

*Pacific
Journal of
Mathematics*

DIFFEOLOGICAL VECTOR SPACES

J. DANIEL CHRISTENSEN AND ENXIN WU

DIFFEOLOGICAL VECTOR SPACES

J. DANIEL CHRISTENSEN AND ENXIN WU

We study the relationship between many natural conditions that one can put on a diffeological vector space: being fine or projective, having enough smooth (or smooth linear) functionals to separate points, having a diffeology determined by the smooth linear functionals, having fine finite-dimensional subspaces, and having a Hausdorff underlying topology. Our main result is that the majority of the conditions fit into a total order. We also give many examples in order to show which implications do not hold, and use our results to study the homological algebra of diffeological vector spaces.

1. Introduction

Diffeological spaces are elegant generalizations of manifolds that include a variety of singular spaces and infinite-dimensional spaces. Many vector spaces that arise in applications are naturally equipped with a compatible structure of a diffeological space. Examples include $C^\infty(M, \mathbb{R}^n)$ for a manifold (or even a diffeological space) M , spaces of smooth or holomorphic sections of vector bundles, tangent spaces of diffeological spaces (as defined in [Christensen and Wu 2016]), smooth linear duals of all of these spaces, etc. Such objects are called diffeological vector spaces and are the topic of this paper.

Diffeological vector spaces have been studied by Iglesias-Zemmour [2007; 2013]. He used them to define diffeological manifolds, and developed the theory of *fine* diffeological vector spaces, a particularly well-behaved kind that forms the beginning of our story. Kriegel and Michor [1997] studied topological vector spaces equipped with a smooth structure, and their examples can be regarded as diffeological vector spaces. Diffeological vector spaces were used in the study of tangent spaces of diffeological spaces in [Vincent 2008] and [Christensen and Wu 2016]. Wu [2015] investigated the homological algebra of *all* diffeological vector spaces and the present paper builds heavily on this foundation.

The second author was partially supported by NNSF of China (No. 112530) and STU Scientific Research Foundation for Talents (No. 760179).

MSC2010: primary 46S99; secondary 57P99.

Keywords: diffeological vector space, homological algebra, fine diffeology, projective diffeological vector space, smooth linear functionals.

In this paper, we study some natural conditions that one can put on a diffeological vector space, and show that the majority of them fit into a total order. In order to state our results, we briefly introduce the conditions here, making use of some background material summarized in [Section 2](#).

Any vector space has a smallest diffeology making it into a diffeological vector space. This is called the *fine* diffeology, and we write \mathcal{FV} for the collection of vector spaces with the fine diffeology. We write \mathcal{FFV} for the collection of diffeological vector spaces whose finite-dimensional subspaces (with the induced diffeology) are all fine.

A diffeological vector space V is *projective* if for every linear subduction $f : W_1 \rightarrow W_2$ and every smooth linear map $g : V \rightarrow W_2$, there exists a smooth linear map $h : V \rightarrow W_1$ such that $g = f \circ h$. We write \mathcal{PV} for the collection of projective diffeological vector spaces.

A diffeological vector space V is in \mathcal{SD} (resp. \mathcal{SV}) if the smooth (resp. smooth linear) functionals $V \rightarrow \mathbb{R}$ separate points of V . That is, for each x and y in V with $x \neq y$, such a functional f can be found so that $f(x) \neq f(y)$.

Each diffeological space has a natural topology called the D -topology. We write \mathcal{HT} for the collection of diffeological vector spaces whose D -topologies are Hausdorff.

The last letter of the abbreviation is \mathcal{V} , \mathcal{D} or \mathcal{T} depending on whether the condition depends on the structure as a diffeological vector space, a diffeological space, or a topological space.

We now state the main results of the paper.

Theorem 1.1. *We have the following chain of containments:*

$$\mathcal{FV} \subset \mathcal{PV} \subset \mathcal{SV} \subseteq \mathcal{SD} \subset \mathcal{FFV} \quad \text{and} \quad \mathcal{SD} \subset \mathcal{HT},$$

where \subset indicates proper containment. Neither of \mathcal{HT} and \mathcal{FFV} contains the other.

We do not know whether the containments $\mathcal{SV} \subseteq \mathcal{SD}$ and $\mathcal{SD} \subseteq \mathcal{FFV} \cap \mathcal{HT}$ are proper.

The property of being finite-dimensional does not imply, nor is it implied by, any of the properties considered above. However, under this assumption, most of the properties agree.

Theorem 1.2. *When restricted to finite-dimensional vector spaces, the collections \mathcal{FV} , \mathcal{PV} , \mathcal{SV} , \mathcal{SD} and \mathcal{FFV} agree.*

Indeed, \mathcal{FV} and \mathcal{FFV} clearly agree for finite-dimensional spaces, so the containments must collapse to equalities. Note that we prove part of [Theorem 1.2](#) (see [Theorem 3.19](#)) on the way to proving [Theorem 1.1](#).

The final property we consider is the following. Write \mathcal{DV} for the collection of diffeological vector spaces V such that a function $p : \mathbb{R}^n \rightarrow V$ is smooth if and only

if $\ell \circ p : \mathbb{R}^n \rightarrow \mathbb{R}$ is smooth for each smooth linear functional $\ell : V \rightarrow \mathbb{R}$. Except for the inclusion $\mathcal{FV} \subset \mathcal{DV}$, the class \mathcal{DV} is independent of all of the others we have considered. However, under this assumption, we again find that many of the other conditions agree.

Theorem 1.3. *When restricted to V in \mathcal{DV} , the collections \mathcal{SV} , \mathcal{SD} , \mathcal{FFV} and \mathcal{HT} agree.*

The proofs of the containments, and the examples showing that many inclusions do not hold, are spread throughout [Section 3](#). For example, we show $\mathcal{FV} \subset \mathcal{PV}$ in [Example 3.7](#) and [Proposition 3.8](#), $\mathcal{PV} \subset \mathcal{SV}$ in [Proposition 3.14](#) and [Remark 3.15](#) (1), $\mathcal{SD} \subset \mathcal{HT}$ in [Proposition 3.16](#) and [Example 3.18](#), $\mathcal{HT} \not\subseteq \mathcal{FFV}$ in [Example 3.18](#), and both $\mathcal{SD} \neq \mathcal{FFV}$ and $\mathcal{FFV} \not\subseteq \mathcal{HT}$ in [Proposition 3.23](#). That $\mathcal{PV} \not\subseteq \mathcal{DV}$ is [Proposition 3.33](#), and the proof of [Theorem 1.3](#) is in [Proposition 3.31](#). The longest argument, which is the proof that $\mathcal{SD} \subseteq \mathcal{FFV}$, is deferred until [Section 5](#). Along the way, we also prove other results, such as the fact that a diffeological vector space V is fine if and only if every linear functional on V is smooth, and some necessary conditions for diffeological vector spaces and free diffeological vector spaces to be projective. In [Section 4](#), we give some applications of our results to the homological algebra of diffeological vector spaces. For example, we show that every finite-dimensional subspace of a diffeological vector space in \mathcal{SV} is a smooth direct summand.

We are thankful to Chengjie Yu for the argument used in Case 1 of the proof of [Theorem 3.22](#) in [Section 5](#) and to the referee for many comments that helped improve the exposition.

2. Background and conventions

In this section, we briefly recall some background on diffeological spaces. For further details, we recommend the standard textbook [[Iglesias-Zemmour 2013](#)]. For a concise introduction to diffeological spaces, we recommend [[Christensen et al. 2014](#)], particularly [Section 2](#) and the introduction to [Section 3](#).

Definition 2.1 [[Souriau 1984](#)]. *A diffeological space is a set X together with a specified set of functions $U \rightarrow X$ (called *plots*) for each open set U in \mathbb{R}^n and each $n \in \mathbb{N}$, such that for all open subsets $U \subseteq \mathbb{R}^n$ and $V \subseteq \mathbb{R}^m$:*

- (1) (covering) Every constant function $U \rightarrow X$ is a plot.
- (2) (smooth compatibility) If $U \rightarrow X$ is a plot and $V \rightarrow U$ is smooth, then the composite $V \rightarrow U \rightarrow X$ is also a plot.
- (3) (sheaf condition) If $U = \bigcup_i U_i$ is an open cover and $U \rightarrow X$ is a function such that each restriction $U_i \rightarrow X$ is a plot, then $U \rightarrow X$ is a plot.

A function $f : X \rightarrow Y$ between diffeological spaces is *smooth* if for every plot $p : U \rightarrow X$ of X , the composite $f \circ p$ is a plot of Y .

The category of diffeological spaces and smooth maps is complete and cocomplete. Given two diffeological spaces X and Y , we write $C^\infty(X, Y)$ for the set of all smooth maps from X to Y . An isomorphism in the category of diffeological spaces will be called a *diffeomorphism*.

Every manifold M is canonically a diffeological space with the plots taken to be all smooth maps $U \rightarrow M$ in the usual sense. We call this the *standard diffeology* on M . It is easy to see that smooth maps in the usual sense between manifolds coincide with smooth maps between them with the standard diffeology.

For a diffeological space X with an equivalence relation \sim , the *quotient diffeology* on X/\sim consists of all functions $U \rightarrow X/\sim$ that locally factor through the quotient map $X \rightarrow X/\sim$ via plots of X . A *subduction* is a map diffeomorphic to a quotient map. That is, it is a map $X \rightarrow Y$ such that the plots in Y are the functions that locally lift to X as plots in X .

For a diffeological space Y and a subset A of Y , the *subdiffeology* consists of all functions $U \rightarrow A$ such that $U \rightarrow A \hookrightarrow Y$ is a plot of Y . An *induction* is an injective smooth map $A \rightarrow Y$ such that a function $U \rightarrow A$ is a plot of A if and only if $U \rightarrow A \rightarrow Y$ is a plot of Y .

For diffeological spaces X and Y , the *product diffeology* on $X \times Y$ consists of all functions $U \rightarrow X \times Y$ whose components $U \rightarrow X$ and $U \rightarrow Y$ are plots of X and Y , respectively.

The *discrete diffeology* on a set is the diffeology whose plots are the locally constant functions. The *indiscrete diffeology* on a set is the diffeology in which every function is a plot.

We can associate to every diffeological space the following topology:

Definition 2.2 [Iglesias-Zemmour 2007]. Let X be a diffeological space. A subset A of X is *D-open* if $p^{-1}(A)$ is open in U for each plot $p : U \rightarrow X$. The collection of *D-open* subsets of X forms a topology on X called the *D-topology*.

Definition 2.3. A *diffeological vector space* is a vector space V with a diffeology such that addition $V \times V \rightarrow V$ and scalar multiplication $\mathbb{R} \times V \rightarrow V$ are smooth.

Let V be a diffeological vector space. We write $L^\infty(V, \mathbb{R})$ for the set of all smooth linear maps $V \rightarrow \mathbb{R}$, and $L(V, \mathbb{R})$ for the set of all linear maps $V \rightarrow \mathbb{R}$. We write DVect for the category of diffeological vector spaces and smooth linear maps.

Conventions. Throughout this paper, we use the following conventions. Every subset of a diffeological space is equipped with the subdiffeology and every product is equipped with the product diffeology. Every vector space is over the field \mathbb{R} of real numbers, and every linear map is \mathbb{R} -linear. By a subspace of a diffeological

vector space, we mean a linear subspace with the subdiffeology. All manifolds are smooth, finite-dimensional, Hausdorff, second countable and without boundary, and are equipped with the standard diffeology.

3. Diffeological vector spaces

In this section, we study a variety of conditions that a diffeological vector space can satisfy. Together, the results described here give the theorems stated in the introduction. In addition, we present some auxiliary results, and give many examples and counterexamples.

Fine diffeological vector spaces. In this subsection, we recall background on the fine diffeology, and then give two new characterizations.

Given a vector space V , the set of all diffeologies on V each of which makes V into a diffeological vector space, ordered by inclusion, is a complete lattice. This follows from [Christensen and Wu 2016, Proposition 4.6], taking X to be a point. The largest element in this lattice is the indiscrete diffeology, which is usually not interesting. Another extreme has the following special name in the literature:

Definition 3.1. The *fine* diffeology on a vector space V is the smallest diffeology on V making it into a diffeological vector space.

For example, the fine diffeology on \mathbb{R}^n is the standard diffeology.

Remark 3.2. The fine diffeology is generated by the injective linear maps $\mathbb{R}^n \rightarrow V$; see [Iglesias-Zemmour 2013, 3.8]. That is, the plots of the fine diffeology are the functions $p : U \rightarrow V$ such that for each $u \in U$, there are an open neighbourhood W of u in U , an injective linear map $i : \mathbb{R}^n \rightarrow V$ for some $n \in \mathbb{N}$, and a smooth map $f : W \rightarrow \mathbb{R}^n$ such that $p|_W = i \circ f$.

One can show that if V is any diffeological vector space and $p : W \rightarrow V$ is a plot that factors smoothly through some linear injection $\mathbb{R}^n \rightarrow V$, then every factorization of p through a linear injection $\mathbb{R}^m \rightarrow V$ is smooth. It follows that every subspace of a fine diffeological vector space is fine; see [Wu 2015].

In fact, fineness of a diffeological vector space can be tested by smooth curves:

Proposition 3.3. *A diffeological vector space V is fine if and only if for every plot $p : \mathbb{R} \rightarrow V$ and every $x \in \mathbb{R}$, there exist an open neighbourhood W of x in \mathbb{R} , an injective linear map $i : \mathbb{R}^n \rightarrow V$ for some $n \in \mathbb{N}$, and a smooth map $f : W \rightarrow \mathbb{R}^n$ such that $p|_W = i \circ f$.*

Proof. (\Rightarrow) This follows from the description of the fine diffeology in Remark 3.2.

(\Leftarrow) Under the given assumptions, we will prove that V is fine. Let $q : U \rightarrow V$ be a plot and let u be a point in U . We first show that there is an open neighbourhood W of u in U such that $q|_W$ lands in a finite-dimensional subspace of V . If not, then

there exists a sequence u_i in U converging to u such that $\{q(u_i) \mid i \in \mathbb{Z}^+\}$ is linearly independent in V . We may assume that the sequence u_i converges fast to u ; see [Kriegl and Michor 1997, I.2.8]. By the special curve lemma [Kriegl and Michor 1997, I.2.8], there exists a smooth map $f : \mathbb{R} \rightarrow U$ such that $f(1/i) = u_i$ and $f(0) = u$. Then $q \circ f : \mathbb{R} \rightarrow V$ is a plot which does not satisfy the hypothesis at $x = 0$.

So let W be an open neighbourhood of u in U such that $q|_W$ factors as $i \circ g$, where $i : \mathbb{R}^m \rightarrow V$ is a linear injection and $g : W \rightarrow \mathbb{R}^m$ is a function. We will prove that g is smooth. By Boman's theorem (see, e.g., [Kriegl and Michor 1997, Corollary 3.14]), it is enough to show that $g \circ r$ is smooth for every smooth curve $r : \mathbb{R} \rightarrow W$. Since $i \circ g \circ r$ is smooth, our assumption implies that it locally factors smoothly through an injective linear map $\mathbb{R}^n \rightarrow V$. Then the last part of Remark 3.2 implies that $g \circ r$ is locally smooth, and therefore smooth, as required. \square

Proposition 3.4. *A diffeological vector space V is fine if and only if $L^\infty(V, \mathbb{R}) = L(V, \mathbb{R})$, i.e., if and only if every linear functional is smooth.*

Proof. This follows from the proof of [Wu 2015, Proposition 5.7]. We give a direct proof here.

It is easy to check that if V is fine, then every linear functional is smooth.

To prove the converse, suppose that every linear functional $V \rightarrow \mathbb{R}$ is smooth. Let $p : U \rightarrow V$ be a plot and let $u \in U$. First we must show that when restricted to a neighbourhood of u , p lands in a finite-dimensional subspace of V . If not, then there is a sequence $\{u_j\}$ converging to u such that the vectors $p(u_j)$ are linearly independent. Thus there is a linear functional $l : V \rightarrow \mathbb{R}$ such that $p(u_j)$ is sent to 1 when j is odd and 0 when j is even. By assumption, l is smooth. But $l \circ p$ is not continuous, contradicting the fact that p is a plot.

So now we know that p locally factors through an injective linear map $i : \mathbb{R}^n \rightarrow V$. (Of course, n may depend on the neighbourhood.) For each $1 \leq j \leq n$, there is a linear map $l_j : V \rightarrow \mathbb{R}$ such that $l_j \circ i$ is projection onto the j -th coordinate. Since $l_j \circ p$ is smooth, it follows that the local factorizations through \mathbb{R}^n are smooth. Thus V is fine. \square

Projective diffeological vector spaces.

Definition 3.5. A diffeological vector space V is *projective* if for every linear subduction $f : W_1 \rightarrow W_2$ and every smooth linear map $g : V \rightarrow W_2$, there exists a smooth linear map $h : V \rightarrow W_1$ making the diagram

$$\begin{array}{ccc} & & W_1 \\ & \nearrow h & \downarrow f \\ V & \xrightarrow{g} & W_2 \end{array}$$

commute. We write \mathcal{PV} for the collection of projective diffeological vector spaces.

We now describe what will be a recurring example in this paper.

Definition 3.6. The *free diffeological vector space generated by a diffeological space* X is the vector space $F(X)$ with basis consisting of the elements of X and with the smallest diffeology making it into a diffeological vector space and such that the natural map $X \rightarrow F(X)$ is smooth.

This has the universal property that for any diffeological vector space V , every smooth map $X \rightarrow V$ extends uniquely to a smooth linear map $F(X) \rightarrow V$. Also, every plot in $F(X)$ is locally of the form

$$u \mapsto \sum_{i=1}^k r_i(u)[p_i(u)]$$

for smooth functions $r_i : U \rightarrow \mathbb{R}$ and $p_i : U \rightarrow X$, where for $x \in X$, $[x]$ denotes the corresponding basis vector in $F(X)$. See [Wu 2015, Proposition 3.5] for details.

Example 3.7. By [Wu 2015, Corollary 6.4], when M is a manifold, $F(M)$ is projective. However, by [Wu 2015, Theorem 5.3], $F(X)$ is fine if and only if X is discrete. So not every projective diffeological vector space is fine.

Proposition 3.8 [Wu 2015, Corollary 6.3]. *Every fine diffeological vector space is projective.*

Proof. This follows immediately from Proposition 3.4. One can take h to be $k \circ g$, where k is a linear section of f (which is not necessarily smooth). \square

Projective diffeological vector spaces and the homological algebra of diffeological vector spaces are studied further in [Wu 2015].

Separation of points.

Definition 3.9. Let X be a diffeological space. A set A of functions with domain X is said to *separate points* if for any $x, y \in X$ with $x \neq y$, there exists $f \in A$ such that $f(x) \neq f(y)$. We say that the *smooth functionals separate points* if $C^\infty(X, \mathbb{R})$ separates points. We write \mathcal{SD}' for the collection of all such diffeological spaces X and \mathcal{SD} for the diffeological vector spaces whose underlying diffeological spaces are in \mathcal{SD}' . If V is a diffeological vector space, we say that the *smooth linear functionals separate points* if $L^\infty(V, \mathbb{R})$ separates points, and we write \mathcal{SV} for the collection of all such diffeological vector spaces V .

We establish basic properties of such diffeological vector spaces below, and show that many familiar diffeological vector spaces have this property. Clearly, $\mathcal{SV} \subseteq \mathcal{SD}$.

Example 3.10. Every fine diffeological vector space is in \mathcal{SV} , since the coordinate functions with respect to any basis are smooth and linear. Every manifold is in \mathcal{SD}' , since the products of local coordinates with bump functions separate points (or by Whitney's embedding theorem).

Proposition 3.11. (1) *If $W \rightarrow V$ is a smooth linear injective map between diffeological vector spaces and $V \in \mathcal{SV}$, then $W \in \mathcal{SV}$. In particular, \mathcal{SV} is closed under taking subspaces.*

(2) *Let $\{V_i\}_{i \in I}$ be a set of diffeological vector spaces. Then $\prod_{i \in I} V_i \in \mathcal{SV}$ if and only if each $V_i \in \mathcal{SV}$.*

(3) *Let $\{V_i\}_{i \in I}$ be a set of diffeological vector spaces. Then $\bigoplus_{i \in I} V_i \in \mathcal{SV}$ if and only if each $V_i \in \mathcal{SV}$, where $\bigoplus_{i \in I} V_i$ is the coproduct in \mathbf{DVect} ; see [Wu 2015, Proposition 3.2].*

Proof. This is straightforward. □

Proposition 3.12. *If $V \in \mathcal{SV}$ and X is a diffeological space, then $C^\infty(X, V) \in \mathcal{SV}$.*

Proof. This follows from the fact that every evaluation map $C^\infty(X, V) \rightarrow V$ is smooth and linear. □

Proposition 3.13. *The following are equivalent:*

- (1) $X \in \mathcal{SD}'$.
- (2) $F(X) \in \mathcal{SV}$.
- (3) $F(X) \in \mathcal{SD}$.

Proof. It is enough to prove (1) \Rightarrow (2), since (2) \Rightarrow (3) \Rightarrow (1) are straightforward. Let $v \in F(X)$ be nonzero. It suffices to show that there is a smooth linear functional $F(X) \rightarrow \mathbb{R}$ which is nonzero on v . Write $v = \sum_{i=1}^k r_i [x_i]$ with $k \geq 1$, r_i nonzero for each i , and the x_i distinct. Since $C^\infty(X, \mathbb{R})$ separates points of X , there exists $f \in C^\infty(X, \mathbb{R})$ such that $f(x_1) = 1$ and $f(x_i) = 0$ for each $i > 1$. By the universal property of $F(X)$, f extends to a smooth linear map $F(X) \rightarrow \mathbb{R}$ which sends v to r_1 , which is nonzero. □

Proposition 3.14. *Every projective diffeological vector space is in \mathcal{SV} .*

Proof. By Example 3.10, every open subset U of a Euclidean space is in \mathcal{SD}' . So Proposition 3.13 implies that $F(U)$ is in \mathcal{SV} . Corollary 6.15 of [Wu 2015] says that every projective diffeological vector space is a retract of a coproduct of $F(U)$'s in \mathbf{DVect} . Therefore, it follows from Proposition 3.11 (3) and (1) that every projective diffeological vector space is in \mathcal{SV} . □

Remark 3.15. (1) Not every diffeological vector space in \mathcal{SV} is projective. For example, let $V := \prod_{\omega} \mathbb{R}$ be the product of countably many copies of \mathbb{R} . By Proposition 3.11 (2), V is in \mathcal{SV} . But [Wu 2015, Example 4.3] shows that V is not projective.

(2) \mathcal{SV} is not closed under taking quotients in \mathbf{DVect} . For example, $F(\pi) : F(\mathbb{R}) \rightarrow F(T_\alpha)$ is a linear subduction, where α is an irrational and

$$\pi : \mathbb{R} \rightarrow T_\alpha := \mathbb{R}/(\mathbb{Z} + \alpha\mathbb{Z})$$

is the projection to the 1-dimensional irrational torus. By [Proposition 3.13](#), $F(\mathbb{R})$ is in \mathcal{SV} , but $F(T_\alpha)$ is not in \mathcal{SV} since T_α is not in \mathcal{SD}' . In particular, the free diffeological vector space $F(T_\alpha)$ is not projective, as observed in [\[Wu 2015, Example 4.3\]](#).

Here is an easy fact:

Proposition 3.16. *The D -topology of every diffeological space in \mathcal{SD}' is Hausdorff. In particular, $\mathcal{SD} \subseteq \mathcal{HT}$.*

Proof. This follows from the fact that every smooth map is continuous when both domain and codomain are equipped with the D -topology. \square

Corollary 3.17. *If $F(X)$ is projective, then X is Hausdorff.*

Proof. If $F(X)$ is projective, then it is in \mathcal{SD} by [Proposition 3.14](#), and so X is in \mathcal{SD}' by [Proposition 3.13](#). Thus X is Hausdorff, by [Proposition 3.16](#). \square

This gives another proof that free diffeological vector spaces are not always projective. For example, if a set X with more than one point is equipped with the indiscrete diffeology, then the D -topology on X is indiscrete as well, and hence $F(X)$ is not projective.

Example 3.18. The converse of [Proposition 3.16](#) does not hold. Write $C(\mathbb{R})$ for the vector space \mathbb{R} equipped with the continuous diffeology, so that a function $p : U \rightarrow C(\mathbb{R})$ is a plot if and only if it is continuous; see [\[Christensen et al. 2014, Section 3\]](#). Then $C(\mathbb{R})$ is a Hausdorff diffeological vector space, as the D -topology on $C(\mathbb{R})$ is the usual topology. But one can show that $C^\infty(C(\mathbb{R}), \mathbb{R})$ consists of constant functions ([\[Christensen and Wu 2016, Example 3.15\]](#)), so $C(\mathbb{R})$ is not in \mathcal{SD} .

We will use the following result in the next subsection.

Theorem 3.19. *Let V be a finite-dimensional diffeological vector space. Then the following are equivalent:*

- (1) V is fine.
- (2) V is projective.
- (3) V is in \mathcal{SV} .

Proof. By [Propositions 3.8](#) and [3.14](#), (1) \implies (2) \implies (3), for all V . So it remains to prove (3) \implies (1). Assume that V is finite-dimensional and in \mathcal{SV} . Choose a basis f_1, \dots, f_k for $L^\infty(V, \mathbb{R})$, and use it to give a smooth linear map $f : V \rightarrow \mathbb{R}^k$. Note that $k \leq \dim V$. Since V is in \mathcal{SV} , f is injective, and hence surjective. The diffeology on \mathbb{R}^k is the fine diffeology, which is the smallest diffeology making it into a diffeological vector space. The map $f : V \rightarrow \mathbb{R}^k$ is a smooth linear bijection, so the diffeology on V must be fine as well (and f must be a diffeomorphism). \square

The implication (3) \implies (1) also follows from [Proposition 3.4](#), since V in \mathcal{SV} implies that $\dim L(V, \mathbb{R}) \geq \dim L^\infty(V, \mathbb{R}) \geq \dim V = \dim L(V, \mathbb{R})$, and so $L^\infty(V, \mathbb{R}) = L(V, \mathbb{R})$.

Diffeological vector spaces whose finite-dimensional subspaces are fine. Write \mathcal{FFV} for the collection of diffeological vector spaces whose finite-dimensional subspaces are fine. One motivation for studying this collection is the following. In [Christensen and Wu 2016], we defined a diffeology on Hector's tangent spaces [1995] which makes them into diffeological vector spaces. While they are not fine in general, we know of no examples that are not in \mathcal{FFV} .

As an example, one can show that $\prod_{\omega} \mathbb{R}$ is in \mathcal{FFV} . This also follows from the next result, which is based on a suggestion of Y. Karshon.

Theorem 3.20. *Every diffeological vector space in \mathcal{SV} is in \mathcal{FFV} .*

This result is a special case of Theorem 3.22 below, but we provide a direct proof, since it follows easily from earlier results.

Proof. Let W be a finite-dimensional subspace of V with $V \in \mathcal{SV}$. W is in \mathcal{SV} , by Proposition 3.11 (1), and so by Theorem 3.19, W is fine. \square

Remark 3.21. (1) Note that it is not in general true that every diffeological vector space in \mathcal{SV} is fine. For example, $\prod_{\omega} \mathbb{R}$ is in \mathcal{SV} by Remark 3.15 (1), but it is not fine. In fact, [Wu 2015, Example 5.4] showed that there is a countable-dimensional subspace of $\prod_{\omega} \mathbb{R}$ which is not fine. Incidentally, it follows that $\prod_{\omega} \mathbb{R}$ is not the colimit in \mathbf{DVect} of its finite-dimensional subspaces, since fine diffeological vector spaces are closed under colimits; see [Wu 2015, Property 6 after Definition 5.2].

(2) When \mathbb{R} is equipped with the continuous diffeology (see Example 3.18), it is Hausdorff but is not in \mathcal{FFV} . We will see in Proposition 3.23 that the reverse inclusion also fails to hold.

The main result of this section is the following:

Theorem 3.22. *Every diffeological vector space in \mathcal{SD} is in \mathcal{FFV} .*

We defer the proof to Section 5.

Furthermore, we have the following result:

Proposition 3.23. *There exists a diffeological vector space which is in \mathcal{FFV} but which is not Hausdorff. In particular, the containment of \mathcal{SD} in \mathcal{FFV} is proper.*

Proof. Let V be the vector space with basis \mathbb{R} , and for $r \in \mathbb{R}$ write $[r]$ for the corresponding basis vector of V . Let $f : \mathbb{R} \rightarrow \mathbb{R}$ be a bijection such that $f^{-1}(U)$ is dense in \mathbb{R} for every open neighbourhood U of 0 in \mathbb{R} . Define $p : \mathbb{R} \rightarrow V$ by $p(x) = [f(x)]$ and $\bar{p} : \mathbb{R} \rightarrow V$ by $\bar{p}(x) = [x]$. Equip V with the vector space diffeology generated by p and \bar{p} . In other words, $q : U \rightarrow V$ is a plot if and only if for every $u_0 \in U$ there exist an open neighbourhood U' of u_0 in U and finitely many smooth functions $\alpha_i, \beta_i, \bar{\alpha}_j, \bar{\beta}_j : U' \rightarrow \mathbb{R}$ such that for any $u \in U'$,

$$(\dagger) \quad q(u) = \sum_i \alpha_i(u) [f(\beta_i(u))] + \sum_j \bar{\alpha}_j(u) [\bar{\beta}_j(u)].$$

(In general, one should include terms with smooth multiples of arbitrary vectors in V , but since $\bar{\beta}_j$ can be constant, this case is included in the above.) First we show that the D -topology on V is not Hausdorff. Suppose that V_0 and V_1 are disjoint D -open subsets of V containing $[0]$ and $[1]$, respectively. Then $U_0 := \bar{p}^{-1}(V_0)$ and $U_1 := \bar{p}^{-1}(V_1)$ are open in \mathbb{R} . Since p and \bar{p} are both bijections onto the subset of basis vectors in V , it follows that $p^{-1}(V_0) = f^{-1}(U_0)$ and $p^{-1}(V_1) = f^{-1}(U_1)$. Therefore, $p^{-1}(V_0)$ is dense in \mathbb{R} and so $p^{-1}(V_1)$, which is contained in the complement, must not be open in \mathbb{R} , contradicting the assumption that V_1 is D -open. So V is not Hausdorff.

Next we show that V is in \mathcal{FFV} . It suffices to show that for any finite subset $A \subseteq \mathbb{R}$, the subspace W spanned by A has the fine diffeology. So let $q : U \rightarrow V$ be a plot which lands in W . We must show that for each $a \in A$, the component q_a of q is a smooth function $U \rightarrow \mathbb{R}$. This is a local property, so we choose $u_0 \in U$ and express q in the form (\dagger) . It suffices to handle each sum in (\dagger) separately, so we begin by assuming that q only has terms involving f . Let $A' = f^{-1}(A)$. By shrinking U' if necessary, we can assume that: (1) for any $b' \in A'$, if $\beta_i(u_0) \neq b'$, then $\beta_i(u) \neq b'$ for all $u \in U'$; and (2) if $\beta_i(u_0) \neq \beta_j(u_0)$, then β_i and β_j have disjoint images. Since f is a bijection, we can rephrase these conditions as: (1') for any $b \in A$, if $f(\beta_i(u_0)) \neq b$, then $f(\beta_i(u)) \neq b$ for all $u \in U'$; and (2') if $f(\beta_i(u_0)) \neq f(\beta_j(u_0))$, then $f \circ \beta_i$ and $f \circ \beta_j$ have disjoint images. Condition (1') implies that for $u \in U'$, $q_a(u)$ is the a -coefficient of

$$\sum_{f(\beta_i(u_0))=a} \alpha_i(u) [f(\beta_i(u))].$$

Since $q(u)$ is in W , condition (2') implies that for $r \in \mathbb{R} \setminus A$, we must have

$$(\diamond) \quad \sum_{f(\beta_i(u_0))=a, f(\beta_i(u))=r} \alpha_i(u) = 0.$$

And condition (1') implies that (\diamond) also holds for $r \in A \setminus \{a\}$, since the sum is empty in that case. Therefore, $q_a(u)$ can be expressed as

$$\sum_{f(\beta_i(u_0))=a} \alpha_i(u),$$

which is a smooth function of $u \in U'$.

The other sum in (\dagger) is handled in a similar way, replacing f by the identity function throughout.

Finally, [Proposition 3.16](#) implies that V is not in SD , giving the last claim. \square

Next we observe that if V is projective (and hence in SV and SD), it does not follow that all countable-dimensional subspaces of V are fine. We will illustrate this with $V = F(\mathbb{R})$. By [\[Wu 2015, Corollary 6.4\]](#), $F(\mathbb{R})$ is projective.

Proposition 3.24. *Let A be a subset of \mathbb{R} , and let V be the subspace of $F(\mathbb{R})$ spanned by A . Then V is fine if and only if A has no accumulation point in \mathbb{R} .*

For example, $F(\mathbb{R})$ is not fine. As a more interesting example,

$$A = \{1/n \mid n = 1, 2, \dots\}$$

spans a countable-dimensional subspace V of $F(\mathbb{R})$ which is not fine. It will follow from [Proposition 3.25](#) that V is not free on any diffeological space.

Proof. (\Leftarrow) Let $p : U \rightarrow V$ be a plot, where U is open in some \mathbb{R}^n . Since V is the span of A , there exist unique functions $h_a : U \rightarrow \mathbb{R}$ such that

$$p(x) = \sum_{a \in A} h_a(x)[a].$$

Since A has no accumulation point in \mathbb{R} , for each a in A there exists a smooth bump function $\phi_a : \mathbb{R} \rightarrow \mathbb{R}$ which takes the value 1 at a and 0 at every other element of A . Associated to ϕ_a is a smooth linear map $\tilde{\phi}_a : F(\mathbb{R}) \rightarrow \mathbb{R}$ which sends $[a]$ to 1 and all other basis elements from A to 0. Then $h_a = \tilde{\phi}_a \circ p$, which shows that h_a is smooth.

Next we show that locally p factors through the span of a finite subset of A . Fix $u \in U$. As V is a subspace of $F(\mathbb{R})$, there is an open neighbourhood U' of u in U such that

$$p(x) = \sum_{j=1}^m f_j(x)[g_j(x)]$$

for $x \in U'$, where f_j and g_j are smooth functions $U' \rightarrow \mathbb{R}$. Shrinking U' if necessary, we can assume that it is contained in a compact subset of U . It follows that the image of each g_j is contained in a compact subset of \mathbb{R} and therefore intersects only finitely many points of A . Since there are only finitely many g_j 's, $p|_{U'}$ factors through the span of A' for some finite subset A' of A . That is, $h_a(x) = 0$ for all $x \in U'$ and all $a \in A \setminus A'$.

In summary, identifying the span of A' with $\mathbb{R}^{A'}$, we have factored $p|_{U'}$ as $U' \rightarrow \mathbb{R}^{A'} \rightarrow V$, where the first map is $x \mapsto (h_a(x))_{a \in A'}$ and the second map sends $f : A' \rightarrow \mathbb{R}$ to $\sum_{a \in A'} f(a)[a]$.

(\Rightarrow) Now we prove that if A has an accumulation point a_0 in \mathbb{R} , then V is not fine. Pick a sequence (a_i) in $A \setminus \{a_0\}$ that converges fast to a_0 . Choose a smooth function $f : \mathbb{R} \rightarrow \mathbb{R}$ such that $f(x) \neq 0$ for $1/(2n+1) < x < 1/2n$ for each $n \in \mathbb{Z}^+$, and $f(x) = 0$ for all other x . Choose another smooth function $g : \mathbb{R} \rightarrow \mathbb{R}$ such that $g(x) = a_n$ for $1/(2n+1) < x < 1/2n$ for each $n \in \mathbb{Z}^+$, with no constraints on g otherwise. It will necessarily be the case that $g(0) = a_0$, and such a smooth g exists because the sequence was chosen to converge fast. Then the function $p : \mathbb{R} \rightarrow V$ defined by $p(x) = f(x)[g(x)]$ is smooth, but there is no open neighbourhood U of 0 so that $p|_U$ factors through a finite-dimensional subspace of V . \square

On the other hand, we have:

Proposition 3.25. *Let X be a diffeological space whose underlying set has cardinality less than the cardinality of \mathbb{R} . Then the following are equivalent:*

- (1) X is discrete.
- (2) $F(X)$ is fine.
- (3) $F(X)$ is projective.
- (4) $F(X)$ is in \mathcal{SV} .
- (5) $F(X)$ is in \mathcal{SD} .
- (6) $F(X)$ is Hausdorff.

Proof. That (1) \implies (2) is straightforward. The implications (2) \implies (3) \implies (4) and (5) \implies (6) follow from Propositions 3.8, 3.14 and 3.16, while (4) \implies (5) is clear. None of these use the assumption on the cardinality of X .

It remains to prove that (6) \implies (1). Since the natural injective map $X \rightarrow F(X)$ is smooth, it is also continuous when X and $F(X)$ are both equipped with the D -topology. Therefore, X is Hausdorff. We must show that the diffeology on X is discrete. Let $p : U \rightarrow X$ be a plot from a connected open subset U of a Euclidean space. We will show that p is constant. If not, then the image of p contains two distinct points $x, x' \in X$ which are connected by a continuous path $q : [0, 1] \rightarrow X$. The image of q is compact Hausdorff, and therefore normal. So by Urysohn's lemma, there is a continuous map $l : \text{Im}(q) \rightarrow \mathbb{R}$ which separates x and x' . Hence, the image of the composite $l \circ q : [0, 1] \rightarrow \text{Im}(q) \rightarrow \mathbb{R}$ has cardinality equal to the cardinality of \mathbb{R} , which is a contradiction, since $\text{Im}(q) \subseteq X$ has cardinality less than the cardinality of \mathbb{R} . \square

Part of the above proof is based on the argument in [Hamkins 2015]. Note that we have proved that every Hausdorff diffeological space with cardinality less than the cardinality of \mathbb{R} is discrete. The implication (2) \implies (1) is also proved in [Wu 2015, Theorem 5.3], without a constraint on the cardinality of X .

Diffeologies determined by smooth linear functionals.

Definition 3.26. The diffeology on a diffeological vector space V is *determined by its smooth linear functionals* if $p : U \rightarrow V$ is a plot if and only if $l \circ p$ is smooth for every $l \in L^\infty(V, \mathbb{R})$. Write \mathcal{DV} for the collection of all such diffeological vector spaces.

Note that any vector space with the indiscrete diffeology is in \mathcal{DV} . It follows that being in \mathcal{DV} does not imply any of the other conditions we have studied.

Also note that every diffeological vector space V in \mathcal{DV} is *Frölicher*: $p : U \rightarrow V$ is a plot if and only if $f \circ p$ is smooth for every $f \in C^\infty(V, \mathbb{R})$. We do not know if the converse holds.

We will see in [Proposition 3.31](#) that for diffeological vector spaces in \mathcal{DV} , the converse of [Theorem 3.20](#) holds. For this, we need the following results.

Lemma 3.27. (1) *If V is in \mathcal{DV} and W is a subspace of V , then W is in \mathcal{DV} .*

(2) *Let $\{V_i\}$ be a set of diffeological vector spaces. Then each V_i is in \mathcal{DV} if and only if $\prod V_i$ is in \mathcal{DV} .*

Since the category \mathcal{DVect} is an additive category, (2) also implies that \mathcal{DV} is closed under taking finite direct sums.

Proof. This is straightforward. \square

Proposition 3.28. *Let V be a diffeological vector space. Then V is in \mathcal{DV} if and only if V can be written as a direct sum $V \cong W_0 \oplus W_1$ of diffeological vector spaces, where W_0 is indiscrete and W_1 is in $\mathcal{SV} \cap \mathcal{DV}$.*

Proof. Given V in \mathcal{DV} , let W_0 be $\bigcap_{l \in L^\infty(V, \mathbb{R})} \ker(l)$ with the subdiffeology. Since $L^\infty(V, \mathbb{R})$ determines the diffeology on V , W_0 is indiscrete. Let W_1 be the quotient V/W_0 , with the quotient diffeology. By [Lemma 3.30](#), we have $V \cong W_0 \oplus W_1$ as diffeological vector spaces. If $v + W_0$ is a nonzero element of W_1 , then $v \notin W_0$, so there is a smooth linear functional $l : V \rightarrow \mathbb{R}$ such that $l(v) \neq 0$. This l factors through W_1 , so it follows that W_1 is in \mathcal{SV} . By [Lemma 3.27](#), we know that $W_1 \in \mathcal{DV}$, and hence $W_1 \in \mathcal{SV} \cap \mathcal{DV}$.

The converse follows from [Lemma 3.27](#) and the comment after [Definition 3.26](#). \square

Definition 3.29. Following [[Wu 2015](#), Definition 3.15], a diagram

$$0 \longrightarrow W_0 \xrightarrow{i} V \xrightarrow{p} W_1 \longrightarrow 0$$

of diffeological vector spaces is a *short exact sequence of diffeological vector spaces* if it is a short exact sequence of vector spaces, i is an induction, and p is a subduction.

Lemma 3.30. *Let*

$$0 \longrightarrow W_0 \xrightarrow{i} V \xrightarrow{p} W_1 \longrightarrow 0$$

be a short exact sequence of diffeological vector spaces. If W_0 is indiscrete, then the sequence splits smoothly, so that $V \cong W_0 \oplus W_1$ as diffeological vector spaces.

Proof. Let $q : V \rightarrow W_0$ be any linear function such that $q \circ i = 1_{W_0}$. Since W_0 is indiscrete, q is smooth. Let $k : V \rightarrow V$ be the smooth linear map sending v to $v - i(q(v))$. Then $k \circ i = 0$, so k factors as $j \circ p$, where $j : W_1 \rightarrow V$ is smooth and linear. The smooth bijection $V \rightarrow W_0 \oplus W_1$ sending v to $(q(v), p(v))$ has a smooth inverse sending (w_0, w_1) to $i(w_0) + j(w_1)$, so the claim follows. \square

It follows that many properties of a diffeological vector space are equivalent in this setting:

Proposition 3.31. *Let V be in \mathcal{DV} . Then the following are equivalent:*

- (1) V is in \mathcal{SV} .
- (2) V is in \mathcal{SD} .
- (3) V is in \mathcal{FFV} .
- (4) $D(V)$ is Hausdorff.
- (5) V has no nonzero indiscrete subspace.

Moreover, being in \mathcal{DV} and satisfying one of these conditions is equivalent to being a subspace of a product of copies of \mathbb{R} .

Proof. Without any assumption on V , we have (1) \implies (2) \implies (3) and (2) \implies (4) using [Theorem 3.22](#) and [Proposition 3.16](#). It is easy to see that (3) \implies (5) and (4) \implies (5). By [Proposition 3.28](#), (5) \implies (1) when V is in \mathcal{DV} , and so we have shown that the five conditions are equivalent for $V \in \mathcal{DV}$.

For the last claim, a product of copies of \mathbb{R} is in both \mathcal{SV} and \mathcal{DV} , and both are closed under taking subspaces. Conversely, if V is in $\mathcal{SV} \cap \mathcal{DV}$, it is easy to check that

$$V \rightarrow \prod_{L^\infty(V, \mathbb{R})} \mathbb{R}$$

defined by $v \mapsto (f(v))_{f \in L^\infty(V, \mathbb{R})}$ is a linear induction, and hence V is a subspace of a product of copies of \mathbb{R} . \square

Remark 3.32. (1) It is not true that every diffeological vector space is in \mathcal{DV} . For example, when \mathbb{R} is equipped with the continuous diffeology (see [Example 3.18](#)), all smooth linear functionals are zero, but the diffeology is not indiscrete.

(2) Other properties we have studied cannot be added to [Proposition 3.31](#). For example, we saw in [Remark 3.15](#) (1) that $\prod_{\omega} \mathbb{R}$ is in \mathcal{SV} but is not fine or projective. And it is easy to see that $\prod_{\omega} \mathbb{R}$ is in \mathcal{DV} .

It is not hard to show that every fine diffeological vector space is in \mathcal{DV} . As a final example, we will show that not every projective diffeological vector space is in \mathcal{DV} , and therefore that none of our other conditions on a diffeological vector space V implies that V is in \mathcal{DV} .

We will again use the diffeological vector space $F(\mathbb{R})$, which is projective by [\[Wu 2015, Corollary 6.4\]](#). We now show that it is not in \mathcal{DV} .

Proposition 3.33. *The free diffeological vector space $F(\mathbb{R})$ generated by \mathbb{R} is not in \mathcal{DV} .*

Proof. Fix a nonzero smooth function $\phi : \mathbb{R} \rightarrow \mathbb{R}$ such that $\text{supp}(\phi) \subset (0, 1)$ and $|\phi(x)| \leq 1$ for all $x \in \mathbb{R}$. For each $n \in \mathbb{Z}^+$, define $\phi_n : \mathbb{R} \rightarrow \mathbb{R}$ by

$$\phi_n(x) = \phi\left(\frac{x - \frac{1}{n+1}}{\frac{1}{n} - \frac{1}{n+1}}\right).$$

Finally, define $g : \mathbb{R} \rightarrow F(\mathbb{R})$ by

$$g(t) = \begin{cases} 2^{-n} \phi_n(t) \sum_{i=1}^n \left[\frac{1}{i}\right] & \text{if } \frac{1}{n+1} \leq t < \frac{1}{n}, \text{ for } n > 0, \\ 0 & \text{else.} \end{cases}$$

Then g is not a plot of $F(\mathbb{R})$, since locally around $0 \in \mathbb{R}$, g cannot be written as a finite sum of $f_i(x)[h_i(x)]$, where f_i and h_i are smooth functions with codomain \mathbb{R} . But for each $l \in L^\infty(F(\mathbb{R}), \mathbb{R})$,

$$l \circ g(t) = \begin{cases} 2^{-n} \phi_n(t) \sum_{i=1}^n l\left(\left[\frac{1}{i}\right]\right) & \text{if } \frac{1}{n+1} \leq t < \frac{1}{n}, \\ 0 & \text{else.} \end{cases}$$

This is smooth, since the set $\left\{l\left(\left[\frac{1}{i}\right]\right)\right\}$ is bounded, using the smoothness of l . \square

As an easy corollary, we have:

Corollary 3.34. $F(\mathbb{R})$ is not a subspace of a product of copies of \mathbb{R} .

4. Some applications

Recall that a diagram

$$0 \longrightarrow V_1 \xrightarrow{f} V_2 \xrightarrow{g} V_3 \longrightarrow 0$$

is a short exact sequence of diffeological vector spaces if it is a short exact sequence of vector spaces such that f is an induction and g is a subduction. We say that the sequence *splits smoothly* if there exists a smooth linear map $r : V_2 \rightarrow V_1$ such that $r \circ f = 1_{V_1}$, or equivalently, if there exists a smooth linear map $s : V_3 \rightarrow V_2$ such that $g \circ s = 1_{V_3}$. In either case, V_2 is smoothly isomorphic to $V_1 \times V_3$; see [Wu 2015, Theorem 3.16].

Not every short exact sequence of diffeological vector spaces splits smoothly. For example, if we write K for the subspace of $C^\infty(\mathbb{R}, \mathbb{R})$ consisting of the smooth functions which are flat at 0, then K is not a smooth direct summand of $C^\infty(\mathbb{R}, \mathbb{R})$ [Wu 2015, Example 4.3].

As a first application of the theory established so far, we can construct additional short exact sequences of diffeological vector spaces which do not split smoothly:

Example 4.1. Let M be a manifold of positive dimension, and let A be a finite subset of M . Write V for the subspace of $F(M)$ spanned by the subset $M \setminus A$ of M . We claim that V is not a smooth direct summand of $F(M)$.

To see this, write W for the quotient diffeological vector space $F(M)/V$. Then, as a vector space, $W = \bigoplus_{a \in A} \mathbb{R}$. So we have a short exact sequence $0 \rightarrow V \rightarrow F(M) \rightarrow W \rightarrow 0$ in DVect . Suppose this sequence splits smoothly. By [Example 3.7](#), $F(M)$ is projective, and therefore W is as well. By [Proposition 3.14](#) and [Theorem 3.20](#), W is in \mathcal{FFV} . Since W is finite-dimensional, it is fine. But the smooth map $M \rightarrow F(M) \rightarrow W = \bigoplus_{a \in A} \mathbb{R}$ sends each $a \in A$ to a basis vector and other points in M to 0, so it is not a smooth map in the usual sense. This contradicts the fact that W is fine.

As a second application, we prove:

Theorem 4.2. *Let V be in \mathcal{SV} . Then every finite-dimensional subspace of V is a smooth direct summand.*

Proof. Let W be a finite-dimensional subspace of $V \in \mathcal{SV}$. By [Theorem 3.20](#), we know that W has the fine diffeology. Moreover, since V is in \mathcal{SV} , there is a smooth linear injective map $V \rightarrow \prod_{i \in I} \mathbb{R}$ for some index set I . Since $\prod_{i \in I} \mathbb{R}$ is in \mathcal{SV} , again by [Theorem 3.20](#), we know that the composite $W \hookrightarrow V \rightarrow \prod_{i \in I} \mathbb{R}$ is an induction, although the second map might not be an induction. So, we are left to prove this statement for the case $V = \prod_{i \in I} \mathbb{R}$.

Write $\dim(W) = m$. By Gaussian elimination, there exist distinct $i_1, \dots, i_m \in I$ such that the composite $W \hookrightarrow V = \prod_{i \in I} \mathbb{R} \rightarrow \mathbb{R}^m$ is an isomorphism of vector spaces, where the second map is the projection onto the i_1, \dots, i_m coordinates, and hence smooth. Since both W and \mathbb{R}^m have the fine diffeology, this isomorphism is a diffeomorphism, and by composing with its inverse we obtain a smooth linear map $r : V \rightarrow W$ such that the composite

$$W \hookrightarrow V \xrightarrow{r} W$$

is 1_W . Therefore, W is a smooth direct summand of V . □

5. Proof of [Theorem 3.22](#)

Theorem 3.22. *Every diffeological vector space in \mathcal{SD} is in \mathcal{FFV} .*

Proof. If a diffeological vector space is in \mathcal{SD} , then so are all of its subspaces. So it suffices to show that every finite-dimensional diffeological vector space in \mathcal{SD} is fine.

Write V for \mathbb{R}^n with the structure of a diffeological vector space which is not fine. We will use the word “smooth” (resp. “continuous”) to describe functions $\mathbb{R} \rightarrow V$ and $V \rightarrow \mathbb{R}$ which are smooth (resp. continuous) with respect to the usual diffeology (resp. topology) on \mathbb{R}^n . We use the word “plot” to describe functions $\mathbb{R} \rightarrow V$ which are in the diffeology on V , and write $f \in C^\infty(V, \mathbb{R})$ to describe functions which are smooth with respect to this diffeology.

By [Proposition 3.3](#), there is a plot $p : \mathbb{R} \rightarrow V$ which is not smooth. Since plots are closed under translation in the domain and codomain, we can assume without loss of generality that $p(0) = 0$ and p is not smooth at $0 \in \mathbb{R}$. We will show that this implies that V is not in \mathcal{SD} .

Case 1: Suppose p is continuous at 0. Consider $A := \{\nabla f(x) \mid f \in C^\infty(V, \mathbb{R}), x \in V\}$. Then A is a subset of \mathbb{R}^n .

We claim that A is a proper subset of \mathbb{R}^n . If A is not proper, then there exist $(f_1, a_1), \dots, (f_n, a_n) \in C^\infty(V, \mathbb{R}) \times V$ such that $\nabla f_1(a_1), \dots, \nabla f_n(a_n)$ are linearly independent. Then $g_i : V \rightarrow \mathbb{R}$ defined by $g_i(x) = f_i(x + a_i)$ is in $C^\infty(V, \mathbb{R})$, $G := (g_1, \dots, g_n) : V \rightarrow \mathbb{R}^n$ is smooth, and the Jacobian $JG(0)$ is invertible. Therefore, by the inverse function theorem, G is a local diffeomorphism near $0 \in V$. Since $p(0) = 0$, p is continuous at $0 \in \mathbb{R}$, and $G \circ p$ is smooth, it follows that p is smooth at 0, contradicting our assumption on p . So A is a proper subset.

By the same method of translation, one sees that A is a subspace of \mathbb{R}^n . Hence, there exists $0 \neq v \in \mathbb{R}^n$ such that $v \perp A$, which implies that $f(x + tv) = f(x)$ for every $f \in C^\infty(V, \mathbb{R})$, $x \in V$ and $t \in \mathbb{R}$, i.e., V is not in \mathcal{SD} .

Case 2: Suppose that p is not continuous at 0.

Case 2a: Suppose there exist $k \in \mathbb{N}$ and $\epsilon > 0$ such that $t^k p(t)$ is bounded on $[-\epsilon, \epsilon]$. Let k be the smallest such exponent and write $q(t) := t^k p(t)$, which is also a plot. We claim that q is not smooth at 0. If $k = 0$, then $q = p$, which is assumed to not be smooth at 0. If $k > 0$ and $q'(0)$ exists, then $q(t)/t \rightarrow q'(0)$ as $t \rightarrow 0$, which implies that $t^{k-1} p(t)$ is also bounded on $[-\epsilon, \epsilon]$, contradicting the minimality of k . So q is not smooth at 0.

If q is continuous at 0, then by Case 1, we are done.

So assume that q is not continuous at 0. Then, since q is bounded on $[-\epsilon, \epsilon]$, there exists a sequence t_i converging to 0 such that $q(t_i)$ converges to a nonzero $v \in V$. If f is in $C^\infty(V, \mathbb{R})$, then $f \circ q$ is smooth, so $f(0) = f(q(0)) = f(q(\lim t_i)) = \lim f(q(t_i)) = f(\lim q(t_i)) = f(v)$. Therefore, the functions in $C^\infty(V, \mathbb{R})$ do not separate points.

Case 2b: Suppose that Case 2a does not apply. Then for each $k \in \mathbb{N}$, $\epsilon > 0$ and $M > 0$, there exists $t \in [-\epsilon, \epsilon]$ such that $\|t^k p(t)\| > M$. (Note that $t \neq 0$, since $p(0) = 0$.) Using this for $k = 0$, choose $t_1 \in [-1, 1]$ such that $\|p(t_1)\| > 1$. Then, for each integer $k > 0$, choose t_k with $|t_k| \leq |t_{k-1}|/2$ such that $\|t_k^k p(t_k)\| > k$. If $m \leq k$, then t_k also satisfies $\|t_k^m p(t_k)\| > k \geq m$, since $|t_k| \leq 1$. Therefore, we can restrict to a subsequence of the t_k all having the same sign. To fix notation, assume that each t_k is positive. Then, for $m \leq k$,

$$\frac{1}{\|p(t_k)\|} < \frac{1}{t_k^m}$$

and so, for each m , the left-hand side goes to 0 as $k \rightarrow \infty$. By [Lemma 5.1](#), there is a smooth curve $c : \mathbb{R} \rightarrow \mathbb{R}$ such that $c(t_k) = 1/\|p(t_k)\|$. It follows that $q(t) := c(t)p(t)$ is a plot such that $q(0) = 0$ and $\|q(t_k)\| = 1$ for each k . Therefore, there is a subsequence converging to a nonzero $v \in V$, and the argument at the end of Case 2a shows that $C^\infty(V, \mathbb{R})$ does not separate points. \square

Lemma 5.1 (extended special curve lemma). *Let $\{x_k\}$ and $\{t_k\}$ be sequences in \mathbb{R} such that $0 < t_k < t_{k-1}/2$ for each k and $x_k/t_k^m \rightarrow 0$ as $k \rightarrow \infty$ for each $m \in \mathbb{Z}^+$. Then there is a smooth function $c : \mathbb{R} \rightarrow \mathbb{R}$ such that $c(t_k) = x_k$ for each k and $c(t) = 0$ for $t < 0$.*

The proof closely follows [\[Kriegl and Michor 1997, page 18\]](#), and can easily be generalized further.

Proof. Let $\phi : \mathbb{R} \rightarrow \mathbb{R}$ be a smooth function such that $\phi(t) = 0$ for $t \leq 0$ and $\phi(t) = 1$ for $t \geq 1$. Define $c : \mathbb{R} \rightarrow \mathbb{R}$ by

$$c(t) = \begin{cases} 0 & \text{for } t \leq 0, \\ x_{k+1} + \phi\left(\frac{t - t_{k+1}}{t_k - t_{k+1}}\right)(x_k - x_{k+1}) & \text{for } t_{k+1} \leq t \leq t_k, \\ x_1 & \text{for } t_1 \leq t. \end{cases}$$

The function c is smooth away from 0 and for $t_{k+1} \leq t \leq t_k$ we have

$$c^{(r)}(t) = \phi^{(r)}\left(\frac{t - t_{k+1}}{t_k - t_{k+1}}\right) \frac{1}{(t_k - t_{k+1})^r} (x_k - x_{k+1}).$$

Since $t_k - t_{k+1} > t_k/2 > t_{k+1}$, the right-hand side goes to zero as $t \rightarrow 0$. Similarly, $c^{(r)}(t)/t \rightarrow 0$, which shows that each $c^{(r+1)}(0)$ exists and is 0. So c is smooth. \square

We are indebted to Chengjie Yu for the argument used in Case 1 of [Theorem 3.22](#). After we completed Case 2, Yongjie Shi and Chengjie Yu proved this case in more generality in [\[Shi and Yu 2017\]](#).

References

- [Christensen and Wu 2016] J. D. Christensen and E. Wu, “Tangent spaces and tangent bundles for diffeological spaces”, *Cah. Topol. Géom. Différ. Catég.* **57**:1 (2016), 3–50. [MR](#) [Zbl](#)
- [Christensen et al. 2014] J. D. Christensen, G. Sinnamon, and E. Wu, “The D -topology for diffeological spaces”, *Pacific J. Math.* **272**:1 (2014), 87–110. [MR](#) [Zbl](#)
- [Hamkins 2015] J. D. Hamkins, [Reply to “Countable path-connected Hausdorff space”](#), MathOverflow, 2015, available at <http://mathoverflow.net/q/214537>.
- [Hector 1995] G. Hector, “Géométrie et topologie des espaces difféologiques”, pp. 55–80 in *Analysis and geometry in foliated manifolds* (Santiago de Compostela, Spain, 1994), edited by X. Masa et al., World Sci., River Edge, NJ, 1995. [MR](#) [Zbl](#)

- [Iglesias-Zemmour 2007] P. Iglesias-Zemmour, “Diffeology of the infinite Hopf fibration”, pp. 349–393 in *Geometry and topology of manifolds* (Będlewo, Poland, 2005), edited by J. Kubarski et al., Banach Center Publ. **76**, Polish Acad. Sci. Inst. Math., Warsaw, 2007. [MR](#) [Zbl](#)
- [Iglesias-Zemmour 2013] P. Iglesias-Zemmour, *Diffeology*, Math. Surveys and Monographs **185**, Amer. Math. Sci., Providence, RI, 2013. [MR](#) [Zbl](#)
- [Kriegl and Michor 1997] A. Kriegl and P. W. Michor, *The convenient setting of global analysis*, Math. Surveys and Monographs **53**, Amer. Math. Sci., Providence, RI, 1997. [MR](#) [Zbl](#)
- [Shi and Yu 2017] Y. Shi and C. Yu, “Smooth compositions with a nonsmooth inner function”, *J. Math. Anal. Appl.* **455**:1 (2017), 52–57. [MR](#) [Zbl](#)
- [Souriau 1984] J.-M. Souriau, “Groupes différentiels de physique mathématique”, pp. 73–119 in *South Rhone seminar on geometry, II* (Lyon, 1983), edited by P. Dazord and N. Desolneux-Moulis, Hermann, Paris, 1984. [MR](#) [Zbl](#)
- [Vincent 2008] M. Vincent, *Diffeological differential geometry*, master’s thesis, University of Copenhagen, 2008, available at <https://tinyurl.com/martinvincent-pdf>.
- [Wu 2015] E. Wu, “Homological algebra for diffeological vector spaces”, *Homology Homotopy Appl.* **17**:1 (2015), 339–376. [MR](#) [Zbl](#)

Received May 6, 2017. Revised January 29, 2019.

J. DANIEL CHRISTENSEN
DEPARTMENT OF MATHEMATICS
UNIVERSITY OF WESTERN ONTARIO
LONDON ON
CANADA
jdc@uwo.ca

ENXIN WU
DEPARTMENT OF MATHEMATICS
SHANTOU UNIVERSITY
GUANGDONG
CHINA
exwu@stu.edu.cn

PACIFIC JOURNAL OF MATHEMATICS

Founded in 1951 by E. F. Beckenbach (1906–1982) and F. Wolf (1904–1989)

msp.org/pjm

EDITORS

Don Blasius (Managing Editor)
Department of Mathematics
University of California
Los Angeles, CA 90095-1555
blasius@math.ucla.edu

Paul Balmer
Department of Mathematics
University of California
Los Angeles, CA 90095-1555
balmer@math.ucla.edu

Vyjayanthi Chari
Department of Mathematics
University of California
Riverside, CA 92521-0135
chari@math.ucr.edu

Matthias Aschenbrenner
Department of Mathematics
University of California
Los Angeles, CA 90095-1555
matthias@math.ucla.edu

Daryl Cooper
Department of Mathematics
University of California
Santa Barbara, CA 93106-3080
cooper@math.ucsb.edu

Wee Teck Gan
Mathematics Department
National University of Singapore
Singapore 119076
matgwt@nus.edu.sg

Kefeng Liu
Department of Mathematics
University of California
Los Angeles, CA 90095-1555
liu@math.ucla.edu

Jiang-Hua Lu
Department of Mathematics
The University of Hong Kong
Pokfulam Rd., Hong Kong
jhlu@maths.hku.hk

Sorin Popa
Department of Mathematics
University of California
Los Angeles, CA 90095-1555
popa@math.ucla.edu

Jie Qing
Department of Mathematics
University of California
Santa Cruz, CA 95064
qing@cats.ucsc.edu

Paul Yang
Department of Mathematics
Princeton University
Princeton NJ 08544-1000
yang@math.princeton.edu

PRODUCTION

Silvio Levy, Scientific Editor, production@msp.org

SUPPORTING INSTITUTIONS

ACADEMIA SINICA, TAIPEI
CALIFORNIA INST. OF TECHNOLOGY
INST. DE MATEMÁTICA PURA E APLICADA
KEIO UNIVERSITY
MATH. SCIENCES RESEARCH INSTITUTE
NEW MEXICO STATE UNIV.
OREGON STATE UNIV.

STANFORD UNIVERSITY
UNIV. OF BRITISH COLUMBIA
UNIV. OF CALIFORNIA, BERKELEY
UNIV. OF CALIFORNIA, DAVIS
UNIV. OF CALIFORNIA, LOS ANGELES
UNIV. OF CALIFORNIA, RIVERSIDE
UNIV. OF CALIFORNIA, SAN DIEGO
UNIV. OF CALIF., SANTA BARBARA

UNIV. OF CALIF., SANTA CRUZ
UNIV. OF MONTANA
UNIV. OF OREGON
UNIV. OF SOUTHERN CALIFORNIA
UNIV. OF UTAH
UNIV. OF WASHINGTON
WASHINGTON STATE UNIVERSITY

These supporting institutions contribute to the cost of publication of this Journal, but they are not owners or publishers and have no responsibility for its contents or policies.


See inside back cover or msp.org/pjm for submission instructions.

The subscription price for 2019 is US \$490/year for the electronic version, and \$665/year for print and electronic. Subscriptions, requests for back issues and changes of subscriber address should be sent to Pacific Journal of Mathematics, P.O. Box 4163, Berkeley, CA 94704-0163, U.S.A. The Pacific Journal of Mathematics is indexed by [Mathematical Reviews](#), [Zentralblatt MATH](#), [PASCAL CNRS Index](#), [Referativnyi Zhurnal](#), [Current Mathematical Publications](#) and [Web of Knowledge \(Science Citation Index\)](#).

The Pacific Journal of Mathematics (ISSN 1945-5844 electronic, 0030-8730 printed) at the University of California, c/o Department of Mathematics, 798 Evans Hall #3840, Berkeley, CA 94720-3840, is published twelve times a year. Periodical rate postage paid at Berkeley, CA 94704, and additional mailing offices. POSTMASTER: send address changes to Pacific Journal of Mathematics, P.O. Box 4163, Berkeley, CA 94704-0163.

PJM peer review and production are managed by EditFLOW[®] from Mathematical Sciences Publishers.

PUBLISHED BY

 **mathematical sciences publishers**
nonprofit scientific publishing

<http://msp.org/>

© 2019 Mathematical Sciences Publishers

PACIFIC JOURNAL OF MATHEMATICS

Volume 303 No. 1 November 2019

Contrasting various notions of convergence in geometric analysis	1
BRIAN ALLEN and CHRISTINA SORMANI	
Explicit formulae and discrepancy estimates for a -points of the Riemann zeta-function	47
SIEGFRED BALUYOT and STEVEN M. GONEK	
Diffeological vector spaces	73
J. DANIEL CHRISTENSEN and ENXIN WU	
Degree-one, monotone self-maps of the Pontryagin surface are near-homeomorphisms	93
ROBERT J. DAVERMAN and THOMAS L. THICKSTUN	
Denoetherianizing Cohen–Macaulay rings	133
LÁSZLÓ FUCHS and BRUCE OLBERDING	
Ordinary points mod p of $GL_n(\mathbb{R})$ -locally symmetric spaces	165
MARK GORESKY and YUNG SHENG TAI	
Real structures on polarized Dieudonné modules	217
MARK GORESKY and YUNG SHENG TAI	
Spectrahedral representations of plane hyperbolic curves	243
MARIO KUMMER, SIMONE NALDI and DANIEL PLAUMANN	
Deformations of linear Lie brackets	265
PIER PAOLO LA PASTINA and LUCA VITAGLIANO	
A mod- p Artin–Tate conjecture, and generalizing the Herbrand–Ribet theorem	299
DIPENDRA PRASAD	
Transitive topological Markov chains of given entropy and period with or without measure of maximal entropy	317
SYLVIE RUETTE	
Restricted sum formula for finite and symmetric multiple zeta values	325
HIDEKI MURAHARA and SHINGO SAITO	
Frobenius–Schur indicators for near-group and Haagerup–Izumi fusion categories	337
HENRY TUCKER	
Compactness theorems for 4-dimensional gradient Ricci solitons	361
YONGJIA ZHANG	