Bilinear form and inner product

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What is a bilinear form. Bilinear list. Bilinear form example.

Scalar-valued bilinear function In mathematics, a bilinear form on a vector space V (the elements of which are called vectors) over a field K (the elements of which are called scalars) is a bilinear map V × V → K. In other words, a bilinear form is a function B : V × V → K that is linear in each argument separately: B(u + v, w) = B(u, w) + B(v, w) and B(λu, v) = λB(u, v) B(u, v + w) = B(u, v) + B(u, w) and B(u, λv) = λB(u, v) The dot product on R n {\displaystyle \mathbb {R} ^{n}} is an example of a bilinear form.[1] The definition of a bilinear form can be extended to include modules over a ring, with linear maps replaced by module homomorphisms. When K is the field of complex numbers C, one is often more interested in sesquilinear forms, which are similar to bilinear forms but are conjugate linear in one argument. Coordinate representation Let V ≅ Kn be an n-dimensional vector space with basis {e1, …, en}. The n × n matrix A, defined by Aij = B(ei, ej) is called the matrix of the bilinear form on the basis {e1, …, en}. If the n × 1 matrix x represents a vector v with respect to this basis, and analogously, y represents another vector w, then: B (v , w) = x T A y = ∑ i , j = 1 n x i A i j y j . {\displaystyle B(\mathbf {v} ,\mathbf {w})=\mathbf {x} ^{\textsf {T}}A\mathbf {y} =\sum _{i,j=1}^{n}x_{i}A_{ij}y_{j}.} A bilinear form has different matrices on different bases. However, the matrices of a bilinear form on different bases are all congruent. More precisely, if {f1, …, fn} is another basis of V, then f j = ∑ i = 1 n S i , j e i , {\displaystyle \mathbf {f} _{j}=\sum _{i=1}^{n}S_{i,j}\mathbf {e} _{i},} where the S i , j {\displaystyle S_{i,j}} form an invertible matrix S. Then, the matrix of the bilinear form on the new basis is STAS. Maps to the dual space Every bilinear form B on V defines a pair of linear maps from V to its dual space V∗. Define B1, B2: V → V∗ by B1(v)(w) = B(v, w) B2(v)(w) = B(w, v) This is often denoted as B1(v) = B(v, ⋅) B2(v) = B(⋅, v) where the dot (⋅) indicates the slot into which the argument for the resulting linear functional is to be placed (see Currying). For a finite-dimensional vector space V, if either of B1 or B2 is an isomorphism, then both are, and the bilinear form B is said to be nondegenerate. More concretely, for a finite-dimensional vector space, non-degenerate means that every non-zero element pairs non-trivially with some other element: B (x , y) = 0 {\displaystyle B(x,y)=0} for all y ∈ V {\displaystyle y\in V} implies that x = 0 and B (x , y) = 0 {\displaystyle B(x,y)=0} for all x ∈ V {\displaystyle x\in V} implies that y = 0. The corresponding notion for a module over a commutative ring is that a bilinear form is unimodular if V → V∗ is an isomorphism. Given a finitely generated module over a commutative ring, the pairing may be injective (hence "nondegenerate" in the above sense) but not unimodular. For example, over the integers, the pairing B(x, y) = 2xy is nondegenerate but not unimodular, as the induced map from V = Z to V∗ = Z is multiplication by 2. If V is finite-dimensional then one can identify V with its double dual V∗∗. One can then show that B2 is the transpose of the linear map B1 (if V is infinite-dimensional then B2 is the transpose of B1 restricted to the image of V in V∗∗). Given B one can define the transpose of B to be the bilinear form given by tB(v, w) = B(w, v). The left radical and right radical of the form B are the kernels of B1 and B2 respectively;[2] they are the vectors orthogonal to the whole space on the left and on the right.[3] If V is finite-dimensional then the rank of B1 is equal to the rank of B2. If this number is equal to dim(V) then B1 and B2 are linear isomorphisms from V to V∗. In this case B is nondegenerate. By the rank–nullity theorem, this is equivalent to the condition that the left and equivalently right radicals be trivial. For finite-dimensional spaces, this is often taken as the definition of nondegeneracy: Definition: B is nondegenerate if B(v, w) = 0 for all w implies v = 0. Given any linear map A : V → V∗ one can obtain a bilinear form B on V via B(v, w) = A(v)(w). This form will be nondegenerate if and only if A is an isomorphism. If V is finite-dimensional then, relative to some basis for V, a bilinear form is degenerate if and only if the determinant of the associated matrix is zero. Likewise, a nondegenerate form is one for which the determinant of the associated matrix is non-zero (the matrix is non-singular). These statements are independent of the chosen basis. For a module over a commutative ring, a unimodular form is one for which the determinant of the associate matrix is a unit (for example 1), hence the term; note that a form whose matrix determinant is non-zero but not a unit will be nondegenerate but not unimodular, for example B(x, y) = 2xy over the integers. Symmetric, skew-symmetric and alternating forms We define a bilinear form to be symmetric if B(v, w) = B(w, v) for all v, w in V; alternating if B(v, v) = 0 for all v in V; skew-symmetric or antisymmetric if B(v, w) = −B(w, v) for all v, w in V; Proposition Every alternating form is skew-symmetric. Proof This can be seen by expanding B(v + w, v + w). If the characteristic of K is not 2 then the converse is also true: every skew-symmetric form is alternating. If, however, char(K) = 2 then a skew-symmetric form is the same as a symmetric form and there exist symmetric/skew-symmetric forms that are not alternating. A bilinear form is symmetric (respectively skew-symmetric) if and only if its coordinate matrix (relative to any basis) is symmetric (respectively skew-symmetric). A bilinear form is alternating if and only if its coordinate matrix is skew-symmetric and the diagonal entries are all zero (which follows from skew-symmetry when char(K) ≠ 2). A bilinear form is symmetric if and only if the maps B1, B2: V → V∗ are equal, and skew-symmetric if and only if they are negatives of one another. If char(K) ≠ 2 then one can decompose a bilinear form into a symmetric and a skew-symmetric part as follows B + = 1 2 (B + t B) B − = 1 2 (B − t B) , {\displaystyle B^{+}={\tfrac {1}{2}}(B+{}^{\text{t}}B)\qquad B^{-}={\tfrac {1}{2}}(B-{}^{\text{t}}B),} where tB is the transpose of B (defined above). Derived quadratic form For any bilinear form B : V × V → K, there exists an associated quadratic form Q : V → K defined by Q : V → K : v ↦ B(v, v). When char(K) ≠ 2, the quadratic form Q is determined by the symmetric part of the bilinear form B and is independent of the antisymmetric part. In this case there is a one-to-one correspondence between the symmetric part of the bilinear form and the quadratic form, and it makes sense to speak of the symmetric bilinear form associated with a quadratic form. When char(K) = 2 and dim V > 1, this correspondence between quadratic forms and symmetric bilinear forms breaks down. Reflexivity and orthogonality Definition: A bilinear form B : V × V → K is called reflexive if B(v, w) = 0 implies B(w, v) = 0 for all v, w in V. Definition: Let B : V × V → K be a reflexive bilinear form. v, w in V are orthogonal with respect to B if B(v, w) = 0. A bilinear form B is reflexive if and only if it is either symmetric or alternating.[4] In the absence of reflexivity we have to distinguish left and right orthogonality. In a reflexive space the left and right radicals agree and are termed the kernel or the radical of the bilinear form: the subspace of all vectors orthogonal with every other vector. A vector v, with matrix representation x, is in the radical of a bilinear form with matrix representation A, if and only if Ax = 0 ⇔ xTA = 0. The radical is always a subspace of V. It is trivial if and only if the matrix A is nonsingular, and thus if and only if the bilinear form is nondegenerate. Suppose W is a subspace. Define the orthogonal complement[5] W ⊥ = { v ∣ B (v , w) = 0 for all w ∈ W } . {\displaystyle W^{\perp }=\left\{\mathbf {v} \mid B(\mathbf {v} ,\mathbf {w})=0{\text{ for all }}\mathbf {w} \in W\right\}.} For a non-degenerate form on a finite-dimensional space, the map V/W → W⊥ is bijective, and the dimension of W⊥ is dim(V) − dim(W). Different spaces Much of the theory is available for a bilinear mapping from two vector spaces over the same base field to that field B : V × W → K. Here we still have induced linear mappings from V to W∗, and from W to V∗. It may happen that these mappings are isomorphisms; assuming finite dimensions, if one is an isomorphism, the other must be. When this occurs, B is said to be a perfect pairing. In finite dimensions, this is equivalent to the pairing being nondegenerate (the spaces necessarily having the same dimensions). For modules (instead of vector spaces), just as how a nondegenerate form is weaker than a unimodular form, a nondegenerate pairing is a weaker notion than a perfect pairing. A pairing can be nondegenerate without being a perfect pairing, for instance Z × Z → Z via (x, y) ↦ 2xy is nondegenerate, but induces multiplication by 2 on the map Z → Z∗. Terminology varies in coverage of bilinear forms. For example, F. Reese Harvey discusses "eight types of inner product".[6] To define them he uses diagonal matrices Aij having only +1 or −1 for non-zero elements. Some of the "inner products" are symplectic forms and some are sesquilinear forms or Hermitian forms. Rather than a general field K, the instances with real numbers R, complex numbers C, and quaternions H are spelled out. The bilinear form ∑ k = 1 p x k y k − ∑ k = p + 1 n x k y k {\displaystyle \sum _{k=1}^{p}x_{k}y_{k}-\sum _{k=p+1}^{n}x_{k}y_{k}} is called the real symmetric case and labeled R(p, q), where p + q = n. Then he articulates the connection to traditional terminology:[7] Some of the real symmetric cases are very important. The positive definite case R(n, 0) is called Euclidean space, while the case of a single minus, R(n−1, 1) is called Lorentzian space. If n = 4, then Lorentzian space is also called Minkowski space or Minkowski spacetime. The special case R(p, p) will be referred to as the split-case. Relation to tensor products By the universal property of the tensor product, there is a canonical correspondence between bilinear forms on V and linear maps V ⊗ V → K. If B is a bilinear form on V the corresponding linear map is given by v ⊗ w ↦ B(v, w) In the other direction, if F : V ⊗ V → K is a linear map the corresponding bilinear form is given by composing F with the bilinear map V × V → V ⊗ V that sends (v, w) to v⊗w. The set of all linear maps V ⊗ V → K is the dual space of V ⊗ V, so bilinear forms may be thought of as elements of (V ⊗ V)∗ which (when V is finite-dimensional) is canonically isomorphic to V∗ ⊗ V∗. Likewise, symmetric bilinear forms may be thought of as elements of Sym2(V∗) (the second symmetric power of V∗), and alternating bilinear forms as elements of Λ2V∗ (the second exterior power of V∗). On normed vector spaces Definition: A bilinear form on a normed vector space (V, ‖⋅‖) is bounded, if there is a constant C such that for all u, v ∈ V, B (u , v) ≤ C ‖ u ‖ ‖ v ‖ . {\displaystyle B(\mathbf {u} ,\mathbf {v})\leq C\left\|\mathbf {u} \right\|\left\|\mathbf {v} \right\|.} Definition: A bilinear form on a normed vector space (V, ‖⋅‖) is elliptic, or coercive, if there is a constant c > 0 such that for all u ∈ V, B (u , u) ≥ c ‖ u ‖ 2 . {\displaystyle B(\mathbf {u} ,\mathbf {u})\geq c\left\|\mathbf {u} \right\|^{2}.} Generalization to modules Given a ring R and a right R-module M and its dual module M∗, a mapping B : M∗ × M → R is called a bilinear form if B(u + v, x) = B(u, x) + B(v, x) B(u, x + y) = B(u, x) + B(u, y) B(αu, xβ) = αB(u, x)β for all u, v ∈ M∗, all x, y ∈ M and all α, β ∈ R. The mapping ⟨⋅,⋅⟩ : M∗ × M → R : (u, x) ↦ u(x) is known as the natural pairing, also called the canonical bilinear form on M∗ × M.[8] A linear map S : M∗ → M∗ : u ↦ S(u) induces the bilinear form B : M∗ × M → R : (u, x) ↦ ⟨S(u), x⟩, and a linear map T : M → M : x ↦ T(x) induces the bilinear form B : M∗ × M → R : (u, x) ↦ ⟨u, T(x)⟩. Conversely, a bilinear form B : M∗ × M → R induces the R-linear maps S : M∗ → M∗ : u ↦ (x ↦ B(u, x)) and T′ : M → M∗∗ : x ↦ (u ↦ B(u, x)). Here, M∗∗ denotes the double dual of M. See also Bilinear map Bilinear operator Inner product space Linear form Multilinear form Polar space Quadratic form Sesquilinear form System of bilinear equations Citations ^ "Chapter 3. Bilinear forms — Lecture notes for MA1212" (PDF). 2021-01-16. ^ Jacobson 2009, p. 346. ^ Zhelobenko 2006, p. 11. ^ Grove 1997. ^ Adkins & Weintraub 1992, p. 359. ^ Harvey 1990, p. 22. ^ Harvey 1990, p. 23. ^ Bourbaki 1970, p. 233. References Adkins, William A.; Weintraub, Steven H. 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This article incorporates material from Unimodular on PlanetMath, which is licensed under the Creative Commons Attribution/Share-Alike License. Retrieved from " example demonstrates the use of high-order and NURBS vector finite element spaces with the linear elasticity bilinear form, meshes with curved elements, and the definition of piece-wise constant and vector coefficient objects. ... inner solver. The example has a serial and a parallel version. It also has a SUNDIALS modification in examples ... This form will be nondegenerate if and only if A is an isomorphism.. If V is finite-dimensional then, relative to some basis for V, a bilinear form is degenerate if and only if the determinant of the associated matrix is zero. Likewise, a nondegenerate form is one for which the determinant of the associated matrix is non-zero (the matrix is non-singular). ... The real dot product is just a special case of an inner product. In fact it's even positive definite, but general inner products need not be so. The modified dot product for complex spaces also has this positive definite property, and has the Hermitian-symmetric I mentioned above. Inner products are generalized by linear forms. I think I've ... In mathematics, a sesquilinear form is a generalization of a bilinear form that, in turn, is a generalization of the concept of the dot product of Euclidean space.A bilinear form is linear in each of its arguments, but a sesquilinear form allows one of the arguments to be "twisted" in a semilinear manner, thus the name; which originates from the Latin numerical prefix sesqui ... The example demonstrates the use of high-order and NURBS vector finite element spaces with the linear elasticity bilinear form, meshes with curved elements, and the definition of piece-wise constant and vector coefficient objects. ... inner solver. The example has a serial and a parallel version. It also has a SUNDIALS modification in examples ... In mathematics, specifically linear algebra, a degenerate bilinear form f ... For example, a manifold with an inner product structure on its tangent spaces is a Riemannian manifold, while relaxing this to a symmetric nondegenerate form yields a pseudo-Riemannian manifold. Using the determinant. If V is finite-dimensional then, ...

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