Geometric Algebra for Special and General Relativity

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Part I.

Special Relativity and Geometric Algebra

Chapter 1.

Introduction

The Special Theory of Relativity is a model of *spacetime* — the geometry in which physical events take place. Spacetime comprises the Euclidean dimensions of space and time, but only in a way relative to each observer moving through it: there exists no single 'universal' ruler or clock. Instead, two observers in relative motion define different decompositions of spacetime, and their respective clocks and rulers are found to disagree according to the Lorentz transformation laws. The insight of special relativity is that one should focus not on the observer-dependent notions of space and time, but on the Lorentzian geometry of spacetime itself.

Seven years after Albert Einstein introduced this theory,[1] he succeeded in formulating a relativistic picture which included gravity. In this General Theory of Relativity, gravitation is identified with the curvature of spacetime over astronomical distances. Both theories coincide locally when confined to sufficiently small extents of spacetime, over which the effects of curvature are negligible. In part I, we will focus on special relativity, leaving gravity and curvature to part II.

In acknowledgement of the Erlangen programme,[2] the study of local spacetime geometry amounts to the study of its intrinsic symmetries. These symmetries form the Poincaré group, and consist of spacetime translations and Lorentz transformations, the latter being the extension of the group of rotations of Euclidean space to the relativistic rotations of spacetime. The standard matrix representation of the Lorentz group, $\mathrm{SO}^+(1,3)$, is the connected component of the orthogonal group

$$\mathrm{O}(1,3) = \left\{\Lambda \in \mathrm{GL}(\mathbb{R}^4) \,\middle|\, \Lambda^\mathsf{T}\eta\Lambda = \eta\right\}$$

with respect to the bilinear form $\eta = \pm\mathrm{diag}(-1,+1,+1,+1)$. The rudimentary tools of matrix algebra are sufficient for an analys the Lorentz group, and are familiar to any physicist.

However, the last century has seen many other mathematical tools be applied to the study of generalised rotation groups such as $\mathrm{SO}^+(1,3)$ or the rotation group $\mathrm{SO}(3)$ of $\mathbb{R}^3$. Among these tools is the *geometric algebra*, invented[3]

[1] Einstein's paper [1] was published in 1905, the so-called *Annus Mirabilis* or "miracle year" during which he also published on the photoelectric effect, Brownian motion and the mass-energy equivalence. Each of the four papers was a monumental contribution to modern physics.

[2] Introduced by Felix Klein in 1872 [2], the Erlangen program is the characterisation of geometries (Euclidean, hyperbolic, projective, etc.) by their symmetry groups and the properties invariant under those groups. E.g., Euclidean geometry studies the invariants of rigid transformations.

by William Clifford in 1878 [4]. Geometric algebra remains largely unknown in the physics community, despite arguably being far superior for the analysis of rotations than traditional matrix techniques. It is informative to glean some of the history that led to this (perhaps unfortunate) state of affairs.

[3] Clifford algebra was independently discovered by Rudolf Lipschitz two years later [3]. He was the first to use them to the study the orthogonal groups.

The quest for an optimal formalism for rotations

Mathematics has seen the invention of a variety of vector formalisms since the 1800s, and the question of which is best suited to physics has a long contentious history.

The vector algebra "war" of 1890–1945 saw William Hamilton's prized quaternion algebra $\mathbb{H}$, hailed as the optimal tool for describing rotations in $\mathbb{R}^3$, struggle for popularity before being eventually left to gather dust as an old-fashioned curiosity.

Chapter 2.

Preliminary Theory

Many of the tools we will develop for the study of spacetime share the property of being associative algebras. As well as the geometric algebra of spacetime, we will encounter tensors, exterior forms, quaternions, and other structures in this category. Instead of defining each algebra axiomatically as needed, it is easier to develop the general theory and then define each algebra succinctly as a particular quotient of the free algebra. This enables the use of the same tools and the same terminology for the analysis of different algebras.

Therefore, this section is an overview of the abstract theory of associative algebras, which more generally belongs to *ring theory*.[4] Algebras, quotients, gradings, homogeneous and inhomogeneous multivectors are defined. Throughout, $\mathbb{F}$ denotes the underlying field of some vector space. (Eventually, $\mathbb{F}$ will always be taken to be $\mathbb{R}$, but we may begin in generality.) Most definitions in this chapter can be readily generalised by replacing the field $\mathbb{F}$ with a ring.

[4] A RING is a field without the requirement that multiplicative inverses exist or that multiplication commutes; a field is a commutative ring in which non-zero elements are invertible.

2.1. Associative Algebras

Definition 1. *An* ASSOCIATIVE ALGEBRA *A is a vector space equipped with a product $\circledast : A \times A \to A$ which is associative and bilinear.*

Associativity means $(\boldsymbol{u} \circledast \boldsymbol{v}) \circledast \boldsymbol{w} = \boldsymbol{u} \circledast (\boldsymbol{v} \circledast \boldsymbol{w})$, while bilinearity means the product is:

- compatible with scalars: $(\lambda \boldsymbol{u}) \circledast \boldsymbol{v} = \boldsymbol{u} \circledast (\lambda \boldsymbol{v}) = \lambda(\boldsymbol{u} \circledast \boldsymbol{v})$ for $\lambda \in \mathbb{F}$; and
- distributive over addition: $(\boldsymbol{u} + \boldsymbol{v}) \circledast \boldsymbol{w} = \boldsymbol{u} \circledast \boldsymbol{w} + \boldsymbol{v} \circledast \boldsymbol{w}$, and similarly for $\boldsymbol{u} \circledast (\boldsymbol{v} + \boldsymbol{w})$.

This definition can be generalised by relaxing associativity or by letting $\mathbb{F}$ be a ring. However, we will use "algebra" exclusively to mean an associative algebra over a field (usually $\mathbb{R}$).

Any ring forms an associative algebra when considered as a one-dimensional vector space. The complex numbers can be viewed as a real 2-dimensional algebra by defining $\circledast$ to be complex multiplication; $(x_1, y_1) \circledast (x_2, y_2) \coloneqq (x_1 x_2 - y_1 y_2, x_1 y_2 + y_1 x_2)$.

The free tensor algebra

The most general (associative) algebra containing a given vector space V is the TENSOR ALGEBRA $V^{\otimes}$. The tensor product $\otimes$ satisfies exactly the relations of definition 1 with no others. Thus, the tensor algebra associative, bilinear and *free* in the sense that no further information is required in its definition.

As a vector space, the tensor algebra is equal to the infinite direct sum

$$V^{\otimes} \cong \bigoplus_{k=0}^{\infty} V^{\otimes k} \equiv \mathbb{F} \oplus V \oplus (V \otimes V) \oplus (V \otimes V \otimes V) \oplus \cdots \tag{2.1}$$

where each $V^{\otimes k}$ is the subspace of TENSORS OF GRADE k.

2.1.1. Quotient algebras

Owing to the maximal generality of the free tensor algebra, any other associative algebras may be constructed as a *quotient* of $V^{\otimes}$. In order for a quotient $V^{\otimes}/\sim$ by an equivalence relation $\sim$ to itself form an algebra, the relation must preserve the associative algebra structure:

Definition 2. *A* CONGRUENCE *on an algebra A is an equivalence relation $\sim$ which is compatible with the algebraic relations, so that if $a \sim a'$ and $b \sim b'$ then $a + b \sim a' + b'$ and $a \circledast b \sim a' \circledast b'$.*

The quotient of an algebra by a congruence naturally has the structure of an algebra, and so is called a QUOTIENT ALGEBRA.

Lemma 1. *The* QUOTIENT *$A/\sim$ of an algebra A by a congruence $\sim$, consisting of equivalence classes $[a] \in A/\sim$ as elements, forms an algebra with the naturally inherited operations $[a] + [b] \coloneqq [a + b]$ and $[a] \circledast [b] \coloneqq [a \circledast b]$.*

Proof. The fact that the operations $+$ and $\circledast$ of the quotient are well-defined follows from the structure-preserving properties of the congruence. Addition is well-defined if $[a] + [b]$ does not depend on the choice of representatives: if $a' \in [a]$ then $[a'] + [b]$ should be $[a] + [b]$. By congruence, we have from $a \sim a'$ so that $[a + b] = [a' + b]$ and indeed $[a] + [b] = [a'] + [b]$. Likewise for $\circledast$. $\square$

Instead of presenting an equivalence relation, it is often easier to define a congruence by specifying the set of elements which are equivalent to zero, from which all other equivalences follow from the algebra axioms. Such a set of all ‘zeroed’ elements is called an ideal.

Definition 3. *A (TWO-SIDED) IDEAL of an algebra A is a subset $I \subseteq A$ which is closed under addition and invariant under multiplication, so that*

- *if $a, b \in I$ then $a + b \in I$; and*
- *if $r \in A$ and $a \in I$ then $r \circledast a \in I \ni a \circledast r$.*

We will use the notation $\{\!\!\{A\}\!\!\}$ to mean the ideal generated by setting $a \sim 0$ for all a in A. For example, $\{\!\!\{a\}\!\!\} = \operatorname{span}\{r \circledast a \circledast r' \mid r, r' \in A\}$ is the ideal consisting of sums and products involving the specified element a, and $\{\!\!\{\boldsymbol{u} \otimes \boldsymbol{u} \mid \boldsymbol{u} \in V\}\!\!\}$, or simply $\{\!\!\{\boldsymbol{u} \otimes \boldsymbol{u}\}\!\!\}$, is the ideal in $V^{\otimes}$ consisting of sums of terms of the form $a \otimes \boldsymbol{u} \otimes \boldsymbol{u} \otimes b$ for vectors $\boldsymbol{u}$ and arbitrary $a, b \in V^{\otimes}$.

Lemma 2. *An ideal uniquely defines a congruence, and vice versa, by the identification of I as the set of elements equivalent to zero; $a \sim 0 \iff a \in I$.*

Proof. The set $I \coloneqq \{a \mid a \sim 0\}$ is indeed an ideal because it is closed under addition (for $a, b \in I$ we have $\implies a+b \sim 0+0 = 0$ so $a+b \in I$) and invariant under multiplication (for any $a \in I$ and $r \in A$, we have $r \circledast a \sim r \circledast 0 = 0 = 0 \circledast r \sim a \circledast r$). Conversely, let $a \sim a'$ and $b \sim b'$. Since $\sim$ respects addition:

$$\left.\begin{aligned} a - a' &\in I \\ b - b' &\in I \end{aligned}\right\} \implies (a+b) - (a'+b') \in I \iff a + b \sim a' + b',$$

and multiplication:

$$\left.\begin{aligned} (a - a') \circledast b &\in I \\ a' \circledast (b - b') &\in I \end{aligned}\right\} \implies a \circledast b - a' \circledast b' \in I \iff a \circledast b \sim a' \circledast b',$$

the equivalence defined by $a \sim b \iff a - b \in I$ is a congruence. □

The equivalence of ideals and congruences is a general feature of abstract algebra.[5] Furthermore, both can be given in terms of a homomorphism between algebras,[6] and this is often the most convenient way to define a quotient.

Theorem 1 (first isomorphism theorem). *If $\Psi : A \to B$ is a homomorphism, between algebras, then*

1. *the relation $a \sim b$ defined by $\Psi(a) = \Psi(b)$ is a congruence;*
2. *the kernel $I \coloneqq \ker \Psi$ is an ideal; and*
3. *the quotients $A/{\sim} \equiv A/I \cong \Psi(A)$ are all isomorphic.*

[5] For example, in group theory, ideals are *normal subgroups* and a congruence is an equivalence relation satisfying $gag^{-1} \sim \mathrm{id}$ whenever $a \sim \mathrm{id}$. A group modulo a normal subgroup forms a quotient group.

[6] A *homomorphism* is a structure-preserving map; in the case of algebras, a linear map $\Psi : A \to A'$ which satisfies $\Psi(a \circledast b) = \Psi(a) \circledast' \Psi(b)$.

Proof. We assume A and B associative algebras. (For a proof in universal algebra, see [5, § 15].)

To verify item 1, suppose that $\Psi(a) = \Psi(a')$ and $\Psi(b) = \Psi(b')$ and note that $\Psi(a + a') = \Psi(b + b')$ by linearity and $\Psi(a \circledast b) = \Psi(a' \circledast b')$ from $\Psi(a \circledast b) = \Psi(a) \circledast \Psi(b)$, so the congruence properties of definition 2 are satisfied.

For item 2, note that $\ker\Psi$ is a vector subspace, and that $a \in \ker\Psi$ implies $a \circledast r \in \ker\Psi$ for any $r \in A$ since $\Psi(a \circledast r) = \Psi(a) \circledast \Psi(r) = 0$. Thus, $\ker\Psi$ is an ideal by definition 3.

The first equivalence in item 3 follows from lemma 2. For an isomorphism $\Phi : A/\ker\Psi \to \Omega(A)$, pick $\Phi([a]) = \Psi(a)$. This is well-defined because the choice of representative of the equivalence class $[a]$ does not matter; $a \sim a'$ if and only if $\Psi(a) = \Psi(a')$ by definition of $\sim$, which simultaneously shows that Φ is injective. Surjectivity follows since any element of $\Psi(A)$ is of the form $\Psi(a)$ which is the image of $[a]$. □

With the free tensor algebra and theorem 1 in hand, we are able to describe any associative algebra as a quotient of the form $V^{\otimes}/I$.

Definition 4. *The* DIMENSION $\dim A$ *of a quotient algebra* $A = V^{\otimes}/I$ *is its dimension as a vector space. The* BASE DIMENSION *of* A *is the dimension of the underlying vector space* V.

Algebras may be infinite-dimensional, as is the case for the tensor algebra itself (which is a quotient by the trivial ideal).

2.1.2. Graded algebras

Associative algebras may possess another layer of useful structure: a grading. The grading of the tensor algebra has already been exhibited in eq. (2.1). A grading is a generalisation of the degree or rank of tensors or forms, and of the notion of parity for objects functions or polynomials.

Definition 5. *An algebra* A *is* R-GRADED *for* $(R, +)$ *a monoid*[7] *if there exists a decomposition*

$$A = \bigoplus_{k \in R} A_k$$

such that $A_i \circledast A_j \subseteq A_{i+j}$, *i.e.,* $a \in A_i, b \in A_j \implies a \circledast b \in A_{i+j}$.

[7] A MONOID is a group without the requirement of inverses; i.e., a set with an associative binary operation for which there is an identity element.

The monoid is usually taken to be $\mathbb{N}$ or $\mathbb{Z}$ with addition, possibly modulo some integer. The tensor algebra $V^{\otimes}$ is $\mathbb{N}$-graded, since if $a \in V^{\otimes p}$ and $b \in V^{\otimes q}$ then $a \otimes b \in V^{\otimes p+q}$. Indeed, $V^{\otimes}$ is also $\mathbb{Z}$-graded if for $k < 0$ we understand

$V^{\otimes k} := \{\mathbf{0}\}$ to be the trivial vector space. The tensor algebra is also $\mathbb{Z}_p$-graded, where $\mathbb{Z}_p \equiv \mathbb{Z}/p\mathbb{Z}$ is addition modulo any $p > 0$, since the decomposition

$$V^{\otimes} = \bigoplus_{k=0}^{p-1} Z_k \quad \text{where} \quad Z_k = \bigoplus_{n=0}^{\infty} V^{\otimes k+np} = V^{\otimes k} \oplus V^{\otimes(k+p)} \oplus \cdots$$

satisfies $Z_i \otimes Z_j \subseteq Z_k$ when $k \equiv i + j \mod p$. In particular, $V^{\otimes}$ is $\mathbb{Z}_2$-graded,[8] its elements admit a notion of *parity*: elements of $Z_0 = \mathbb{F} \otimes V^{\otimes 2} \otimes \cdots$ are even, while elements of $Z_1 = V \otimes V^{\otimes 3} \otimes \cdots$ are odd, and parity is respected by $\otimes$ as it is for integers.

[8] Algebras which are $\mathbb{Z}_2$-graded are sometimes called *superalgebras*, with the prefix 'super-' originating from supersymmetry theory.

Importantly, just as not all functions $f : \mathbb{R} \to \mathbb{R}$ are even or odd, not all elements of a $\mathbb{Z}_2$-graded algebra are even or odd; and more generally not all elements of a graded algebra belong to a single graded subspace.

Definition 6. *If $A = \bigoplus_{k\in R} A_k$ is an R-graded algerba, then an element $a \in A$ is* HOMOGENEOUS *if it belongs to some A_k, in which case it is said to be a k-*VECTOR*. If $a \in A_{k_1} \oplus \cdots \oplus A_{k_n}$ is inhomogeneous, we may call it a $\{k_1, ..., k_n\}$-multivector.*

All elements of a graded algebra are either inhomogeneous or a k-vector for some k; and each k-vector is either a k-*blade* or a sum of k-blades.

Definition 7. *A k-*BLADE *is a k-vector $a \in A_k$ of the form $a = \boldsymbol{u}_1 \circledast \cdots \circledast \boldsymbol{u}_k$ where each $\boldsymbol{u}_i \in A_1$ is a 1-vector.*

Note that not all k-vectors are blades. The simplest counterexample requires at least four dimensions: the bivector $\boldsymbol{e}_1 \otimes \boldsymbol{e}_2 + \boldsymbol{e}_3 \otimes \boldsymbol{e}_4 \in (\mathbb{R}^4)^{\otimes 2}$, where $\{\boldsymbol{e}_i\}$ are the standard basis of $\mathbb{R}^4$, cannot be factored into a blade of the form $\boldsymbol{u} \otimes \boldsymbol{v}$ for any $\boldsymbol{u}, \boldsymbol{v} \in V$.

{TO DO: Does this even make sense for a general graded algebra??}

Graded quotient algebras

A grading structure may or may not be inherited by a quotient — in particular, not all quotients of $V^{\otimes}$ inherit its $\mathbb{Z}$-grading. When reasoning about quotients of graded algebras, the following fact is useful.

Lemma 3. *Quotients commute with direct sums, so if*

$$A = \bigoplus_{k\in R} A_k \quad \textit{and} \quad I = \bigoplus_{k\in R} I_k \quad \textit{then} \quad A/I = \bigoplus_{k\in R} (A_k/I_k)$$

where R is some index set.

Proof. It is sufficient to prove the case for direct sums of length two. We then seek an isomorphism $\Phi : (A \oplus B)/(I \oplus J) \to (A/I) \oplus (B/J)$. Elements of the domain are equivalence classes of pairs $[(a,b)]$ with respect to the ideal $I \oplus J$. The direct sum ideal $I \oplus J$ corresponds to the congruence defined by $(a,b) \sim (a',b') \iff a \sim a'$ and $b \sim b'$. Therefore, the assignment $\Phi = [(a,b)] \mapsto ([a],[b])$ is well-defined. Injectivity and surjectivity follow immediately. □

This motivates the following strengthening to the notion of an ideal:

Definition 8. *An ideal I of an R-graded algebra $A = \bigoplus_{k\in R} A_k$ is* HOMOGENEOUS *if $I = \bigoplus_{k\in R} I_k$ where $I_k = I \cap A_k$.*

Not all ideals are homogeneous.[9] The additional requirement that an ideal be homogeneous ensures that the associated equivalence relation, as well as respecting the basic algebraic relations of definition 2, also preserves the grading structure. And so, we have a graded analogue to lemma 1:

[9] For example, the ideal $I = \{\!\{\boldsymbol{e}_1 + \boldsymbol{e}_2 \otimes \boldsymbol{e}_3\}\!\}$ is distinct from $\bigoplus_{k=0}^{\infty}(I \cap V^{\otimes k}) = \{\!\{\boldsymbol{e}_1, \boldsymbol{e}_2 \otimes \boldsymbol{e}_3\}\!\}$ because the former does not contain $\operatorname{span}\{\boldsymbol{e}_1\}$, while the latter does.

Theorem 2. *If A is an R-graded algebra and I a homogeneous ideal, then the quotient A/I is also R-graded.*

Proof. By lemma 3 and the homogeneity of I, we have $A/I = \bigoplus_{k\in R}(A_k/I_k)$. Elements of A_k/I_k are equivalence classes $[a_k]$ where the representative is of grade k. Thus, $(A_p/I_p) \circledast (A_q/I_q) \subseteq A_{p+q}/I_{p+q}$ since $[a_p] \circledast [a_q] = [a_p \circledast a_q] = [b]$ for some $b \in A_{p+q}$. Hence, A/I is R-graded. □

2.2. The Wedge Product: Multivectors

One of the simplest algebras to construct as a quotient of the tensor algebra, yet still one of the most useful, is the *exterior algebra*, first introduced by Hermann Grassmann in 1844.

Definition 9. *The* EXTERIOR ALGEBRA *over a vector space V is*

$$\bigwedge V \coloneqq V^{\otimes} \big/ \{\!\{\boldsymbol{u} \otimes \boldsymbol{u}\}\!\} .$$

The product in $\bigwedge V$ is denoted $\wedge$ and called the WEDGE PRODUCT.

The ideal $\{\!\{\boldsymbol{u} \otimes \boldsymbol{u}\}\!\} \equiv \{\!\{\boldsymbol{u} \otimes \boldsymbol{u} \mid \boldsymbol{u} \in V\}\!\}$ corresponds to the congruence $\boldsymbol{u} \otimes \boldsymbol{u} \sim 0$ for any vectors $\boldsymbol{u} \in V$. The wedge product is also called the *exterior*, *alternating* or *antisymmetric* product. The property suggested by its names may easily be seen by expanding the square of a sum;

$$(\boldsymbol{u} + \boldsymbol{v}) \wedge (\boldsymbol{u} + \boldsymbol{v}) = \boldsymbol{u} \wedge \boldsymbol{u} + \boldsymbol{u} \wedge \boldsymbol{v} + \boldsymbol{v} \wedge \boldsymbol{u} + \boldsymbol{v} \wedge \boldsymbol{v}.$$

Since all terms of the form $\boldsymbol{w} \wedge \boldsymbol{w} = 0$ are definitionally zero, we have

$$\boldsymbol{u} \wedge \boldsymbol{v} = -\boldsymbol{v} \wedge \boldsymbol{u}$$

for all vectors $\boldsymbol{u}, \boldsymbol{v} \in V$. By associativity, it follows that $\boldsymbol{v}_1 \wedge \boldsymbol{v}_2 \wedge \cdots \wedge \boldsymbol{v}_k$ vanishes exactly when the $\boldsymbol{v}_i$ are linearly dependent.[10]

10 *Proof.* Blades of the form $a = \boldsymbol{u}_1 \wedge \cdots \wedge \boldsymbol{u}_k$ vanish when two or more vectors are repeated. If $\{\boldsymbol{u}_i\}$ is linearly dependent, then any one $\boldsymbol{u}_i$ can be written in terms of the others, and thus a can be expanded into a sum of such vanishing terms. □

The ideal $\{\!\{\boldsymbol{u} \otimes \boldsymbol{u}\}\!\}$ is homogeneous with respect to the $\mathbb{Z}$-grading of the parent tensor algebra. Therefore, $\bigwedge V$ is itself $\mathbb{Z}$-graded. In particular, it is the direct sum of fixed-grade subspaces

$$\bigwedge V = \bigoplus_{k=0}^{\dim V} \bigwedge^k V \quad \text{where} \quad \bigwedge^k V = \operatorname{span}\{\boldsymbol{v}_1 \wedge \boldsymbol{v}_2 \wedge \cdots \wedge \boldsymbol{v}_k \mid \boldsymbol{v}_i \in V\},$$

and the wedge product respects grade, $(\bigwedge^p V) \wedge (\bigwedge^q V) \subseteq \bigwedge^{p+q} V$. By counting the number of possible linearly independent sets of k vectors in $\dim V$ dimensions, it follows that

$$\dim \bigwedge^k V = \binom{\dim V}{k}, \quad \text{and hence} \quad \dim \bigwedge V = 2^{\dim V}.$$

Thus, the exterior algebra with base dimension n is 2^n-dimensional.

2.2.1. As antisymmetric tensors

The exterior algebra may equivalently be viewed as the space of antisymmetric tensors equipped with an antisymmetrising product. Consider the map

$$\operatorname{Sym}^{\pm}(\boldsymbol{u}_1 \otimes \cdots \otimes \boldsymbol{u}_k) = \frac{1}{k!} \sum_{\sigma \in S_k} (\pm 1)^{\sigma} \boldsymbol{u}_{\sigma(1)} \otimes \cdots \otimes \boldsymbol{u}_{\sigma(k)} \tag{2.2}$$

where $(-1)^{\sigma}$ denotes the sign of the permutation σ in the symmetric group of k elements, S_k. By enforcing linearly, $\operatorname{Sym}^{\pm} : V^{\otimes} \to V^{\otimes}$ is defined on all tensors. A tensor a is called SYMMETRIC if $\operatorname{Sym}^{+}(a) = a$ and ANTISYMMETRIC if $\operatorname{Sym}^{-}(a) = a$.

Denote the image $\operatorname{Sym}^{-}(V^{\otimes})$ by S. The linear map $\operatorname{Sym}^{-} : V^{\otimes} \to S$ is not an algebra homomorphism with respect to the tensor product on S, since, e.g., $\operatorname{Sym}^{-}(\boldsymbol{u} \otimes \boldsymbol{v}) \neq \operatorname{Sym}^{-}(\boldsymbol{u}) \otimes \operatorname{Sym}^{-}(\boldsymbol{v}) = \boldsymbol{u} \otimes \boldsymbol{v}$. However, it is if we instead equip S with the antisymmetrising product $\wedge : S \times S \to S$ defined by

$$a \wedge b := \operatorname{Sym}^{-}(a \otimes b). \tag{2.3}$$

This makes $\operatorname{Sym}^{-} : V^{\otimes} \to S$ an algebra homomorphism, and by theorem 1, we have

$$S \cong V^{\otimes} \big/ \ker \operatorname{Sym}^{-}. \tag{2.4}$$

Furthermore, note that the kernel of Sym^- consists of tensor products of linearly dependent vectors, and sums thereof,[11]

$$\ker \mathrm{Sym}^- = \mathrm{span}\{\boldsymbol{u}_1 \otimes \cdots \otimes \boldsymbol{u}_k \mid k \in \mathbb{N}, \{\boldsymbol{u}_i\} \text{ linearly dependent}\},$$

which is exactly the ideal $\{\!\{\boldsymbol{u} \otimes \boldsymbol{u}\}\!\}$. Therefore, the left-hand side of eq. (2.4) is the exterior algebra of definition 9, and we have an algebra isomorphism $\bigwedge V \cong \mathrm{Sym}^-(V^{\otimes})$, where the right-hand side is equipped with the product (2.3). This gives an alternative construction of the exterior algebra.

[11] *Proof.* If $a = \boldsymbol{u}_1 \otimes \cdots \otimes \boldsymbol{u}_k$ where two vectors $\boldsymbol{u}_i = \boldsymbol{u}_j$ are equal, then $\mathrm{Sym}^-(a) = 0$ since each term in the sum in eq. (2.2) is paired with an equal and opposite term with $i \leftrightarrow j$ swapped. If $\{\boldsymbol{u}_i\}$ is linearly dependent, any one vector is a sum of the others, so a is a sum of blades with at least two vectors repeated. □

Note on conventions

The factor of $\frac{1}{k!}$ present in eq. (2.2) is not necessary for the above demonstration that $\bigwedge V \cong \mathrm{Sym}^-(V^{\otimes})$. Indeed, some authors omit the normalisation factor, which has the effect of changing eq. (2.3) to

$$a \wedge b = \frac{(p+q)!}{p!q!}\mathrm{Sym}^-(a \otimes b)$$

for $a \in \mathrm{Sym}^-(V^{\otimes p})$ and $b \in \mathrm{Sym}^-(V^{\otimes q})$, in terms of our convention (2.2). The different definitions of $\wedge$ as an antisymmetrising product lead to different identifications of $\bigwedge V$ with S, as clarified in table 2.1.

Kobayashi–Nomizu [6]	*Spivak* [7]
$a \wedge b := \mathrm{Sym}^-(a \otimes b)$	$a \wedge b := \frac{(p+q)!}{p!q!}\mathrm{Sym}^-(a \otimes b)$
$\boldsymbol{u} \wedge \boldsymbol{v} = \frac{1}{2}(\boldsymbol{u} \otimes \boldsymbol{v} - \boldsymbol{v} \otimes \boldsymbol{u})$	$\boldsymbol{u} \wedge \boldsymbol{v} = \boldsymbol{u} \otimes \boldsymbol{v} - \boldsymbol{v} \otimes \boldsymbol{u}$

Table 2.1.: Different embeddings of $\bigwedge V$ into $V^{\otimes}$. We employ the Kobayashi–Nomizu convention as this is coincides with the wedge product of geometric algebra. The Spivak convention is dominant for differential forms in physics.

2.2.2. Exterior forms

The exterior algebra is most frequently encountered by physicists in the context of *exterior (differential) forms*, which are alternating[12] multilinear maps.

We may wish to use the exterior algebra $\bigwedge V^*$ over the dual space of linear maps $V \to \mathbb{R}$ as a model for exterior forms. Using the dual basis $\{\boldsymbol{e}^i\} \subset V^*$, any element $f \in \bigwedge^k V^*$ has the form $f = f_{i_1 \cdots i_k} \boldsymbol{e}^{i_1} \wedge \cdots \wedge \boldsymbol{e}^{i_k}$, and each component acts on $\boldsymbol{u}_1 \otimes \cdots \otimes \boldsymbol{u}_k \in V^{\otimes k}$ as

$$(\boldsymbol{e}^{i_1} \wedge \cdots \wedge \boldsymbol{e}^{i_k})(\boldsymbol{u}_1 \otimes \cdots \otimes \boldsymbol{u}_k) = \frac{1}{k!}\sum_{\sigma \in S_k}(-1)^\sigma \boldsymbol{e}^{i_{\sigma(1)}}(\boldsymbol{u}_1) \cdots \boldsymbol{e}^{i_{\sigma(k)}}(\boldsymbol{u}_k). \tag{2.5}$$

[12] An ALTERNATING linear map is one which changes sign upon any transposition of any pair of arguments. E.g., if f is alternating, then $f(\boldsymbol{u}, \boldsymbol{v}, \boldsymbol{w}) = -f(\boldsymbol{v}, \boldsymbol{u}, \boldsymbol{w})$.

However, this differs from the standard definition of exterior forms in two important ways:

1. In eq. (2.5), the dual vectors $\boldsymbol{e}^i \in V^*$ are permuted while the order of the arguments $\boldsymbol{u}_i$ are preserved; but for standard exterior forms, the opposite is true. This prevents the proper extension of $\bigwedge V^*$ to non-Abelian vector-valued forms, where the values $\boldsymbol{e}^i(\boldsymbol{u}_j)$ may not commute.

2. Trivially, we insist on the the Kobayashi—Nomizu convention of normalisation factor for $\bigwedge V^*$; but the Spivak convention for exterior forms is much more standard in physics.

Thus, we define exterior forms separately in order to match convention.

Definition 10. *For a vector space V, a k-FORM $\varphi \in \Omega^k(V)$ is an alternating multilinear map $\varphi : V^{\otimes k} \to \mathbb{R}$. For another vector space A, an A-VALUED k-FORM $\varphi \in \Omega^k(V, A)$ is such a map $\varphi : V^{\otimes k} \to A$ into A.*

The evaluation of a form is denoted $\varphi(\boldsymbol{u}_1 \otimes \cdots \otimes \boldsymbol{u}_k)$ or $\varphi(\boldsymbol{u}_1, \ldots, \boldsymbol{u}_k)$, and the wedge product of a p-form φ and q-form ϕ is defined (in the Spivak convention)

$$\varphi \wedge \phi = \frac{(p+q)!}{p!q!}(\varphi \otimes \phi) \circ \mathrm{Sym}^{-}. \tag{2.6}$$

Explicitly, eq. (2.6) acts to antisymmetrise arguments. To see this, choose a basis $\{\mathrm{d}x^\mu\}$ of $\Omega(V)$, and compare to eq. (2.5),

$$(\mathrm{d}x^{\mu_1} \wedge \cdots \wedge \mathrm{d}x^{\mu_k})(\boldsymbol{u}_1 \otimes \cdots \otimes \boldsymbol{u}_k) = \sum_{\sigma \in S_k} (-1)^\sigma \mathrm{d}x^{\mu_1}(\boldsymbol{u}_{\sigma(1)}) \cdots \mathrm{d}x^{\mu_k}(\boldsymbol{u}_{\sigma(k)}).$$

If $\varphi, \phi \in \Omega(V, A)$ are A-valued forms, where A is equipped with a bilinear product $\circledast : A \times A \to A$, then scalar multiplication may be replaced this product, so that

$$(\varphi \wedge \phi)(\boldsymbol{u}_1 \otimes \cdots \otimes \boldsymbol{u}_k) = \sum_{\sigma \in S_k} (-1)^\sigma \varphi(\boldsymbol{u}_1 \otimes \cdots \otimes \boldsymbol{u}_p) \circledast \phi(\boldsymbol{u}_1 \otimes \cdots \otimes \boldsymbol{u}_q).$$

The product $\circledast$ need not be commutative or associative; in particular, we may have Lie algebra–valued forms. For example, if $\varphi, \phi \in \Omega^1(V, \mathfrak{g})$ are Lie algebra–valued, then

$$(\varphi \wedge \phi)(\boldsymbol{u}, \boldsymbol{v}) = [\varphi(\boldsymbol{u}), \phi(\boldsymbol{v})] - [\varphi(\boldsymbol{v}), \phi(\boldsymbol{u})],$$

where $[\ ,\ ] : \mathfrak{g} \times \mathfrak{g} \to \mathfrak{g}$ is the Lie bracket. Note that this implies that $\varphi \wedge \varphi$ does not necessarily vanish for non-Abelian forms — in the case above we have $(\varphi \wedge \varphi)(\boldsymbol{u}, \boldsymbol{v}) = 2[\varphi(\boldsymbol{u}), \varphi(\boldsymbol{v})]$.

2.3. The Metric: Length and Angle

The tensor and exterior algebras considered so far are build from a vector space V alone. Notions of length and angle are central to geometry, but are not intrinsic to a vector space — additional structure must be provided.

Definition 11. *A METRIC*[13] *is a function $\eta : V \times V \to \mathbb{F}$, often written $\eta(\boldsymbol{u}, \boldsymbol{v}) \equiv \langle \boldsymbol{u}, \boldsymbol{v} \rangle$ which satisfies*

- *symmetry, $\langle \boldsymbol{u}, \boldsymbol{v} \rangle = \langle \boldsymbol{v}, \boldsymbol{u} \rangle$; and*
- *linearity, $\langle \alpha \boldsymbol{u} + \beta \boldsymbol{v}, \boldsymbol{w} \rangle = \alpha \langle \boldsymbol{u}, \boldsymbol{w} \rangle + \beta \langle \boldsymbol{v}, \boldsymbol{w} \rangle$ for $\alpha, \beta \in \mathbb{F}$.*

[13] a.k.a. an *inner product*, or *symmetric bilinear form*

Linearity in either argument implies linearity in the other by symmetry, so η is bilinear.

A vector space V together with a metric η is called an INNER PRODUCT SPACE (V, η). Alternatively, instead of a metric, an inner product space may be constructed with a quadratic form:

Definition 12. *A QUADRATIC FORM is a function $q : V \to \mathbb{F}$ satisfying*

- *$q(\lambda \boldsymbol{v}) = \lambda^2 q(\boldsymbol{v})$ for all $\lambda \in \mathbb{F}$; and*
- *the requirement that the POLARIZATION OF q,*

$$(\boldsymbol{u}, \boldsymbol{v}) \mapsto q(\boldsymbol{u} + \boldsymbol{v}) - q(\boldsymbol{u}) - q(\boldsymbol{v}),$$

  is bilinear.

To any quadratic form q there is a unique associated bilinear form, which is *compatible* in the sense that $q(\boldsymbol{u}) = \langle \boldsymbol{u}, \boldsymbol{u} \rangle$. It is recovered[14] by the *polarization identity*

$$\langle \boldsymbol{u}, \boldsymbol{v} \rangle = \frac{1}{2}\big(q(\boldsymbol{u} + \boldsymbol{v}) - q(\boldsymbol{u}) - q(\boldsymbol{v})\big).$$

[14] Except, of course, if the characteristic of $\mathbb{F}$ is two. We only consider fields of characteristic zero.

The prescription of either η or q is therefore equivalent — but the notion of a metric is more common in physics, whereas the mathematical viewpoint often starts with a quadratic form.

Part II.

General Relativity and Manifold Geometry

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