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The Hahn Banach Theorem in the Vector Space over the Field of Complex Numbers

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Summary. This article contains the Hahn Banach theorem in the vector space over the field of complex numbers.

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The articles [13], [4], [20], [16], [6], [7], [12], [11], [18], [8], [17], [19], [2], [3], [1], [21], [15], [14], [5], [10], and [9] provide the notation and terminology for this paper.

1. Preliminaries

The following propositions are true:

(1) For every element z of $\mathbb{C}$ holds $||z|| = |z|$.

(2) For all real numbers x_1, y_1, x_2, y_2 holds $(x_1 + y_1 i) \cdot (x_2 + y_2 i) = (x_1 \cdot x_2 - y_1 \cdot y_2) + (x_1 \cdot y_2 + x_2 \cdot y_1)i$.

(3) For every real number r holds $(r + 0i) \cdot i = 0 + ri$.

(4) For every real number r holds $|r + 0i| = |r|$.

(5) For every element z of $\mathbb{C}$ such that $|z| \neq 0$ holds $|z| + 0i = \frac{\overline{z}}{|z|+0i} \cdot z$.

2. Some Facts on the Field of Complex Numbers

Let x, y be real numbers. The functor $x + yi_{\mathbb{C}_{\rm F}}$ yielding an element of $\mathbb{C}_{\rm F}$ is defined as follows:

(Def. 1) $x + yi_{\mathbb{C}_{\rm F}} = x + yi$.

The element $i_{\mathbb{C}_{\rm F}}$ of $\mathbb{C}_{\rm F}$ is defined as follows:

(Def. 2) $i_{\mathbb{C}_{\rm F}} = i$.

We now state several propositions:

(6) $i_{\mathbb{C}_{\rm F}} = 0 + 1i$ and $i_{\mathbb{C}_{\rm F}} = 0 + 1i_{\mathbb{C}_{\rm F}}$.

(7) $|i_{\mathbb{C}_{\rm F}}| = 1$.

(8) $i_{\mathbb{C}_{\rm F}} \cdot i_{\mathbb{C}_{\rm F}} = -\mathbf{1}_{\mathbb{C}_{\rm F}}$.

(9) $(-\mathbf{1}_{\mathbb{C}_{\rm F}}) \cdot -\mathbf{1}_{\mathbb{C}_{\rm F}} = \mathbf{1}_{\mathbb{C}_{\rm F}}$.

(10) For all real numbers x_1, y_1, x_2, y_2 holds $(x_1 + y_1 i_{\mathbb{C}_{\rm F}}) + (x_2 + y_2 i_{\mathbb{C}_{\rm F}}) = (x_1 + x_2) + (y_1 + y_2) i_{\mathbb{C}_{\rm F}}$.

(11) For all real numbers x_1, y_1, x_2, y_2 holds $(x_1 + y_1 i_{\mathbb{C}_{\rm F}}) \cdot (x_2 + y_2 i_{\mathbb{C}_{\rm F}}) = (x_1 \cdot x_2 - y_1 \cdot y_2) + (x_1 \cdot y_2 + x_2 \cdot y_1) i_{\mathbb{C}_{\rm F}}$.

(12) For every element z of $\mathbb{C}_{\rm F}$ holds $||z|| = |z|$.

(13) For every real number r holds $|r + 0 i_{\mathbb{C}_{\rm F}}| = |r|$.

(14) For every real number r holds $(r + 0 i_{\mathbb{C}_{\rm F}}) \cdot i_{\mathbb{C}_{\rm F}} = 0 + r i_{\mathbb{C}_{\rm F}}$.

Let z be an element of $\mathbb{C}_{\rm F}$. The functor $\Re(z)$ yields a real number and is defined by:

(Def. 3) There exists an element z' of $\mathbb{C}$ such that $z = z'$ and $\Re(z) = \Re(z')$.

Let z be an element of $\mathbb{C}_{\rm F}$. The functor $\Im(z)$ yields a real number and is defined by:

(Def. 4) There exists an element z' of $\mathbb{C}$ such that $z = z'$ and $\Im(z) = \Im(z')$.

Next we state several propositions:

(15) For all real numbers x, y holds $\Re(x + y i_{\mathbb{C}_{\rm F}}) = x$ and $\Im(x + y i_{\mathbb{C}_{\rm F}}) = y$.

(16) For all elements x, y of $\mathbb{C}_{\rm F}$ holds $\Re(x + y) = \Re(x) + \Re(y)$ and $\Im(x + y) = \Im(x) + \Im(y)$.

(17) For all elements x, y of $\mathbb{C}_{\rm F}$ holds $\Re(x \cdot y) = \Re(x) \cdot \Re(y) - \Im(x) \cdot \Im(y)$ and $\Im(x \cdot y) = \Re(x) \cdot \Im(y) + \Re(y) \cdot \Im(x)$.

(18) For every element z of $\mathbb{C}_{\rm F}$ holds $\Re(z) \leq |z|$.

(19) For every element z of $\mathbb{C}_{\rm F}$ holds $\Im(z) \leq |z|$.

3. Functionals of Vector Space

Let K be a 1-sorted structure and let V be a vector space structure over K. A functional in V is a function from the carrier of V into the carrier of K.

Let K be a non empty loop structure, let V be a non empty vector space structure over K, and let f, g be functionals in V. The functor $f + g$ yielding a functional in V is defined as follows:

(Def. 6)[1] For every element x of V holds $(f + g)(x) = f(x) + g(x)$.

Let K be a non empty loop structure, let V be a non empty vector space structure over K, and let f be a functional in V. The functor $-f$ yields a functional in V and is defined by:

(Def. 7) For every element x of V holds $(-f)(x) = -f(x)$.

Let K be a non empty loop structure, let V be a non empty vector space structure over K, and let f, g be functionals in V. The functor $f - g$ yields a functional in V and is defined as follows:

(Def. 8) $f - g = f + -g$.

Let K be a non empty groupoid, let V be a non empty vector space structure over K, let v be an element of K, and let f be a functional in V. The functor $v \cdot f$ yields a functional in V and is defined as follows:

(Def. 9) For every element x of V holds $(v \cdot f)(x) = v \cdot f(x)$.

Let K be a non empty zero structure and let V be a vector space structure over K. The functor 0Functional$V$ yields a functional in V and is defined by:

[1] The definition (Def. 5) has been removed.

(Def. 10) $0\text{Functional}V = \Omega_V \longmapsto 0_K$.

Let K be a non empty loop structure, let V be a non empty vector space structure over K, and let F be a functional in V. We say that F is additive if and only if:

(Def. 11) For all vectors x, y of V holds $F(x+y) = F(x)+F(y)$.

Let K be a non empty groupoid, let V be a non empty vector space structure over K, and let F be a functional in V. We say that F is homogeneous if and only if:

(Def. 12) For every vector x of V and for every scalar r of V holds $F(r \cdot x) = r \cdot F(x)$.

Let K be a non empty zero structure, let V be a non empty vector space structure over K, and let F be a functional in V. We say that F is 0-preserving if and only if:

(Def. 13) $F(0_V) = 0_K$.

Let K be an add-associative right zeroed right complementable Abelian associative left unital distributive non empty double loop structure and let V be a vector space over K. One can check that every functional in V which is homogeneous is also 0-preserving.

Let K be a right zeroed non empty loop structure and let V be a non empty vector space structure over K. One can verify that $0\text{Functional}V$ is additive.

Let K be an add-associative right zeroed right complementable right distributive non empty double loop structure and let V be a non empty vector space structure over K. One can check that $0\text{Functional}V$ is homogeneous.

Let K be a non empty zero structure and let V be a non empty vector space structure over K. Note that $0\text{Functional}V$ is 0-preserving.

Let K be an add-associative right zeroed right complementable right distributive non empty double loop structure and let V be a non empty vector space structure over K. Note that there exists a functional in V which is additive, homogeneous, and 0-preserving.

The following propositions are true:

(20) Let K be an Abelian non empty loop structure, V be a non empty vector space structure over K, and f, g be functionals in V. Then $f+g = g+f$.

(21) Let K be an add-associative non empty loop structure, V be a non empty vector space structure over K, and f, g, h be functionals in V. Then $(f+g)+h = f+(g+h)$.

(22) Let K be a non empty zero structure, V be a non empty vector space structure over K, and x be an element of V. Then $(0\text{Functional}V)(x) = 0_K$.

(23) Let K be a right zeroed non empty loop structure, V be a non empty vector space structure over K, and f be a functional in V. Then $f + 0\text{Functional}V = f$.

(24) Let K be an add-associative right zeroed right complementable non empty loop structure, V be a non empty vector space structure over K, and f be a functional in V. Then $f - f = 0\text{Functional}V$.

(25) Let K be a right distributive non empty double loop structure, V be a non empty vector space structure over K, r be an element of K, and f, g be functionals in V. Then $r \cdot (f+g) = r \cdot f + r \cdot g$.

(26) Let K be a left distributive non empty double loop structure, V be a non empty vector space structure over K, r, s be elements of K, and f be a functional in V. Then $(r+s) \cdot f = r \cdot f + s \cdot f$.

(27) Let K be an associative non empty groupoid, V be a non empty vector space structure over K, r, s be elements of K, and f be a functional in V. Then $(r \cdot s) \cdot f = r \cdot (s \cdot f)$.

(28) Let K be a left unital non empty double loop structure, V be a non empty vector space structure over K, and f be a functional in V. Then $\mathbf{1}_K \cdot f = f$.

Let K be an Abelian add-associative right zeroed right complementable right distributive non empty double loop structure, let V be a non empty vector space structure over K, and let f, g be additive functionals in V. Observe that $f+g$ is additive.

Let K be an Abelian add-associative right zeroed right complementable right distributive non empty double loop structure, let V be a non empty vector space structure over K, and let f be an additive functional in V. One can check that $-f$ is additive.

Let K be an add-associative right zeroed right complementable right distributive non empty double loop structure, let V be a non empty vector space structure over K, let v be an element of K, and let f be an additive functional in V. One can verify that $v \cdot f$ is additive.

Let K be an add-associative right zeroed right complementable right distributive non empty double loop structure, let V be a non empty vector space structure over K, and let f, g be homogeneous functionals in V. Observe that $f+g$ is homogeneous.

Let K be an Abelian add-associative right zeroed right complementable right distributive non empty double loop structure, let V be a non empty vector space structure over K, and let f be a homogeneous functional in V. Observe that $-f$ is homogeneous.

Let K be an add-associative right zeroed right complementable right distributive associative commutative non empty double loop structure, let V be a non empty vector space structure over K, let v be an element of K, and let f be a homogeneous functional in V. Observe that $v \cdot f$ is homogeneous.

Let K be an add-associative right zeroed right complementable right distributive non empty double loop structure and let V be a non empty vector space structure over K. A linear functional in V is an additive homogeneous functional in V.

4. The Vector Space of Linear Functionals

Let K be an Abelian add-associative right zeroed right complementable right distributive associative commutative non empty double loop structure and let V be a non empty vector space structure over K. The functor $\overline{V}$ yields a non empty strict vector space structure over K and is defined by the conditions (Def. 14).

(Def. 14)(i) For every set x holds $x \in$ the carrier of $\overline{V}$ iff x is a linear functional in V,

(ii) for all linear functionals f, g in V holds (the addition of $\overline{V})(f, g) = f+g$,

(iii) the zero of $\overline{V} =$ 0Functional$V$, and

(iv) for every linear functional f in V and for every element x of K holds (the left multiplication of $\overline{V})(x, f) = x \cdot f$.

Let K be an Abelian add-associative right zeroed right complementable right distributive associative commutative non empty double loop structure and let V be a non empty vector space structure over K. Note that $\overline{V}$ is Abelian.

Let K be an Abelian add-associative right zeroed right complementable right distributive associative commutative non empty double loop structure and let V be a non empty vector space structure over K. One can check the following observations:

* $\overline{V}$ is add-associative,
* $\overline{V}$ is right zeroed, and
* $\overline{V}$ is right complementable.

Let K be an Abelian add-associative right zeroed right complementable left unital distributive associative commutative non empty double loop structure and let V be a non empty vector space structure over K. Note that $\overline{V}$ is vector space-like.

5. SEMI NORM OF VECTOR SPACE

Let K be a 1-sorted structure and let V be a vector space structure over K. A RFunctional of V is a function from the carrier of V into $\mathbb{R}$.

Let K be a 1-sorted structure, let V be a non empty vector space structure over K, and let F be a RFunctional of V. We say that F is subadditive if and only if:

(Def. 16)[2] For all vectors x, y of V holds $F(x+y) \leq F(x)+F(y)$.

Let K be a 1-sorted structure, let V be a non empty vector space structure over K, and let F be a RFunctional of V. We say that F is additive if and only if:

(Def. 17) For all vectors x, y of V holds $F(x+y) = F(x)+F(y)$.

Let V be a non empty vector space structure over $\mathbb{C}_{\mathrm{F}}$ and let F be a RFunctional of V. We say that F is Real-homogeneous if and only if:

(Def. 18) For every vector v of V and for every real number r holds $F((r+0i_{\mathbb{C}_{\mathrm{F}}})\cdot v) = r\cdot F(v)$.

We now state the proposition

(29) Let V be a vector space-like non empty vector space structure over $\mathbb{C}_{\mathrm{F}}$ and F be a RFunctional of V. Suppose F is Real-homogeneous. Let v be a vector of V and r be a real number. Then $F((0+ri_{\mathbb{C}_{\mathrm{F}}})\cdot v) = r\cdot F(i_{\mathbb{C}_{\mathrm{F}}}\cdot v)$.

Let V be a non empty vector space structure over $\mathbb{C}_{\mathrm{F}}$ and let F be a RFunctional of V. We say that F is homogeneous if and only if:

(Def. 19) For every vector v of V and for every scalar r of V holds $F(r\cdot v) = |r|\cdot F(v)$.

Let K be a 1-sorted structure, let V be a vector space structure over K, and let F be a RFunctional of V. We say that F is 0-preserving if and only if:

(Def. 20) $F(0_V) = 0$.

Let K be a 1-sorted structure and let V be a non empty vector space structure over K. Observe that every RFunctional of V which is additive is also subadditive.

Let V be a vector space over $\mathbb{C}_{\mathrm{F}}$. Observe that every RFunctional of V which is Real-homogeneous is also 0-preserving.

Let K be a 1-sorted structure and let V be a vector space structure over K. The functor 0RFunctional$V$ yields a RFunctional of V and is defined as follows:

(Def. 21) 0RFunctional$V = \Omega_V \longmapsto 0$.

Let K be a 1-sorted structure and let V be a non empty vector space structure over K. Observe that 0RFunctional$V$ is additive and 0RFunctional$V$ is 0-preserving.

Let V be a non empty vector space structure over $\mathbb{C}_{\mathrm{F}}$. Note that 0RFunctional$V$ is Real-homogeneous and 0RFunctional$V$ is homogeneous.

Let K be a 1-sorted structure and let V be a non empty vector space structure over K. One can check that there exists a RFunctional of V which is additive and 0-preserving.

Let V be a non empty vector space structure over $\mathbb{C}_{\mathrm{F}}$. Observe that there exists a RFunctional of V which is additive, Real-homogeneous, and homogeneous.

Let V be a non empty vector space structure over $\mathbb{C}_{\mathrm{F}}$. A Semi-Norm of V is a subadditive homogeneous RFunctional of V.

[2] The definition (Def. 15) has been removed.

6. THE HAHN BANACH THEOREM

Let V be a non empty vector space structure over $\mathbb{C}_{\rm F}$. The functor RealVSV yielding a strict RLS structure is defined by the conditions (Def. 22).

(Def. 22)(i) The loop structure of RealVSV = the loop structure of V, and

(ii) for every real number r and for every vector v of V holds (the external multiplication of RealVS$V)(r, v) = (r + 0i_{\mathbb{C}_{\rm F}}) \cdot v$.

Let V be a non empty vector space structure over $\mathbb{C}_{\rm F}$. One can check that RealVSV is non empty.

Let V be an Abelian non empty vector space structure over $\mathbb{C}_{\rm F}$. Observe that RealVSV is Abelian.

Let V be an add-associative non empty vector space structure over $\mathbb{C}_{\rm F}$. Note that RealVSV is add-associative.

Let V be a right zeroed non empty vector space structure over $\mathbb{C}_{\rm F}$. One can check that RealVSV is right zeroed.

Let V be a right complementable non empty vector space structure over $\mathbb{C}_{\rm F}$. Observe that RealVSV is right complementable.

Let V be a vector space-like non empty vector space structure over $\mathbb{C}_{\rm F}$. One can verify that RealVSV is real linear space-like.

One can prove the following propositions:

(30) For every non empty vector space V over $\mathbb{C}_{\rm F}$ and for every subspace M of V holds RealVSM is a subspace of RealVSV.

(31) For every non empty vector space structure V over $\mathbb{C}_{\rm F}$ holds every RFunctional of V is a functional in RealVSV.

(32) For every non empty vector space V over $\mathbb{C}_{\rm F}$ holds every Semi-Norm of V is a Banach functional in RealVSV.

Let V be a non empty vector space structure over $\mathbb{C}_{\rm F}$ and let l be a functional in V. The functor projRe$\,l$ yields a functional in RealVSV and is defined by:

(Def. 23) For every element i of V holds $(\text{projRe}\,l)(i) = \Re(l(i))$.

Let V be a non empty vector space structure over $\mathbb{C}_{\rm F}$ and let l be a functional in V. The functor projIm$\,l$ yielding a functional in RealVSV is defined by:

(Def. 24) For every element i of V holds $(\text{projIm}\,l)(i) = \Im(l(i))$.

Let V be a non empty vector space structure over $\mathbb{C}_{\rm F}$ and let l be a functional in RealVSV. The functor $l_{\mathbb{R}\to\mathbb{C}}$ yields a RFunctional of V and is defined by:

(Def. 25) $l_{\mathbb{R}\to\mathbb{C}} = l$.

Let V be a non empty vector space structure over $\mathbb{C}_{\rm F}$ and let l be a RFunctional of V. The functor $l_{\mathbb{C}\to\mathbb{R}}$ yielding a functional in RealVSV is defined by:

(Def. 26) $l_{\mathbb{C}\to\mathbb{R}} = l$.

Let V be a non empty vector space over $\mathbb{C}_{\rm F}$ and let l be an additive functional in RealVSV. Note that $l_{\mathbb{R}\to\mathbb{C}}$ is additive.

Let V be a non empty vector space over $\mathbb{C}_{\rm F}$ and let l be an additive RFunctional of V. One can check that $l_{\mathbb{C}\to\mathbb{R}}$ is additive.

Let V be a non empty vector space over $\mathbb{C}_{\rm F}$ and let l be a homogeneous functional in RealVSV. One can check that $l_{\mathbb{R}\to\mathbb{C}}$ is Real-homogeneous.

Let V be a non empty vector space over $\mathbb{C}_{\rm F}$ and let l be a Real-homogeneous RFunctional of V. Note that $l_{\mathbb{C}\to\mathbb{R}}$ is homogeneous.

Let V be a non empty vector space structure over $\mathbb{C}_{\rm F}$ and let l be a RFunctional of V. The functor i-shift$\,l$ yields a RFunctional of V and is defined by:

(Def. 27) For every element v of V holds $(\text{i-shift}\, l)(v) = l(i_{\mathbb{C}_{\rm F}} \cdot v)$.

Let V be a non empty vector space structure over $\mathbb{C}_{\rm F}$ and let l be a functional in RealVS V. The functor prodReIm l yielding a functional in V is defined as follows:

(Def. 28) For every element v of V holds $(\text{prodReIm}\, l)(v) = (l_{\mathbb{R}\to\mathbb{C}})(v) + (-(\text{i-shift}\, l_{\mathbb{R}\to\mathbb{C}})(v)) i_{\mathbb{C}_{\rm F}}$.

One can prove the following propositions:

(33) Let V be a non empty vector space over $\mathbb{C}_{\rm F}$ and l be a linear functional in V. Then projRe l is a linear functional in RealVS V.

(34) Let V be a non empty vector space over $\mathbb{C}_{\rm F}$ and l be a linear functional in V. Then projIm l is a linear functional in RealVS V.

(35) Let V be a non empty vector space over $\mathbb{C}_{\rm F}$ and l be a linear functional in RealVS V. Then prodReIm l is a linear functional in V.

(36) Let V be a non empty vector space over $\mathbb{C}_{\rm F}$, p be a Semi-Norm of V, M be a subspace of V, and l be a linear functional in M. Suppose that for every vector e of M and for every vector v of V such that $v = e$ holds $|l(e)| \leq p(v)$. Then there exists a linear functional L in V such that $L \restriction$the carrier of $M = l$ and for every vector e of V holds $|L(e)| \leq p(e)$.

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