Vector Spaces

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Abstract

This article contains Z Notation type declarations for vector spaces and some related objects. It has been type checked by *f*UZZ.

1 Introduction

Real vector spaces are multidimensional generalizations of real numbers. They are the objects studied in linear algebra and are foundational to differential geometry.

2 Real n-tuples

Let n be a natural number. A finite sequence of n real numbers is called a real n-tuple. Define $\mathbb{R}^\infty$ to be the set of all real n-tuples for any n.

$$\mathbb{R}^\infty == \operatorname{seq} \mathbb{R}$$

Define $\mathbb{R}(n)$ to be $\mathbb{R}^n$, the set of all n-tuples.

$$\begin{array}{|l}
\mathbb{R} : \mathbb{N} \longrightarrow \mathbb{P}\, \mathbb{R}^\infty \\
\hline
\forall\, n : \mathbb{N} \bullet \\
\qquad \mathbb{R}(n) = \{\, v : \mathbb{R}^\infty \mid \# v = n \,\}
\end{array}$$

The real numbers that comprise an n-tuple are called its components. The real number $v(i)$ is the i-th component of the n-tuple v where $1 \leq i \leq n$. Let $\pi(i)$ be the projection function that maps an n-tuple v to its i-th component $v(i)$.

$$\begin{array}{|l}
\pi : \mathbb{N}_1 \longrightarrow \mathbb{R}^\infty \mathrel{+\!\!\!\rightarrow} \mathbb{R} \\
\hline
\forall\, i : \mathbb{N}_1 \bullet \\
\qquad \pi(i) = (\lambda\, v : \mathbb{R}^\infty \mid i \in \operatorname{dom} v \bullet v(i))
\end{array}$$

3 Scalar Multiplication

Let v be an n-tuple and let c be a real number. Scalar multiplication of v by c is the n-tuple $c * v$ defined by component-wise multiplication.

$$
\begin{array}{|l}
\_ * \_ : \mathbb{R} \times \mathbb{R}^{\infty} \longrightarrow \mathbb{R}^{\infty} \\
\hline
\forall\, c : \mathbb{R} \bullet \\
\qquad c * \langle\rangle = \langle\rangle \\
\forall\, c : \mathbb{R};\ n : \mathbb{N}_1 \bullet \\
\qquad \forall\, v : \mathbb{R}(n);\ i : 1 \mathinner{..} n \bullet \\
\qquad\qquad (c * v)(i) = c * v(i)
\end{array}
$$

4 Vector Addition and Subtraction

Let v and w be n-tuples. Vector addition of v and w is the n-tuple $v + w$ defined by component-wise addition.

$$
\begin{array}{|l}
\_ + \_ : \mathbb{R}^{\infty} \times \mathbb{R}^{\infty} \mathrel{+\!\!\!\rightarrow} \mathbb{R}^{\infty} \\
\hline
\operatorname{dom}(\_ + \_) = \{\, v, w : \mathbb{R}^{\infty} \mid \#v = \#w \,\} \\
\langle\rangle + \langle\rangle = \langle\rangle \\
\forall\, n : \mathbb{N}_1 \bullet \\
\qquad \forall\, v, w : \mathbb{R}(n);\ i : 1 \mathinner{..} n \bullet \\
\qquad\qquad (v + w)(i) = v(i) + w(i)
\end{array}
$$

Vector subtraction is defined similarly.

$$
\begin{array}{|l}
\_ - \_ : \mathbb{R}^{\infty} \times \mathbb{R}^{\infty} \mathrel{+\!\!\!\rightarrow} \mathbb{R}^{\infty} \\
\hline
\operatorname{dom}(\_ - \_) = \{\, v, w : \mathbb{R}^{\infty} \mid \#v = \#w \,\} \\
\langle\rangle - \langle\rangle = \langle\rangle \\
\forall\, n : \mathbb{N}_1 \bullet \\
\qquad \forall\, v, w : \mathbb{R}(n);\ i : 1 \mathinner{..} n \bullet \\
\qquad\qquad (v - w)(i) = v(i) - w(i)
\end{array}
$$

Each $\mathbb{R}(n)$ is a real vector space under the operations of scalar multiplication and vector addition defined above.

5 Linear Transformations

Let n and m be natural numbers. A mapping L from $\mathbb{R}^n$ to $\mathbb{R}^m$ is said to be a linear transformation if it preserves scalar multiplication and vector addition.

Linear

$$n, m : \mathbb{N}$$
$$L : \mathbb{R}^\infty \nrightarrow \mathbb{R}^\infty$$

$$L \in \mathbb{R}(n) \longrightarrow \mathbb{R}(m)$$

$$\forall\, c : \mathbb{R};\ v : \mathbb{R}(n) \bullet$$
$$\quad L(c * v) = c * L(v)$$

$$\forall\, v, w : \mathbb{R}(n) \bullet$$
$$\quad L(v + w) = L(v) + L(w)$$

Define $\mathrm{lin}(n, m)$ to be the set of all linear transformations from $\mathbb{R}^n$ to $\mathbb{R}^m$.

$$\mathrm{lin} : \mathbb{N} \times \mathbb{N} \longrightarrow \mathbb{P}(\mathbb{R}^\infty \nrightarrow \mathbb{R}^\infty)$$

$$\forall\, n, m : \mathbb{N} \bullet$$
$$\quad \mathrm{lin}(n, m) = \{\, L : \mathbb{R}^\infty \nrightarrow \mathbb{R}^\infty \mid \mathit{Linear} \,\}$$

6 The Dot Product

The inner or dot product of n-tuples v and w is the real number $v \cdot w$ defined by the sum of the component-wise products.

$$\_ \cdot \_ : \mathbb{R}^\infty \times \mathbb{R}^\infty \nrightarrow \mathbb{R}$$

$$\mathrm{dom}(\_ \cdot \_) = \{\, v, w : \mathbb{R}^\infty \mid \#v = \#w \,\}$$

$$\langle\rangle \cdot \langle\rangle = 0$$

$$\forall\, x, y : \mathbb{R};\ v, w : \mathbb{R}^\infty \mid \#v = \#w \bullet$$
$$\quad (\langle x \rangle \frown v) \cdot (\langle y \rangle \frown w) = x * y + v \cdot w$$

Each $\mathbb{R}(n)$ is a real inner product space under the operation of dot product defined above.

7 The Norm

The norm $\|v\|$ of the n-tuple v is the positive square root of its dot product with itself.

$$\|v\| = \sqrt{v \cdot v}$$

Define norm(v) to be $\|v\|$.

$$
\begin{array}{|l}
\text{norm} : \mathbb{R}^\infty \longrightarrow \mathbb{R} \\
\hline
\forall\, v : \mathbb{R}^\infty \bullet \\
\qquad \text{norm}(v) = \text{sqrt}(v \cdot v)
\end{array}
$$

The concepts of continuity, limits, and differentiability extend to functions between normed vector spaces such as $\mathbb{R}^n$.

8 Differentiability

Let $f : \mathbb{R}^n \longrightarrow \mathbb{R}^m$ and let $x \in \mathbb{R}^n$. Then f is differentiable at x if there exists a linear transformation $L : \mathbb{R}^n \longrightarrow \mathbb{R}^m$ such that f is approximately linear very near x.

$$f(x+h) \approx f(x) + L(h) \quad \text{when} \quad \|h\| \approx 0$$