is a finite cover of A by closed rectangles. Then each point of A lies in some closed rectangle, i.e. A is bounded.

The set $\{1, 2, 3, \dots\}$ is clearly unbounded, but the cover $n \in [n - \frac{\varepsilon}{2^{n+1}}, n + \frac{\varepsilon}{2^{n+1}}]$ has volume ε , which is as small as we like.

□

Problem. 3.10 A bounded set of content zero has boundary of content zero, but a bounded set of measure zero may have boundary with positive measure.

Proof. Using results from topology. Let C be a bounded set, \overline{C} the closure of C and U_i a finite cover of C by closed rectangles. Then $U = \cup U_i$ is a finite union of closed sets, hence closed. The closure of C is by definition the smallest closed set containing C . Furthermore it can be shown that it also contains the boundary of C , whence $\partial C \subset \overline{C} \subset U$ and so ∂C has content zero.

On the other hand the set $\mathbb{Q} \cap [0, 1]$ is bounded and has zero measure but its boundary is that whole interval.

□

Would be better to give a proof using only the theorems introduced in the book so far.

Problem. 3.11 Let $A \subset [0, 1]$ be the union over countably many intervals (a_i, b_i) such that each rational number in $(0, 1)$ is contained in some interval. Problem 1 – 18 states that $\partial A = [0, 1] - A$. Show that if each $b_i > a_i$ then A does not have zero measure.

Proof. Follows from the subadditivity of a measure, but since that tool has not been introduced need a different proof. \square

Problem. 3.12 Let $f : [a, b] \rightarrow \mathbb{R}$ be increasing. Then the set $X = \{x : f \text{ discontinuous at } x\}$ has measure zero.

Proof. \square

Problem. 3.13 Any open cover admits a countable subcover.

Proof. The first result is that the collection of ‘rational rectangles’ - closed rectangles with all rational endpoints - is countable. This is a consequence of theorem which says a finite cartesian product of countable sets is countable, after identifying the rectangle in \mathbb{Q}^n with a point in \mathbb{Q}^{2n} .

For the main result, let C_i be any open cover. For any x in our set, there is some C_i containing x . Then there is a closed rectangle B with $x \in B \subset C_i$. By a generalisation of the argument that any interval contains infinitely many rational numbers, there is a rational rectangle A_x with $x \in A_x \subset B \subset C_i$. Then the union of all the A_x is obviously a cover, which cannot be larger than $\cup_{\mathbb{N}} A_j$ since there are only countably many rational rectangles A . Then each x is in some $A_j \subset C_j$, whence C_j is a cover. \square

Problem. 3.14 If f and g are integrable then so is $f \cdot g$.

Proof. Let D_f, D_g be the sets on which f and g are not continuous. Then (Theorem 3.8) both are measure zero and so (Theorem 3.4 / subadditivity of measure) $D_{f \cdot g} \subset D_f \cup D_g$ is measure zero. By Theorem 3.8 again $f \cdot g$ is integrable. \square

Problem. 3.15 If C has content zero then C is Jordan Measurable and then volume of C is zero.

Proof. Since C is content zero it can be covered by finitely many closed rectangles. Let a_i, b_i be the smallest and largest of the endpoints in each dimension, then define $A = \prod [a_i, b_i]$. Then A contains C which is therefore bounded. By problem 3.10 the boundary of C has content zero, hence measure zero and so the C is Jordan Measurable.

To compute the integral take $\varepsilon > 0$ and let U_1, \dots, U_n be some cover of C which has volume smaller than ε . Let P be some partition of A consisting of each U together with other rectangles V . Then

$$L(\chi_C, P) = \sum 1 \cdot v(U) + \sum 0 \cdot v(V) = \sum v(U) < \varepsilon$$

and so $\int_C 1 = 0$. \square

Problem. 3.16 The same does not hold for bounded sets of measure zero.

Proof. Consider $\mathbb{Q} \cap [0, 1]$. The set is bounded and has zero measure but (because the boundary is large) not integrable. If P is any partition, then each subrectangle S contains both rational and irrational numbers, so $M_s(\chi_C) = 1$ and $m_s(\chi_C) = 0$. Clearly the upper and lower sums over P can never agree. \square

Problem. 3.17 If C is a bounded set of measure zero and $\int_C 1$ exists then it must be zero.

Proof. Let A be some rectangle containing C so that $\int_C 1 = \int_A \chi_C$ and let P be a partition of A . Then

$$L(\chi_C, P) = \sum m(\chi_C, S) \cdot v(S) + \sum m(\chi_C, Q) \cdot v(Q) = \sum v(S)$$

where S are the subrectangles contained in C and Q are the rest. The inclusion $S \subset C$ implies S is also zero measure, and so by problem 3.8 is a degenerate rectangle. This is not allowed in our definition of a partition and so all subrectangles are of the type Q , so $L(\chi_C, P) = 0$ for any partition P . We have assumed that the integral exists, and so its value must be zero. \square

Problem. 3.18 If $f : A \rightarrow \mathbb{R}$ is non-negative and $\int f = 0$ then the support of f has measure zero.

Proof. For any integer n and $\varepsilon > 0$ let P be a partition with $\sum M_S(f) \cdot v(S) < \varepsilon/n$. Then either $M_S(f) > 1/n$ or $M_S(f) \leq 1/n$ and so

$$\sum_{M \leq 1/n} M_S(f) \cdot v(S) + \sum_{M > 1/n} \frac{1}{n} v(S) < \varepsilon/n$$

from which (since both sums are finite)

$$\sum_{i=1, \dots, k} v(S_i) < \varepsilon.$$

If D_n is defined as $\{x : f(x) > 1/n\}$ then it is surely covered by these S , which the argument above shows to be a cover of content zero. The support of $\text{supp}(f) = D_1 \cup D_2 \cup \dots$ is a countable union of measure zero sets, hence measure zero. \square

Problem. 3.19 Let U be the open set in problem 3.11. If $f = \chi_U$ except on a set of measure zero then f is not integrable.

Proof. ? \square

Problem. 3.20 An increasing function from $[a, b]$ to \mathbb{R} is integrable.

Proof. By problem 3.12 the subset of the domain where the function is discontinuous has measure zero. The function is therefore integrable by theorem 3.8. \square

Problem. 3.21 Let A be a closed rectangle and $C \subset A$ and let P be some partition in which every subrectangle is either contained in C , or intersects C (without being contained.) That is, there are no subrectangles in $A - C$.

Proof. ? \square

Problem. 3.22 If A is a JM set and $\varepsilon > 0$ there is a compact JM set $C \subset A$ such that $\int_{A-C} 1 < \varepsilon$.

Proof. Baffling statement. □

Problem. 3.23 Let $C = A \times B$ be a set of content zero. Let $A' \subset A$ be the set of $x \in A$ such that $\{y \in B : (x, y) \in C\}$ is not content zero. Then A' is measure zero.

Proof. By problem 3.15 C is Jordan Measurable and has volume 0. □

Problem. 3.24 The result of problem 3.23 does not hold in general for sets of measure zero.

Proof. Let $C \subset [0, 1] \times [0, 1]$ be the union of all $\{p/q\} \times [0, 1]$ where p/q is a rational number in $[0, 1]$ with p/q in lowest terms. It's a weird comb kind of thing. The C has content zero as the bounded countable union of measure zero sets, but for any p/q the set $\{y \in [0, 1] : (p/q, y) \in C\} = [0, p/q]$ is not content zero for any p/q , i.e. A' is all rationals in $[0, 1]$, which is not content zero. □

Problem. 3.25 Non-degenerate rectangles have positive measure. (Alternative proof to problem 3.8. Useful, because that proof sucks.)

Proof. Seems to be more going on than I thought. □

Problem. 3.26 Let $f : [a, b] \rightarrow \mathbb{R}$ be integrable and non-negative and let A_f be the region between the graph of $f(x)$ and the x -axis. Then A_f is Jordan Measurable and has area $\int_a^b f$.

Proof. The boundary of A consists of three bounded line segments and the graph of f . Since f is integrable, it is continuous almost everywhere and so the the graph is a countable union² of continuous plane curves. Together with the obvious fact that A_f is bounded establishes that A_f is Jordan measurable.

Let M be some upper bound for f . Then

$$\mathcal{L}(x) = \int_{[0, M]} \chi_{A_f}(x, y) dy = f(x)$$

and so by Fubini the volume of A_f is

$$\int_{A_f} 1 = \int_{[a, b] \times [0, M]} \chi_{A_f} \int_{[a, b]} \mathcal{L}(x) = \int_a^b f.$$

□

Problem. 3.27 If $f : [a, b] \times [a, b] \rightarrow \mathbb{R}$ is continuous then

$$\int_a^b \int_a^y f(x, y) dx dy = \int_a^b \int_x^b f(x, y) dy dx.$$

²A measure zero subset of an interval must be a countable union of singletons.

Proof. Let C be the region above the diagonal, that is

$$\{(x, y) : y \in [a, b] \text{ and } x \in [a, y]\} = \{(x, y) : x \in [a, b] \text{ and } y \in [x, b]\}.$$

Then

$$\int_C f = \int_{[a,b],[a,b]} \chi_C \cdot f = \int_{[a,b]} \left(\int_{[a,b]} (f \cdot \chi_C)(x, y) dy \right) dx = \int_a^b \left(\int_x^b f dy \right) dx$$

with the other side following from a similar calculation. \square

Problem. 3.28 $D_{1,2}f = D_{2,1}f$ so long as these are continuous.

Proof. ? \square

Problem. 3.29 Find the volume of the solid obtained by rotating a JM set in the yz plane about the z -axis.

Proof. ? \square

Problem. 3.30 Let C be the set in problem 1.17 (the evil dense subset of the unit square containing at most one point on any horizontal or vertical line.) Then both $\int_0^1 \int_0^1 \chi_C dy dx$ and $\int_0^1 \int_0^1 \chi_C dx dy$ are zero but the integral over C does not exist.

In other words, the converse of Fubini's theorem does not hold in general.

Proof. For any fixed x , the integral $\int_0^1 \chi_C(x, y) dy$ is clearly zero since C contains at most a single point on the line $\{x\} \times [0, 1]$ from which it follows that the first double integral is 0. The argument for the other one is exactly the same.

Since C is dense, any rectangle contains both a point inside C and a point outside C and so $M_S = 1, m_S = 0$ for any rectangle S . Clearly the upper and lower integrals cannot coincide. \square

Problem. 3.31 For $A = [a_1, b_1] \times \dots \times [a_n, b_n]$ and $f : A \rightarrow \mathbb{R}$ define $F : A \rightarrow \mathbb{R}$ by

$$F(x) = \int_{[a_1, b_1] \times \dots \times [a_n, b_n]} f.$$

What is $D_i f(x)$ for x in the interior of A ?

Proof. ? \square

Problem. 3.32: Leibnitz' Rule Let $f : [a, b] \times [c, d] \rightarrow \mathbb{R}$ be continuous and suppose $D_2 f$ is continuous. Define $F(y) = \int_a^b f(x, y) dx$. Then $F'(y) = \int_a^b D_2 f(x, y) dx$.

Proof. Rewrite $F(y)$ as

$$\int_a^b \int_c^y D_2 f(x, t) dt dx + \int_a^b f(x, c) dx.$$

By continuity of $D_2 f$ the order of integration may be reversed. The result follows from the fundamental theorem of calculus applied to the first integral and the y -independence of the second. \square

Problem. 3.33 If $f : [a, b] \times [c, d] \rightarrow \mathbb{R}$ is continuous, define $F(x, y) = \int_a^x f(t, y) dt$. Find $D_1 F$ and $D_2 F$.

Proof. By the FTC, $D_1 F(x, y) = f(x, y)$ and by Leibnitz' rule $D_2 F(x, y) = \int_a^x D_2 f(t, y) dt$. \square

Problem. 3.34 Let $g_1, g_2 : \mathbb{R}^2 \rightarrow \mathbb{R}$ be continuously differentiable and suppose $D_1 g_2 = D_2 g_1$. Define

$$f(x, y) = \int_0^x g_1(t, 0) dt + \int_0^y g_2(x, t) dt.$$

Then $D_1 f(x, y) = g_1(x, y)$.

Proof. By FTC and Leibnitz' rule

$$\begin{aligned} D_1 f(x, y) &= g_1(x, 0) + \int_0^y D_1 g_2(x, t) dt \\ &= g_1(x, 0) + \int_0^y D_2 g_1(x, t) dt \\ &= g_1(x, 0) + g_1(x, y) - g_1(x, 0) \\ &= g_1(x, y). \end{aligned}$$

\square

Problem. 3.35 If $G : \mathbb{R}^n \rightarrow \mathbb{R}^n$ is a invertible linear transformation and U a rectangle, then the volume of $G(U)$ is $|\det G| \cdot v(U)$.

Proof. Let $U = [a_1, b_1] \times \dots \times [a_n, b_n]$ and consider first of all three kinds of elementary transformations.

1. G takes one of the basis vectors e^i to ce^i and fixes the rest. If c is positive then

$$\begin{aligned} v(G(U)) &= v([a_1, b_1] \times \dots \times [ca_i, cb_i] \times \dots \times [a_n, b_n]) \\ &= (b_1 - a_1) \cdot \dots \cdot (cb_i - ca_i) \cdot \dots \cdot (b_n - a_n) \\ &= c \cdot v(U). \end{aligned}$$

The matrix representation of G is the identity with the i -th entry replaced by c , which has determinant c . If c is negative then the absolute value signs are needed but the volume is unchanged, although $[a, b]$ must become $[cb, ca]$.

2. G swaps two dimensions and fixes the rest, i.e. $g(e_i) = e_j$ and $g(e_j) = e_i$. As a matrix G is the identity with zeros in the i and j -th positions, and ones in the $G_{i,j}$ and $G_{j,i}$ positions. In \mathbb{R}^3 it might look like

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}$$

and in any dimension larger than one has determinant -1 . Clearly this operation has no effect on the volume of the rectangle

3. G adds basis vector to another and fixes the rest, i.e.

$$G(x^1, \dots, x^i, \dots, x^j, \dots, x^n) = (x^1, \dots, x^i + x^j, \dots, x^j, \dots, x^n).$$

As a matrix G is the identity with a single extra one somewhere, and so it is easy to see that $\det G = 1$.

Linear operators on \mathbb{R}^n are bounded, so the volume of $G(U)$ can be calculated as

$$\int_{[-M_n, M_n] \times \dots \times [-M_1, M_1]} \chi_{G(U)} dx^1 \dots dx^n$$

for some upper bound M of both U and $G(U)$. Since Fubini's theorem will allow us to interchange the order of integration, we can assume that G adds e_2 to e_1 and leaves the rest. Then $v(G(U)) =$

$$\int_{[-M_n, M_n] \times \dots \times [-M_3, M_3]} \left(\int_{[-M_2, M_2] \times [-M_1, M_1]} \chi_{G(U)}(x^1, x^2, \dots) dx^1 dx^2 \right) dx^3 \dots dx^n.$$

The value of the inner integral is the area of a parallelogram, which coincides with the area of the rectangle which fell over. Hence this inner integral would not be changed by replacing $\chi_{G(U)}$ with χ_U . Furthermore, for fixed a^1 and a^2 and varying coordinates in the remaining positions, $\chi_U(a_1, a_2, x_3, \dots, x_n)$ and $\chi_{G(U)}(a_1, a_2, x_3, \dots, x_n)$ coincide exactly. So for the purposes of evaluating this integral, χ_U will do just as well as $\chi_{G(U)}$, or in other words their volumes are equal.

Finally if G is the composition of elementary operations as described above then G alters the volume of U by a factor of

$$|\det G_1| \cdot \dots \cdot |\det G_m| = |\det G_1 \cdot \dots \cdot \det G_m| = |\det(G_1 \cdot \dots \cdot G_m)| = |\det G|.$$

We take as a fact that these elementary operations generate the whole group of invertible matrices and so this scaling factor is good for any invertible linear map. \square

Problem. 3.36 Cavalieri's Principle. Let A and B be JM subsets of \mathbb{R}^3 . Let $A_c = \{(x, y) : (x, y, c) \in A\}$ and define B_c similarly. If each A_c and B_c are JM and have the same area then A and B have the same volume.

Proof. Let $[-M, M]^3$ be a rectangle bounding A and B . Then

$$\begin{aligned} \int_{[-M, M]^3} \chi_A &= \int_{-M}^M \left(\int_{[-M, M]^2} \chi_A \right) dz \\ &= \int_{-M}^M \left(\int_{A_z} 1 \right) dz = \int_{-M}^M \left(\int_{B_z} 1 \right) dz \\ &= \int_{-M}^M \left(\int_{[-M, M]^2} \chi_B \right) dz = \int_{[-M, M]^3} \chi_B. \end{aligned}$$

\square

Problem. 3.37 Suppose that $f : (0, 1) \rightarrow \mathbb{R}$ is non-negative and continuous. Then $\int_{(0,1)} f$ exists if and only if $\lim_{\varepsilon \rightarrow 0} \int_{\varepsilon}^{1-\varepsilon} f$ exists.

Proof. Let o be the cover of $(0, 1)$ consisting of the intervals $(1/n, 1 - 1/n)$ and Φ a C^∞ partition of unity for $(0, 1)$ subordinate to o . Then each φ_i in Φ has support contained in some $(1/m_i, 1 - 1/m_i)$ in o . Choose an ordering of Φ so that if $i < j$ then $m_i \leq m_j$, that way the support of φ_i is in $(1/m_j, 1 - 1/m_j)$ for all $j > i$.

Then the partial sums can be written as

$$\sum_{k=1}^n \int_{(0,1)} \varphi_k \cdot f = \sum_{k=1}^n \int_{1/m_k}^{1-1/m_k} \varphi_k \cdot f = \sum_{k=1}^n \int_{1/m_n}^{1-1/m_n} \varphi_k \cdot f = \int_{1/m_n}^{1-1/m_n} \sum_{k=1}^n \varphi_k \cdot f = \int_{1/m_n}^{1-1/m_n} f.$$

Since $\varphi \cdot f$ is non-negative, convergence and absolute convergence are the same thing. Thus the extended integral exists if and only if the given limit exists. \square

Problem. 3.38 Let A_n be a closed set in $(n, n+1)$. Suppose that $f : \mathbb{R} \rightarrow \mathbb{R}$ satisfies $\int_{A_n} f = (-1)^n/n$ and $f = 0$ outside A_n . Then f is not integrable.

Proof. Let Φ_n be a partition of unity for A_n and extend each φ to a function on \mathbb{R} by setting $\varphi = 0$ outside A_n . Then their union Φ is a partition of unity for all of \mathbb{R} and

$$\sum_{\Phi} \int_{\mathbb{R}} \varphi \cdot |f| = \sum_{\mathbb{N}} \left(\sum_{\Phi_n} \int_{\mathbb{R}} \varphi \cdot |f| \right) = \sum_{\mathbb{N}} \left(\sum_{\Phi_n} \int_{A_n} \varphi \cdot |f| \right) = \sum_{\mathbb{N}} \int_{A_n} f = -\log 2.$$

Following the example in the wiki for conditional convergence, define the sets

$$B_n = A_{2n-1} \cup A_{2(2n-1)} \cup A_{4n}$$

and let Φ_n be a partition of unity for B_n , taking the value 0 outside B_n . Then as above

$$\sum_{\Phi} \int_{\mathbb{R}} \varphi \cdot |f| = \sum_{\mathbb{N}} \left(\sum_{\Phi_n} \int_{\mathbb{R}} \varphi \cdot |f| \right) = \sum_{\mathbb{N}} \left(\sum_{\Phi_n} \int_{B_n} \varphi \cdot |f| \right) = \sum_{\mathbb{N}} \int_{B_n} f.$$

Each of the integrals in the last sum has the value

$$\begin{aligned} \int_{B_n} f &= \int_{A_{2n-1}} f + \int_{A_{2(2n-1)}} f + \int_{A_{4n}} f \\ &= \frac{(-1)^{2n-1}}{2n-1} + \frac{(-1)^{2(2n-1)}}{2(2n-1)} + \frac{(-1)^{4n}}{4n} \\ &= \frac{1}{2(2n-1)} + \frac{1}{4n} - \frac{1}{2n-1} \\ &= \frac{1}{2} \left(\frac{-1}{2n-1} + \frac{1}{2n} \right) \end{aligned}$$

and so the sum converges to $-1/2 \log 2$. \square

Problem. 3.39 The condition that $\det g$ in the formula for change of variables is superfluous, due to Sard's Theorem.

Proof. ?

□

Problem. 3-40 If $g : \mathbb{R}^n \rightarrow \mathbb{R}^n$ and $\det g'(x) \neq 0$ then there is an open set containing x in which $g = T \circ g_n \circ \dots \circ g_1$ where each g_i is of the form $g_i(x) = (x^i, \dots, f_i(x^i), \dots, x^n)$ and T is a linear transformation. Furthermore g can be written as $g = g_n \circ \dots \circ g_1$ if and only if g' is diagonal.

Proof. ?

□

Problem.

$$\int_{-\infty}^{\infty} e^{-x^2} dx = \sqrt{\pi}.$$

Proof. 1. Define $f : \{r : r > 0\} \times (0, 2\pi) \rightarrow \mathbb{R}^2$ by $f(r, \vartheta) = r(\cos \vartheta, \sin \vartheta)$. If $r(\cos \vartheta, \sin \vartheta) = r'(\cos \vartheta', \sin \vartheta')$ then the Pythagorean identity easily gives $r = r'$, and so

$$\cos \vartheta = \cos \vartheta', \quad \sin \vartheta = \sin \vartheta'.$$

□

5 Integration on Chains

Problem. 4.1 Let e_1, \dots, e_n be the usual basis of \mathbb{R}^n and let φ_i be the dual basis. Then (a) $\varphi_{i_1} \wedge \dots \wedge \varphi_{i_k}(e_{i_1}, e_{i_k}) = 1$ and (b) $\varphi_{i_1} \wedge \dots \wedge \varphi_{i_k}(v_1, \dots, v_k)$ is the determinant of the $k \times k$ minor of

$$\begin{pmatrix} v_1 \\ \dots \\ v_k \end{pmatrix}$$

obtained by selecting i_1, \dots, i_k .

Proof. By induction on k . If $k = 1$ then $\varphi_i(e_i) = 1$. Assume the result for $k - 1$. Then

$$(\varphi_{i_1} \wedge \dots \wedge \varphi_{i_{k-1}}) \wedge \varphi_{i_k}(e_{i_1}, \dots, e_{i_{k-1}}, e_{i_k}) = \frac{1}{(k-1)!} \sum_{S_k} \text{sign}(\sigma)(\varphi_{i_1} \wedge \dots \wedge \varphi_{i_{k-1}})(e_{\sigma(i_1)}, \dots, e_{\sigma(i_{k-1})}) \cdot \varphi_{i_k}(e_{\sigma(i_k)}).$$

Since $\varphi_{i_k}(e_{\sigma(i_k)})$ is one if σ fixes i_k and zero otherwise and $\varphi_{i_1} \wedge \dots \wedge \varphi_{i_{k-1}}$ is alternating this reduces to

$$\begin{aligned} \frac{1}{(k-1)!} \sum_{S_{k-1}} \text{sign}(\sigma)(\varphi_{i_1} \wedge \dots \wedge \varphi_{i_{k-1}})(e_{\sigma(i_1)}, \dots, e_{\sigma(i_{k-1})}) &= \\ \frac{1}{(k-1)!} \sum_{S_{k-1}} \text{sign}(\sigma)^2(\varphi_{i_1} \wedge \dots \wedge \varphi_{i_{k-1}})(e_{i_1}, \dots, e_{i_{k-1}}) &= \\ \frac{|S_{k-1}|}{(k-1)!} \cdot \varphi_{i_1} \wedge \dots \wedge \varphi_{i_{k-1}}(e_{i_1}, \dots, e_{i_{k-1}}) &= 1 \end{aligned}$$

by the inductive hypothesis.

Part (b) ? □

Problem. 4.2 Let $f : V \rightarrow V$ be linear and $\dim V = n$. Then $f^* : \Omega^n(V) \rightarrow \Omega^n(V)$ is multiplication by $\det f$.

Proof. Let v_1, \dots, v_n be a basis and let w_1, \dots, w_n be n vectors. Let A be the matrix such that $w_i = Av_i$ and let F be the matrix of f with respect to the basis v_i . Then, taking huge liberties with notation, $\omega(f(w_1), f(w_n)) =$

$$\omega(F(w_1, w_n)) = \omega(FA(v_1, v_n)) = \det(FA) \cdot \omega(v_1, v_n) = \det F \cdot \omega(A(v_1, v_n)) = \det F \cdot \omega(w_1, w_n).$$

□

Problem. 4.3 If ω is the volume element determined by T and μ and w_1, \dots, w_n are vectors in V then

$$|\omega(w_1, \dots, w_n)| = \sqrt{\det(g_{ij})}.$$

Note that the hint for the problem has the indices around the wrong way.

Proof. Let v_1, \dots, v_n be an orthonormal basis with respect to T and $A = a_{ih}$ numbers such that $w_i = \sum_{h=1}^n a_{ih} v_h$. Then

$$g_{ij} := T(w_i, w_j) = \sum_{h,g=1}^n a_{ih} a_{jg} T(v_i, v_j) = \sum_{k=1}^n a_{ik} a_{jk},$$

that is $(g_{ij}) = A \cdot A^T$ and

$$\sqrt{\det G} = \det A.$$

By theorem 4.6 we have $\omega(w_1, \dots, w_n) = \det A \cdot \omega(v_1, \dots, v_n) = \pm \det(A)$ (since ω is the volume element with respect to the orthonormal basis v_i) which proves the result. \square

Problem. 4.4 If ω is the volume element of V determined by T and μ and $f : \mathbb{R}^n \rightarrow V$ is an isomorphism such that $f^*T = \langle, \rangle$ and such that $[f(e_1), \dots, f(e_n)] = \mu$ then $f^* \omega = \det$.

Proof. If $(f(e_i))$ were an orthonormal basis with positive orientation then

$$1 = \omega(f(e_1), \dots, f(e_n)) = f^* \omega(e_1, \dots, e_n)$$

i.e. $f^* \omega$ is the volume element in \mathbb{R}^n . Since this is unique it equals \det .

Orthonormality of $(f(e_i))$ follows from the easy calculation

$$T(f(e_i), f(e_j)) = f^*T(e_i, e_j) = \langle e_i, e_j \rangle = \delta_{ij}.$$

\square

Problem. 4.5 If $c : [0, 1] \rightarrow (\mathbb{R}^n)^n$ is continuous and each $(c^1(t), \dots, c^n(t))$ is a basis, then any two have the same orientation.

Proof. Since $c(t)$ is a basis for any t it must always be non-singular. Hence $\det \circ c \neq 0$ on $[0, 1]$, which means it is always positive, or always negative. Let C_1 and C_2 be the matrices of two bases in this family, and A the transformation between them. Then

$$\det A = \det(C_1^{-1}) \cdot \det C_2 > 0$$

as the argument above ensures the determinants on the right have the same sign. \square

Problem. 4.6 If $v_1, \dots, v_{n-1} \in \mathbb{R}^n$ are linearly independent then $[v_1, \dots, v_{n-1}, v_1 \times \dots \times v_{n-1}]$ is the usual orientation for \mathbb{R}^n .

Proof. If $n = 2$ then it follows from the definition that

$$\begin{pmatrix} v_1 \\ v_2 \end{pmatrix} \times = \begin{pmatrix} -v_2 \\ v_1 \end{pmatrix}.$$

It is clear that $\times v$ is just v rotated 90 degrees anticlockwise, which is the usual orientation. To be extra sure, the matrix taking $(1, 0)$ to (v_1, v_2) and $(0, 1)$ to $(-v_2, v_1)$ is

$$\begin{pmatrix} v_1 & -v_2 \\ v_2 & v_1 \end{pmatrix}$$

which has positive determinant so long as at least one of v is non-zero.

Rest of it???

\square

Problem. 4.8 If $\omega \in \Omega^n(V)$ is a volume element define a ‘cross product’ in terms of ω .

Problem. 4.11 Let f be a self-adjoint linear map on V with respect to the inner product T . If v_1, v_n is an orthonormal basis and $A = (a_{ij})$ is the matrix of f with respect to v_i then A is symmetric.

Proof. Going straight into jumbo calculations, $T(x, f(y)) =$

$$T\left(\sum_i x^i v_i, f\left(\sum_j y^j v_j\right)\right) = \sum_{i,j=1}^n x^i y^j T(v_i, f(v_j)) = \sum_{i,j=1}^n x^i y^j \sum_k a_{jk} T(v_i, v_k) = \sum_{i,j=1}^n x^i y^j a_{ji}.$$

By a similar calculation $T(f(x), y) = \sum_{i,j=1}^n x^i y^j a_{ij}$. Since f is self-adjoint we have

$$\sum_{i,j=1}^n x^i y^j a_{ji} = \sum_{i,j=1}^n x^i y^j a_{ij}$$

for all x, y , and so a_{ij} must equal a_{ji} . □

Problem. 4.13(a) If $f : \mathbb{R}^n \rightarrow \mathbb{R}^m$ and $g : \mathbb{R}^m \rightarrow \mathbb{R}^p$ then $(g \circ f)_* = g_* \circ f_*$.

Proof.

$$\begin{aligned} (g \circ f)_*(v_q) &= [D(g \circ f)(q)](v) = [Dg(f(q)) \circ Df(q)](v) = \\ &= Dg(f(q))(Df(q)(v)) = Dg(f(q))(f_*(v_q)) = g_*(f_*(v_q)) \end{aligned}$$

□

Problem. 4.13(b) Let $f, g : \mathbb{R}^n \rightarrow \mathbb{R}$. Then $d(f \cdot g) = f \cdot dg + g \cdot df$.

Proof.

$$d(f \cdot g) = \sum_{j=1}^n D_j(f \cdot g) \cdot dx^j = \sum_{j=1}^n [f \cdot D_j g + g \cdot D_j f] \cdot dx^j.$$

□