

# ON CERTAIN GEOMETRIC OPERATORS BETWEEN SOBOLEV SPACES OF SECTIONS OF TENSOR BUNDLES ON COMPACT MANIFOLDS EQUIPPED WITH ROUGH METRICS

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ABSTRACT. The study of Einstein constraint equations in general relativity naturally leads to considering Riemannian manifolds equipped with nonsmooth metrics. There are several important differential operators on Riemannian manifolds whose definitions depend on the metric: gradient, divergence, Laplacian, covariant derivative, conformal Killing operator, and vector Laplacian, among others. In this article, we study the approximation of such operators, defined using a rough metric, by the corresponding operators defined using a smooth metric. This paves the road to understanding to what extent the nice properties such operators possess, when defined with smooth metric, will transfer over to the corresponding operators defined using a nonsmooth metric. These properties are often assumed to hold when working with rough metrics, but to date the supporting literature is slim. As part of our work we present a coherent rigorous study of the main properties of Sobolev-Slobodeckij spaces of sections of vector bundles; results of this type are scattered through the literature and can be difficult to find. A special emphasis has been put on spaces with noninteger smoothness order. As it turns out, the study of Sobolev spaces of sections of vector bundles on compact manifolds is closely related to the study of locally Sobolev functions on domains in the Euclidean space. Considering this, part of the appendix is devoted to the study of locally Sobolev-Slobodeckij functions. A special attention has been paid to the peculiar fact that for a general nonsmooth domain  $\Omega$  in  $\mathbb{R}^n$ ,  $0 < t < 1$ , and  $1 < p < \infty$ , it is not necessarily true that  $W^{1,p}(\Omega) \hookrightarrow W^{t,p}(\Omega)$  and its dire consequences in the multiplication properties of Sobolev-Slobodeckij spaces and subsequently in the study of Sobolev spaces on manifolds. To the authors' knowledge, some of the proofs in the appendices, especially those that are pertinent to the properties of spaces of locally Slobodeckij functions and Sobolev-Slobodeckij spaces of sections of vector bundles, cannot be found in the literature in the generality appearing here.

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*Date:* April 25, 2017.

*Key words and phrases.* Sobolev spaces, Compact manifolds, Tensor bundles, Convergence, Laplacian, Vector Laplacian, Covariant derivative.

AB was supported by NSF Award 1262982.

MH was supported in part by NSF Awards 1262982, 1318480, and 1620366.

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## 1. INTRODUCTION

The study of Einstein constraint equations in general relativity naturally leads to considering Riemannian manifolds equipped with metrics that are not  $C^\infty$  (see e.g. [11, 12, 34, 27, 8]). Some of the motivation for developing this understanding came from studies of the Einstein evolution equation with rough metric [28, 31]. In order to fully understand the implications of a rough metric, one needs to understand the impact of a nonsmooth metric on the various geometric and differential operators that arise in the formulation of stationary and evolution problems on Riemannian manifolds. These questions all fall into the following general form, which will be the focus of this article: Let  $(M^n, g)$  be a compact Riemannian manifold. Suppose  $g \in W^{s,p}(T^2M)$  where  $sp > n$  (it is reasonable to assume that the metric is continuous; the condition  $sp > n$  guarantees that  $g$  has a continuous representative, and also it implies that  $W^{s,p}(M)$  is a Banach algebra, which plays an important role in some of the calculations). Let  $\{g_m\}$  be a sequence of smooth Riemannian metrics on  $M$  such that  $g_m \rightarrow g$  in  $W^{s,p}(T^2M)$ . For each  $m$ , let  $A_m$  be an operator whose definition depends on the metric  $g_m$ . Let  $A$  be the corresponding operator that is defined in terms of  $g$ . What can be said about the relationship between the operators that are defined in terms of  $g_m$  and those that are defined in terms of  $g$ ? Does  $\{A_m\}$  converge to  $A$  (in an appropriate norm)? In particular, we are interested in the gradient, Laplacian, divergence, covariant derivative, and vector Laplacian operators. Additionally, we will study the relationship between the corresponding Riemannian curvature tensors, Ricci curvatures, and scalar curvatures.

One of the main applications of such results is in the study of elliptic partial differential equations on manifolds. There are a number of standard sources for properties of integer order Sobolev spaces of functions and related elliptic operators on domains in  $\mathbb{R}^n$  (cf. [2, 17, 37]), real order Sobolev spaces of functions ([20, 44, 40, 35, 9]), Sobolev spaces

of functions on manifolds ([45, 24, 5, 25]), and Sobolev spaces of sections of vector bundles on manifolds ([36, 16]). Most of these works focus on spaces of functions rather than general sections, and in many cases the focus is on integer order spaces. However, when trying to assemble the tools one needs to study our main question here, namely the impact of a rough metric on various geometric differential operators, one needs to work with real order Sobolev spaces of sections of vector bundles on Riemannian manifolds; the intersection of these topics among the books listed above thins out very quickly. An example of the type of question we hope to address is the following: the Laplacian and vector Laplacian of a smooth metric on a compact Riemannian manifold are Fredholm of index zero. Considering that the index of an operator is locally constant, in order to see whether this useful property carry over to the case of nonsmooth metrics we need to determine whether the Laplacian or vector Laplacian defined using a nonsmooth metric can be approximated by corresponding operators defined by smooth metrics. Results of this type and other related results have been used in literature without complete proof; they are well-motivated and reasonable assumptions in most cases, but it seems that a careful study is missing in the literature. This is particularly true in the case of noninteger Sobolev classes. In this manuscript, we have attempted to fill some of the gaps.

***Outline of Main Body of Paper.*** In Section 2 we summarize some of the basic notations and conventions used throughout the paper. In sections 3-13 we rigorously study the aforementioned question of convergence for various geometric operators that appear in the study of elliptic partial differential equations on compact manifolds. The paper is organized to get to the answers of these questions as quickly as possible. However, in order to make the paper self contained, we have included several appendices. Although the purpose of the appendices is to give a quick overview of the prerequisites that are needed to understand the proofs of the results in the main part of the manuscript and set the notations straight, as it was pointed out earlier, several theorems and proofs that appear in the appendices cannot be found elsewhere in the generality that are stated here.

***Outline of Appendices.*** In Appendix A we will review a number of basic constructions in linear algebra that are essential in the study of function spaces of generalized sections of vector bundles. In Appendix B we will recall some useful tools from analysis and topology. In particular, a concise overview of some of the main properties of topological vector spaces is presented in this appendix. Appendix C deals with reviewing some results from differential geometry. The main purpose of this appendix is to set the notations, definitions, and conventions straight. This appendix also includes some less well known facts about topics such as higher order covariant derivatives in vector bundles. In Appendix D we collect the results that we need from the theory of generalized functions on Euclidean spaces and vector bundles. Appendix E and Appendix F are concerned with various definitions and properties of Sobolev spaces that are needed for developing a coherent theory of such spaces on the vector bundles. In Appendix G and Appendix H we introduce Lebesgue spaces and Sobolev spaces of sections of vector bundles and we present a rigorous account of their various properties. Finally in Appendix I we study the continuity of certain differential operators between Sobolev spaces of sections of vector bundles.

## 2. NOTATION AND CONVENTIONS

In this manuscript, Lipschitz domain in  $\mathbb{R}^n$  refers to a nonempty bounded open set in  $\mathbb{R}^n$  with Lipschitz continuous boundary.

Throughout the manuscript we use the notation  $A \preceq B$  to mean  $A \leq cB$ , where  $c$  is a positive constant that does not depend on the non-fixed parameters appearing in  $A$  and  $B$ .

For any nonempty set  $X$  and  $r \in \mathbb{N}$ ,  $X^{\times r}$  stands for  $\underbrace{X \times \cdots \times X}_{r \text{ times}}$ .

For any two nonempty sets  $X$  and  $Y$ ,  $\text{Func}(X, Y)$  denotes the collection of all functions from  $X$  to  $Y$ .

We write  $L(X, Y)$  for the space of all *continuous* linear maps from the normed space  $X$  to the normed space  $Y$ . We use the notation  $X \hookrightarrow Y$  to mean  $X \subseteq Y$  and the inclusion map is continuous.

$\text{GL}(n, \mathbb{R})$  is the set of all  $n \times n$  invertible matrices with real entries. Note that  $\text{GL}(n, \mathbb{R})$  can be identified with an open subset of  $\mathbb{R}^{n^2}$  and so it can be viewed as a smooth manifold (more precisely,  $\text{GL}(n, \mathbb{R})$  is a Lie group).

Throughout this manuscript, all manifolds are assumed to be smooth, Hausdorff, and second countable.

Let  $M$  be an  $n$ -dimensional compact smooth manifold. Sometimes we use the shorthand notation  $M^n$  to indicate that  $M$  is  $n$ -dimensional. The tangent space of the manifold  $M$  at point  $p \in M$  is denoted by  $T_p M$ , and the cotangent space by  $T_p^* M$ . If  $(U, \varphi = (x^i))$  is a local coordinate chart and  $p \in U$ , we denote the corresponding coordinate basis for  $T_p M$  by  $\partial_i|_p$  while  $\frac{\partial}{\partial x^i}|_x$  denotes the basis for the tangent space to  $\mathbb{R}^n$  at  $x = \varphi(p) \in \mathbb{R}^n$ ; that is

$$\varphi_* \partial_i = \frac{\partial}{\partial x^i}$$

Note that for any smooth function  $f : M \rightarrow \mathbb{R}$  we have

$$(\partial_i f) \circ \varphi^{-1} = \frac{\partial}{\partial x^i} (f \circ \varphi^{-1})$$

The vector space of all  $k$ -covariant,  $l$ -contravariant tensors on  $T_p M$  is denoted by  $T_l^k(T_p M)$ . So each element of  $T_l^k(T_p M)$  is a multilinear map of the form

$$F : \underbrace{T_p^* M \times \cdots \times T_p^* M}_{l \text{ copies}} \times \underbrace{T_p M \times \cdots \times T_p M}_{k \text{ copies}} \rightarrow \mathbb{R}$$

We denote by  $\pi : E \rightarrow M$  (or just  $E$ ) a smooth vector bundle over  $M$ . For each  $p \in M$ ,  $E_p := \pi^{-1}(p)$  denotes the fiber over  $p$ . We denote the space of all smooth sections of  $E$  by  $C^\infty(M, E)$ . Note that a section of the trivial vector bundle  $E = M \times \mathbb{R}$  can be identified with a scalar function on  $M$ . In fact,  $C^\infty(M, M \times \mathbb{R})$  can be identified with  $C^\infty(M)$  where  $C^\infty(M)$  is the collection of all smooth functions from  $M$  to  $\mathbb{R}$ . The Lebesgue spaces and Sobolev spaces of sections of  $E$  are defined in Appendices. Following definitions and theorems in Appendix C, Appendix G, and Appendix H, for  $e \in \mathbb{R}$  and  $q \in (1, \infty)$  we set  $W^{e,q}(M, E) := W^{e,q}(M, E; \Lambda)$  where if  $e$  is not a noninteger less than  $-1$

$\Lambda =$  any augmented total trivialization atlas

and if  $e$  is a noninteger less than  $-1$

$\Lambda =$  any augmented total trivialization atlas that is GL compatible with itself

We are primarily interested in the bundle of  $\binom{k}{l}$ -tensors on  $M$  whose total space is

$$T_l^k(M) = \bigsqcup_{p \in M} T_l^k(T_p M)$$

A section of this bundle is called a  $\binom{k}{l}$ -tensor field. We set  $T^k M := T_0^k(M)$ .  $TM$  denotes the tangent bundle of  $M$  and  $T^*M$  is the cotangent bundle of  $M$ . We set  $\tau_l^k(M) = C^\infty(M, T_l^k(M))$  and  $\chi(M) = C^\infty(M, TM)$ .

A symmetric positive definite section of  $T^2 M$  is called a Riemannian metric on  $M$ . If  $M$  is equipped with a Riemannian metric  $g$ , the combination  $(M, g)$  will be referred to as a Riemannian manifold. If there is no possibility of confusion, we may write  $\langle X, Y \rangle$  instead of  $g(X, Y)$ . The norm induced by  $g$  on each tangent space will be denoted by  $\|\cdot\|_g$ . We say that  $g$  is smooth (or the Riemannian manifold is smooth) if  $g \in C^\infty(M, T^2 M)$ .  $d$  denotes the exterior derivative and  $\text{grad} : C^\infty(M) \rightarrow C^\infty(M, TM)$  denotes the gradient operator which is defined by  $g(\text{grad} f, X) = df(X)$  for all  $f \in C^\infty(M)$  and  $X \in C^\infty(M, TM)$ .

Given a metric  $g$  on  $M$ , one can define the musical isomorphisms as follows:

$$\begin{aligned} \text{flat}_g : T_p M &\rightarrow T_p^* M \\ X &\mapsto X^\flat := g(X, \cdot), \\ \text{sharp}_g : T_p^* M &\rightarrow T_p M \\ \psi &\mapsto \psi^\sharp := \text{flat}_g^{-1}(\psi). \end{aligned}$$

Using  $\text{sharp}_g$  we can define the  $\binom{0}{2}$ -tensor field  $g^{-1}$  (which is called the **inverse metric tensor**) as follows

$$g^{-1}(\psi_1, \psi_2) := g(\text{sharp}_g(\psi_1), \text{sharp}_g(\psi_2)).$$

Let  $\{E_i\}$  be a local frame on an open subset  $U \subset M$  and  $\{\eta^i\}$  be the corresponding dual coframe. So we can write  $X = X^i E_i$  and  $\psi = \psi_i \eta^i$ . It is standard practice to denote the  $i^{\text{th}}$  component of  $\text{flat}_g X$  by  $X_i$  and the  $i^{\text{th}}$  component of  $\text{sharp}_g(\psi)$  by  $\psi^i$ :

$$\text{flat}_g X = X_i \eta^i, \quad \text{sharp}_g \psi = \psi^i E_i.$$

It is easy to show that

$$X_i = g_{ij} X^j, \quad \psi^i = g^{ij} \psi_j,$$

where  $g_{ij} = g(E_i, E_j)$  and  $g^{ij} = g^{-1}(\eta^i, \eta^j)$ . It is said that  $\text{flat}_g X$  is obtained from  $X$  by lowering an index and  $\text{sharp}_g \psi$  is obtained from  $\psi$  by raising an index.

Let  $(M, g)$  be a Riemannian manifold. Suppose for each  $m \in \mathbb{N}$  and  $p \in M$ ,  $B_m(p) : T_p M \rightarrow T_p M$  is a linear map. Define  $f_m : M \rightarrow \mathbb{R}$  by

$$f_m(p) = \|B_m(p)\|_{op} \stackrel{\text{Theorem B.13}}{=} \sup_{\|X\|_g = \|Y\|_g = 1} |g(B_m X, Y)|$$

We let

$$\|B_m\|_\infty := \|f_m\|_{L^\infty(M)}$$

In particular note that for all  $X, Y \in T_p M$

$$|g(B_m X, Y)| \leq \|B_m\|_\infty \|X\|_g \|Y\|_g$$

## 3. PRELIMINARY RESULTS

Suppose  $(M^n, g)$  is a compact Riemannian manifold with  $g \in W^{s,p}(T^2M)$ ,  $sp > n$ , and  $s \geq 1$ . Suppose  $\{g_m\}$  is a sequence of smooth metrics that converges to  $g$  in  $W^{s,p}(T^2M)$ . In this section we go over some of the immediate consequences of this assumption which will be useful in the study of the main results presented in this work. As it was pointed out in the introduction, the ultimate goal of the main section of this manuscript is to study the relationship between various geometric operators (like Laplacian) that are defined in terms of  $g_m$ 's and those that are defined in terms of  $g$ . We will present two rather distinct methods to accomplish this goal:

- (1) The first approach works for a limited range of Sobolev spaces and follows (and extends) the argument presented in [26] for the Laplace operator with the domain  $H^1(M) = W^{1,2}(M)$ . This method is based on the notion of "metric distortion tensor" and duality arguments.
- (2) The second approach works for a wider range of Sobolev spaces and will be based on a characterization of Sobolev spaces in terms of local coordinates and several theorems on multiplication properties of Sobolev spaces and behavior of Sobolev functions under composition.

Let's begin with the notion of metric distortion tensor. By Theorem A.3 for each  $m$  and at each  $p \in M$  there exists a positive definite linear operator  $A_m|_p : T_pM \rightarrow T_pM$  (when the basepoint is clear from the context instead of  $A_m|_p$  we just write  $A_m$ ) such that

$$\forall X, Y \in T_pM \quad g_m(X, Y) = g(A_m X, Y)$$

$A_m$  is called the **metric distortion tensor** associated with  $g_m$  (see [26]). We have

$$\|A_m - Id\|_\infty := \left\| \sup_{\|X\|_g = \|Y\|_g = 1} |g((A_m - Id)X, Y)| \right\|_{L^\infty(M)}$$

where  $Id_p : T_pM \rightarrow T_pM$  is the identity map. In particular, note that for all  $p \in M$  and  $X, Y \in T_pM$

$$|g((A_m - Id)X, Y)| \leq \|A_m - Id\|_\infty \|X\|_g \|Y\|_g$$

The following two theorems play a key role in the first approach mentioned above.

**Theorem 3.1.** *Let  $M^n$  be a Riemannian manifold equipped with a smooth Riemannian metric  $\tilde{g}$ . Denote the norm induced by the fiber metric on the bundle of  $\binom{2}{0}$  tensors by  $|\cdot|_F$ . If  $S$  is a symmetric covariant tensor field of order 2, then*

$$\forall p \in M \quad \sup\{|S_p(X, Y)| : X, Y \in T_pM, \|X\|_g = \|Y\|_g = 1\} \leq |S|_F(p)$$

*Note that the left hand side of the above inequality is the norm of  $S_p$  as a bilinear form on the inner product space  $(T_pM, \tilde{g}_p)$ .*

*Proof.* Let  $p \in M$ . Let  $(U, \varphi)$  be a normal coordinate neighborhood centered at  $p$  (see the proof of Theorem C.16 or [32] for a description of normal coordinate neighborhood; the assumption that  $\tilde{g}$  is smooth is used in the construction of normal coordinate neighborhood). Let  $\{E_i\}$  be the orthonormal basis for  $T_pM$  that is used to define the normal chart  $(U, \varphi)$ . At  $p$  the components of the metric with respect to  $(U, \varphi)$  are given by  $\tilde{g}_{ij} = \delta_{ij}$ . We have

$$|S|_F^2(p) = \tilde{g}^{ir} \tilde{g}^{js} S_{ij} S_{rs}|_p = \delta^{ir} \delta^{js} S_{ij} S_{rs}|_p = \sum_{i=1}^n \sum_{j=1}^n S_{ij}^2(p)$$

Now let  $A : T_p M \rightarrow T_p M$  be the unique linear transformation such that (see Theorem A.3)

$$\forall X, Y \in T_p M \quad S_p(X, Y) = \tilde{g}_p(AX, Y)$$

If  $X \in T_p M$  is such that  $\|X\|_{\mathfrak{g}} = 1$  (note that since  $\tilde{g} = \delta$  at  $p$ , we have  $\|X\|_{\mathfrak{g}} = \tilde{g}_{ij} X^i X^j = \sum_{i=1}^n |X^i|^2$ ), then

$$\begin{aligned} |S_p(X, X)|^2 &= |\tilde{g}_p(AX, X)|^2 \leq \|AX\|_{\mathfrak{g}}^2 \|X\|_{\mathfrak{g}}^2 \\ &= \|AX\|_{\mathfrak{g}}^2 = \|X^i (AE_i)\|_{\mathfrak{g}}^2 \\ &\leq \left( \sum_{i=1}^n |X^i| \|AE_i\|_{\mathfrak{g}} \right)^2 \leq \left( \sum_{i=1}^n |X^i|^2 \right) \left( \sum_{i=1}^n \|AE_i\|_{\mathfrak{g}}^2 \right) \\ &= \sum_{i=1}^n \|AE_i\|_{\mathfrak{g}}^2 = \sum_{i=1}^n \sum_{j=1}^n \tilde{g}_p(AE_i, E_j)^2 = \sum_{i=1}^n \sum_{j=1}^n S_{ij}^2(p) = |S|_F^2(p) \end{aligned}$$

Note that we used the fact that since  $\{E_i\}$  is orthonormal

$$AE_i = \sum_{j=1}^n \tilde{g}_p(AE_i, E_j) E_j \implies \|AE_i\|_{\mathfrak{g}}^2 = \sum_{j=1}^n \tilde{g}_p(AE_i, E_j)^2$$

Therefore,

$$\begin{aligned} \sup\{|S_p(X, Y)| : X, Y \in T_p M, \|X\|_{\mathfrak{g}} = \|Y\|_{\mathfrak{g}} = 1\} \\ \stackrel{\text{Theorem B.12}}{=} \sup\{|S_p(X, X)| : X \in T_p M, \|X\|_{\mathfrak{g}} = 1\} \\ \leq |S|_F(p) \end{aligned}$$

□

**Theorem 3.2.** *Let  $(M^n, g)$  be a compact smooth manifold. Let  $\{g_m\}$  be a sequence of smooth metrics on  $M$ . Let  $g \in \Gamma(M, T^2 M)$  be a metric that belongs to  $W^{s,p}(T^2 M)$  with  $sp > n$  and  $s \geq 1$ . Suppose  $g_m \rightarrow g$  in  $W^{s,p}(T^2 M)$ . Denote the metric distortion tensor associated with  $g_m$  by  $A_m$ . Then*

(1)  $\|A_m - Id\|_{\infty} \leq \|g_m - g\|_{s,p}$ . As a result, since  $\|g_m - g\|_{s,p} \rightarrow 0$ , we have  $\|A_m - Id\|_{\infty} \rightarrow 0$ .

(2) If  $\|A_m - Id\|_{\infty} \rightarrow 0$ , then

- $\det A_m \rightarrow \det Id = 1$  (at almost all  $p \in M$ )
- $\|A_m^{-1} - Id\|_{\infty} \rightarrow 0$
- $\|\sqrt{\det A_m} A_m^{-1} - Id\|_{\infty} \rightarrow 0$

(3)  $A_m^{-1} \text{grad}_g = \text{grad}_{g_m}$

(4)  $dV_{g_m} = \sqrt{\det A_m} dV_g$  ( $dV_g$  denotes the Riemannian density with respect to the metric  $g$ )

*Proof.*

(1) Fix a smooth Riemannian metric  $\tilde{g}$  on  $M$ . Denote the norm induced by the corresponding fiber metric on the bundle of  $\binom{2}{0}$  tensors by  $|\cdot|_F$ .

$$\begin{aligned} \|g_m - g\|_{s,p} &\succeq \|g_m - g\|_{L^\infty(T^2 M)} = \||g_m - g|_F\|_{L^\infty(M)} \quad (W^{s,p} \hookrightarrow L^\infty) \\ &\geq \sup_{\|X\|_{\tilde{g}} = \|Y\|_{\tilde{g}} = 1} |g_m(X, Y) - g(X, Y)| \|L^\infty(M) \quad (\text{see Theorem 3.1}) \end{aligned}$$

Since all norms on finite dimensional spaces are equivalent, we have

$$\sup_{\|X\|_g = \|Y\|_g = 1} |g_m(X, Y) - g(X, Y)| \simeq \sup_{\|X\|_g = \|Y\|_g = 1} |g_m(X, Y) - g(X, Y)|$$

Therefore

$$\begin{aligned} \|g_m - g\|_{s,p} &\succeq \left\| \sup_{\|X\|_g = \|Y\|_g = 1} |g_m(X, Y) - g(X, Y)| \right\|_{L^\infty(M)} \\ &= \left\| \sup_{\|X\|_g = \|Y\|_g = 1} |g(A_m X, Y) - g(X, Y)| \right\|_{L^\infty(M)} \\ &= \left\| \sup_{\|X\|_g = \|Y\|_g = 1} |g((A_m - Id)X, Y)| \right\|_{L^\infty(M)} \\ &= \|A_m - Id\|_\infty \end{aligned}$$

Items (2)-(4) are discussed in [26] based on the assumption that  $\|A_m - Id\|_\infty \rightarrow 0$ .  $\square$

The next theorem plays an important role in the second approach that was mentioned in the beginning of this section.

**Theorem 3.3.** *Let  $(M^n, g)$  be a Riemannian manifold. Suppose  $g_m \rightarrow g$  in  $W^{s,p}(T^2M)$  with  $sp > n$  and  $s \geq 1$ . Let  $\{(U_\alpha, \varphi_\alpha, \rho_\alpha)\}_{1 \leq \alpha \leq N}$  and  $\{(U_\alpha, \varphi_\alpha, \tilde{\rho}_\alpha)\}_{1 \leq \alpha \leq N}$  be GGL standard total trivialization atlases for  $T^2M$  and  $T_2M$ , respectively. Then*

- (1) For all  $1 \leq \alpha \leq N$ ,  $1 \leq i, j \leq n$ :  $(g_m)_{ij} \circ \varphi_\alpha^{-1} \rightarrow g_{ij} \circ \varphi_\alpha^{-1}$  in  $W_{loc}^{s,p}(\varphi_\alpha(U_\alpha))$
- (2) For all  $1 \leq \alpha \leq N$ ,  $1 \leq i, j \leq n$ :  $(g_m)^{ij} \circ \varphi_\alpha^{-1} \rightarrow g^{ij} \circ \varphi_\alpha^{-1}$  in  $W_{loc}^{s,p}(\varphi_\alpha(U_\alpha))$
- (3)  $(g_m)^{-1} \rightarrow g^{-1}$  in  $W^{s,p}(T_2M)$
- (4) For all  $1 \leq i, j, k \leq n$ :  $(\Gamma_{g_m})_{ij}^k \circ \varphi_\alpha^{-1} \rightarrow (\Gamma_g)_{ij}^k \circ \varphi_\alpha^{-1}$  in  $W_{loc}^{s-1,p}(\varphi_\alpha(U_\alpha))$

( $\Gamma_{ij}^k$ 's denote the Christoffel symbols)

*Proof.* First let us define a suitable family of *admissible* test functions (see Theorem F.3) on  $\varphi_\alpha(U_\alpha)$ . For each  $x \in \varphi_\alpha(U_\alpha)$ , choose  $r_x > 0$  such that

$$\bar{B}_{r_x}(x) \subseteq \varphi_\alpha(U_\alpha)$$

Let  $V_x = \varphi_\alpha^{-1}(B_{r_x}(x))$ . Clearly  $V_x \subseteq \bar{V}_x \subseteq U_\alpha$ . Therefore by Lemma C.11 there exists a partition of unity  $\{\psi_{\beta,x}\}$  subordinate to  $\{U_\beta\}_{1 \leq \beta \leq N}$  such that  $\psi_{\alpha,x} = 1$  on  $\bar{V}_x$ . We define  $\tilde{\psi}_x = \psi_{\alpha,x} \circ \varphi_\alpha^{-1}$ .  $\{\tilde{\psi}_x\}_{x \in \varphi_\alpha(U_\alpha)}$  is an admissible family of test functions on  $\varphi_\alpha(U_\alpha)$ . So in order to prove that a sequence  $\{f_m\}$  converges to  $f$  in  $W_{loc}^{s,p}(\varphi_\alpha(U_\alpha))$  it is enough to show that

$$\forall x \in \varphi_\alpha(U_\alpha) \quad \tilde{\psi}_x f_m \rightarrow \tilde{\psi}_x f \quad \text{in } W^{s,p}(\varphi_\alpha(U_\alpha))$$

(1) Let  $x \in \varphi_\alpha(U_\alpha)$ . We have

$$\begin{aligned} \|g_m - g\|_{s,p} &\simeq \sum_{\beta=1}^N \sum_{i,j=1}^n \|(\rho_\beta)_{ij} \circ (\psi_{\beta,x}(g_m - g)) \circ \varphi_\beta^{-1}\|_{W^{s,p}(\varphi_\beta(U_\beta))} \\ &\simeq \sum_{\beta=1}^N \sum_{i,j=1}^n \|\psi_{\beta,x}[(g_m)_{ij} - g_{ij}] \circ \varphi_\beta^{-1}\|_{W^{s,p}(\varphi_\beta(U_\beta))} \end{aligned}$$

By assumption  $\|g_m - g\|_{s,p} \rightarrow 0$  and so

$$\forall 1 \leq \beta \leq N \quad \forall 1 \leq i, j \leq n \quad \|\psi_{\beta,x}[(g_m)_{ij} - g_{ij}] \circ \varphi_\beta^{-1}\|_{W^{s,p}(\varphi_\beta(U_\beta))} \rightarrow 0$$

In particular

$$\forall 1 \leq i, j \leq n \quad \|\psi_{\alpha,x}[(g_m)_{ij} - g_{ij}] \circ \varphi_\alpha^{-1}\|_{W^{s,p}(\varphi_\alpha(U_\alpha))} \rightarrow 0$$



Considering that  $\psi_{\alpha,x} \circ \varphi_\alpha^{-1} = \tilde{\psi}_x$  we get

$$\forall 1 \leq i, j \leq n \quad \|\tilde{\psi}_x[((g_m)_{ij} - g_{ij}) \circ \varphi_\alpha^{-1}]\|_{W^{s,p}(\varphi_\alpha(U_\alpha))} \rightarrow 0$$

Since  $x \in \varphi_\alpha(U_\alpha)$  is arbitrary and  $\{\tilde{\psi}_y\}_{y \in \varphi_\alpha(U_\alpha)}$  form an admissible family of test functions we can conclude that

$$(g_m)_{ij} \circ \varphi_\alpha^{-1} \rightarrow g_{ij} \circ \varphi_\alpha^{-1} \quad \text{in } W_{loc}^{s,p}(\varphi_\alpha(U_\alpha)).$$

- (2) Let  $C = (C_{ij})$  and  $C_m = ((C_m)_{ij})$  where  $C_{ij} = g_{ij} \circ \varphi_\alpha^{-1}$  and  $(C_m)_{ij} = (g_m)_{ij} \circ \varphi_\alpha^{-1}$ . Our goal is to show that

$$(C_m^{-1})_{ij} \rightarrow (C^{-1})_{ij} \quad \text{in } W_{loc}^{s,p}(\varphi_\alpha(U_\alpha))$$

Recall that

$$(C^{-1})_{ij} = \frac{(-1)^{i+j}}{\det C} M_{ij}$$

$$((C_m)^{-1})_{ij} = \frac{(-1)^{i+j}}{\det C_m} (M_m)_{ij}$$

where  $M_{ij}$  and  $(M_m)_{ij}$  are the determinants of the  $(n-1) \times (n-1)$  matrices formed by removing the  $j^{\text{th}}$  row and  $i^{\text{th}}$  column of  $C$  and  $C_m$ , respectively. By item 1 we know that  $(C_m)_{ij} \rightarrow C_{ij}$  in  $W_{loc}^{s,p}(\varphi_\alpha(U_\alpha))$ . So it follows from Lemma F.12 that

$$\det C_m \rightarrow \det C, \quad (M_m)_{ij} \rightarrow M_{ij} \quad \text{in } W_{loc}^{s,p}(\varphi_\alpha(U_\alpha))$$

and so as a direct consequence of Theorem F.13,

$$\frac{1}{\det C_m} \rightarrow \frac{1}{\det C} \quad \text{in } W_{loc}^{s,p}(\varphi_\alpha(U_\alpha))$$

Hence by Lemma F.9 and Corollary F.11 we can conclude that

$$\frac{(-1)^{i+j}}{\det C_m} (M_m)_{ij} \rightarrow \frac{(-1)^{i+j}}{\det C} M_{ij} \quad \text{in } W_{loc}^{s,p}(\varphi_\alpha(U_\alpha))$$

- (3) Let  $\{\theta_\beta\}_{1 \leq \beta \leq N}$  be a partition of unity subordinate to  $\{U_\beta\}_{1 \leq \beta \leq N}$ . We have

$$\|(g_m)^{-1} - g^{-1}\|_{s,p} \simeq \sum_{\beta=1}^N \sum_{i,j=1}^n \|(\theta_\beta((g_m)^{ij} - g^{ij})) \circ \varphi_\beta^{-1}\|_{W^{s,p}(\varphi_\beta(U_\beta))}$$

According to item 2, for all  $1 \leq \beta \leq N$ ,

$$(g_m)^{ij} \circ \varphi_\beta^{-1} \rightarrow g^{ij} \circ \varphi_\beta^{-1} \quad \text{in } W_{loc}^{s,p}(\varphi_\beta(U_\beta))$$

Therefore it follows from the definition of convergence in  $W_{loc}^{s,p}(\varphi_\beta(U_\beta))$  that

$$\|(\theta_\beta((g_m)^{ij} - g^{ij})) \circ \varphi_\beta^{-1}\|_{W^{s,p}(\varphi_\beta(U_\beta))} \rightarrow 0$$

Hence  $\|(g_m)^{-1} - g^{-1}\|_{s,p} \rightarrow 0$ .

- (4) Recall that

$$\Gamma_{ij}^k = \frac{1}{2} g^{kl} (\partial_i g_{jl} + \partial_j g_{il} - \partial_l g_{ij})$$

$$(\Gamma_m)_{ij}^k = \frac{1}{2} (g_m)^{kl} (\partial_i (g_m)_{jl} + \partial_j (g_m)_{il} - \partial_l (g_m)_{ij})$$

By item 1 and item 2 we have

$$(g_m)^{kl} \rightarrow g^{kl}, \quad (g_m)_{jl} \rightarrow g_{jl}, \quad (g_m)_{il} \rightarrow g_{il}, \quad (g_m)_{ij} \rightarrow g_{ij} \quad \text{in } W_{loc}^{s,p}(\varphi_\alpha(U_\alpha))$$

By Theorem F.6 partial differentiation with respect to any one of the variables is continuous from  $W_{loc}^{s,p}(\varphi_\alpha(U_\alpha))$  to  $W_{loc}^{s-1,p}(\varphi_\alpha(U_\alpha))$ . Also it follows from Lemma F.9 that

$$W_{loc}^{s,p}(\varphi_\alpha(U_\alpha)) \times W_{loc}^{s-1,p}(\varphi_\alpha(U_\alpha)) \hookrightarrow W_{loc}^{s-1,p}(\varphi_\alpha(U_\alpha))$$

The claim of this item is a direct consequence of the above observations.  $\square$

#### 4. SHARP OPERATOR WITH ROUGH METRIC

**Theorem 4.1.** *Let  $(M^n, g)$  be a compact Riemannian manifold. Let  $g \in W^{s,p}(T^2M)$  with  $sp > n$  and  $s \geq 1$ . Suppose  $e \in \mathbb{R}$  and  $q \in (1, \infty)$  are such that for balls  $\Omega \subseteq \mathbb{R}^n$  or for  $\Omega = \mathbb{R}^n$*

$$W^{s,p}(\Omega) \times W^{e,q}(\Omega) \hookrightarrow W^{e,q}(\Omega)$$

Then  $\text{sharp}_g : (C^\infty(M, T^*M), \|\cdot\|_{e,q}) \rightarrow W^{e,q}(TM)$  is continuous and so it has a unique extension to a continuous operator  $\text{sharp}_g : W^{e,q}(T^*M) \rightarrow W^{e,q}(TM)$ .

*Proof.* Let  $\Lambda = \{(U_\alpha, \varphi_\alpha, \rho_\alpha)\}_{\alpha=1}^N$  be a standard total trivialization atlas for  $TM$  and  $\tilde{\Lambda} = \{(U_\alpha, \varphi_\alpha, \tilde{\rho}_\alpha)\}_{\alpha=1}^N$  be a standard total trivialization atlas for  $T^*M$ . Without loss of generality we may assume that each of  $\Lambda$  and  $\tilde{\Lambda}$  is nice (or super nice) and GL compatible with itself (see Appendix C.2.). Let  $\{\psi_\alpha\}_{\alpha=1}^N$  be a partition of unity subordinate to the open cover  $\{U_\alpha\}_{\alpha=1}^N$ . Let  $\tilde{\psi}_\alpha = \frac{\psi_\alpha^2}{\sum_{\beta=1}^N \psi_\beta^2}$ . Note that  $\frac{1}{\sum_{\beta=1}^N \psi_\beta^2} \circ \varphi_\alpha^{-1} \in BC^\infty(\varphi_\alpha(U_\alpha))$ . We have

$$\begin{aligned} \|\text{sharp}_g \omega\|_{W^{e,q}(TM)} &\simeq \sum_{\alpha=1}^N \sum_{i=1}^n \|\tilde{\psi}_\alpha(\rho_\alpha)^i (\text{sharp}_g \omega) \circ \varphi_\alpha^{-1}\|_{W^{e,q}(\varphi_\alpha(U_\alpha))} \\ &\simeq \sum_{\alpha=1}^N \sum_{i=1}^n \|\tilde{\psi}_\alpha g^{ij} \omega_j \circ \varphi_\alpha^{-1}\|_{W^{e,q}(\varphi_\alpha(U_\alpha))} \\ &\leq \sum_{\alpha=1}^N \sum_{i=1}^n \|\psi_\alpha^2 g^{ij} \omega_j \circ \varphi_\alpha^{-1}\|_{W^{e,q}(\varphi_\alpha(U_\alpha))} \\ &\leq \sum_{\alpha=1}^N \sum_{i=1}^n \sum_{j=1}^n \|\psi_\alpha g^{ij} \circ \varphi_\alpha^{-1}\|_{W^{s,p}(\varphi_\alpha(U_\alpha))} \|\psi_\alpha \omega_j \circ \varphi_\alpha^{-1}\|_{W^{e,q}(\varphi_\alpha(U_\alpha))} \\ &\leq \|g^{-1}\|_{W^{s,p}(T_2^0M)} \|\omega\|_{W^{e,q}(T^*M)} \end{aligned}$$

Note that the inequality in the third line follows from Theorem E.15 and Corollary E.27.  $\square$

**Theorem 4.2.** *Let  $(M^n, g)$  be a compact Riemannian manifold. Let  $g \in W^{s,p}(T^2M)$  with  $sp > n$  and  $s \geq 1$ . Suppose  $e \in \mathbb{R}$  and  $q \in (1, \infty)$  are such that for balls  $\Omega \subseteq \mathbb{R}^n$  or for  $\Omega = \mathbb{R}^n$*

$$W^{s,p}(\Omega) \times W^{e,q}(\Omega) \hookrightarrow W^{e,q}(\Omega)$$

Suppose  $\{g_m\}$  is a sequence of smooth ( $C^\infty$ ) metrics on  $M$  such that  $g_m \rightarrow g$  in  $W^{s,p}(T^2M)$ . Then

$$\text{sharp}_{g_m} \rightarrow \text{sharp}_g \quad \text{in } L(W^{e,q}(T^*M), W^{e,q}(TM))$$

*Proof.*

$$\| \text{sharp}_{g_m} - \text{sharp}_g \|_{op} = \sup_{\|\omega\|_{e,q} \neq 0} \frac{\| (\text{sharp}_{g_m} - \text{sharp}_g)\omega \|_{W^{e,q}(TM)}}{\|\omega\|_{W^{e,q}(T^*M)}}$$

Let  $\Lambda = \{(U_\alpha, \varphi_\alpha, \rho_\alpha)\}_{\alpha=1}^N$  be a standard total trivialization atlas for  $TM$  and  $\tilde{\Lambda} = \{(U_\alpha, \varphi_\alpha, \tilde{\rho}_\alpha)\}_{\alpha=1}^N$  be a standard total trivialization atlas for  $T^*M$ . Without loss of generality we may assume that each of  $\Lambda$  and  $\tilde{\Lambda}$  is nice (or super nice) and GL compatible with itself. Let  $\{\psi_\alpha\}_{\alpha=1}^N$  be a partition of unity subordinate to the open cover  $\{U_\alpha\}_{\alpha=1}^N$ . Let  $\tilde{\psi}_\alpha = \frac{\psi_\alpha^2}{\sum_{\beta=1}^N \psi_\beta^2}$ . Note that  $\frac{1}{\sum_{\beta=1}^N \psi_\beta^2} \circ \varphi_\alpha^{-1} \in BC^\infty(\varphi_\alpha(U_\alpha))$ . We have

$$\begin{aligned} \| (\text{sharp}_{g_m} - \text{sharp}_g)\omega \|_{W^{e,q}(TM)} &\simeq \sum_{\alpha=1}^N \sum_{i=1}^n \|\tilde{\psi}_\alpha(\rho_\alpha)^i (\text{sharp}_{g_m} - \text{sharp}_g)\omega \circ \varphi_\alpha^{-1}\|_{W^{e,q}(\varphi_\alpha(U_\alpha))} \\ &\simeq \sum_{\alpha=1}^N \sum_{i=1}^n \|\tilde{\psi}_\alpha(g_m^{ij} - g^{ij})\omega_j \circ \varphi_\alpha^{-1}\|_{W^{e,q}(\varphi_\alpha(U_\alpha))} \\ &\lesssim \sum_{\alpha=1}^N \sum_{i=1}^n \sum_{j=1}^n \|\psi_\alpha(g_m^{ij} - g^{ij}) \circ \varphi_\alpha^{-1}\|_{W^{s,p}(\varphi_\alpha(U_\alpha))} \|\psi_\alpha \omega_j \circ \varphi_\alpha^{-1}\|_{W^{e,q}(\varphi_\alpha(U_\alpha))} \\ &\lesssim \|g_m^{-1} - g^{-1}\|_{W^{s,p}(T_2M)} \|\omega\|_{W^{e,q}(T^*M)} \end{aligned}$$

Now the claim follows from Theorem 3.3.  $\square$

If  $F$  is a general covariant  $k$ -tensor field ( $k \geq 2$ ), we let  $\text{sharp}_g F$  to be a  $\binom{k-1}{1}$ -tensor field defined by

$$\text{sharp}_g F(\omega, X_1, \dots, X_{k-1}) := F(X_1, \dots, X_{k-1}, \text{sharp}_g(\omega))$$

In any local coordinate chart

$$(\text{sharp}_g F)_{i_1 \dots i_{k-1}}^j = g^{jl} F_{i_1 \dots i_{k-1} l}$$

The proof of the next two theorems is completely analogous to the proof of Theorems 4.1 and 4.2 and will be omitted.

**Theorem 4.3.** *Let  $(M^n, g)$  be a compact Riemannian manifold. Let  $g \in W^{s,p}(T^2M)$  with  $sp > n$  and  $s \geq 1$ . Suppose  $e \in \mathbb{R}$  and  $q \in (1, \infty)$  are such that for balls  $\Omega \subseteq \mathbb{R}^n$  or for  $\Omega = \mathbb{R}^n$*

$$W^{s,p}(\Omega) \times W^{e,q}(\Omega) \hookrightarrow W^{e,q}(\Omega)$$

*Then  $\text{sharp}_g : (C^\infty(M, T^k M), \|\cdot\|_{e,q}) \rightarrow W^{e,q}(T_1^{k-1}M)$  is continuous and so it has a unique extension to a continuous operator  $\text{sharp}_g : W^{e,q}(T^k M) \rightarrow W^{e,q}(T_1^{k-1}M)$ .*

**Theorem 4.4.** *Let  $(M^n, g)$  be a compact Riemannian manifold. Let  $g \in W^{s,p}(T^2M)$  with  $sp > n$  and  $s \geq 1$ . Suppose  $e \in \mathbb{R}$  and  $p \in (1, \infty)$  are such that for balls  $\Omega \subseteq \mathbb{R}^n$  or for  $\Omega = \mathbb{R}^n$*

$$W^{s,p}(\Omega) \times W^{e,q}(\Omega) \hookrightarrow W^{e,q}(\Omega)$$

*Suppose  $\{g_m\}$  is a sequence of smooth ( $C^\infty$ ) metrics on  $M$  such that  $g_m \rightarrow g$  in  $W^{s,p}(T^2M)$ . Then*

$$\text{sharp}_{g_m} \rightarrow \text{sharp}_g \quad \text{in } L(W^{e,q}(T^k M), W^{e,q}(T_1^{k-1} M))$$

## 5. GRADIENT WITH ROUGH METRIC

Let  $M$  be a compact manifold and let  $g$  be a Riemannian metric on  $M$ . Let  $f : M \rightarrow \mathbb{R}$  be a scalar function.  $\text{grad } f$  is defined as  $\text{sharp}_g(df)$ . If  $(U, (x^i))$  is any local coordinate chart, then

$$df = \frac{\partial f}{\partial x^i} dx^i, \quad \text{grad } f = [g^{ij}(\frac{\partial f}{\partial x^i})] \frac{\partial}{\partial x^j}.$$

**Theorem 5.1.** *Let  $(M^n, g)$  be a compact Riemannian manifold. Let  $g \in W^{s,p}(T^2M)$  with  $sp > n$  and  $s \geq 1$ . Suppose  $e \in \mathbb{R}$  and  $p \in (1, \infty)$  are such that for balls  $\Omega \subseteq \mathbb{R}^n$  or for  $\Omega = \mathbb{R}^n$*

$$W^{s,p}(\Omega) \times W^{e,q}(\Omega) \hookrightarrow W^{e,q}(\Omega)$$

*Suppose  $\{g_m\}$  is a sequence of smooth  $(C^\infty)$  metrics on  $M$  such that  $g_m \rightarrow g$  in  $W^{s,p}(T^2M)$ . Then*

$$\text{grad}_{g_m} \rightarrow \text{grad}_g \quad \text{in } L(W^{e+1,q}(M), W^{e,q}(TM))$$

*Proof.* First note that according to Example 2 in Appendix I, under the hypotheses of the theorem,  $\text{grad}_{g_m}$  and  $\text{grad}_g$  belong to  $L(W^{e+1,q}(M), W^{e,q}(TM))$ .

$$\begin{aligned} \|\text{grad}_{g_m} - \text{grad}_g\|_{L(W^{e+1,q}, W^{e,q})} &= \|(\text{sharp}_{g_m} - \text{sharp}_g) \circ d\|_{L(W^{e+1,q}, W^{e,q})} \\ &\leq \|\text{sharp}_{g_m} - \text{sharp}_g\|_{L(W^{e,q}(T^*M), W^{e,q}(TM))} \|d\|_{L(W^{e+1,q}(M), W^{e,q}(T^*M))} \end{aligned}$$

However, we have already proved that under the hypothesis of the theorem

$$\|\text{sharp}_{g_m} - \text{sharp}_g\|_{L(W^{e,q}(T^*M), W^{e,q}(TM))} \rightarrow 0$$

Also in Appendix I it is shown that  $d : W^{e+1,q}(M) \rightarrow W^{e,q}(T^*M)$  is continuous. Therefore

$$\|\text{grad}_{g_m} - \text{grad}_g\|_{L(W^{e+1,q}, W^{e,q})} \rightarrow 0$$

□

Alternatively, a rather special case of the above result can be proved using the technique introduced in [26] for  $H^1(M)$ . This will be the context of the following theorem.

**Theorem 5.2.** *Let  $(M^n, g)$  be a compact Riemannian manifold. Let  $g \in W^{s,p}(T^2M)$  with  $sp > n$ ,  $s \geq 1$ . Suppose  $\{g_m\}$  is a sequence of smooth  $(C^\infty)$  metrics on  $M$  such that  $g_m \rightarrow g$  in  $W^{s,p}(T^2M)$ . Then*

$$\text{grad}_{g_m} \rightarrow \text{grad}_g \quad \text{in } L(W^{1,q}(M), L^q(TM))$$

*Proof.* First note that since  $sp > n$ ,  $W^{s,p} \hookrightarrow L^\infty$  and therefore for all  $1 < q < \infty$ , we have

$$W^{s,p} \times L^q \hookrightarrow L^q$$

Thus, this theorem is indeed a special case of the previous theorem. Denote the distortion tensor associated with  $g_m$  by  $A_m$ .

$$\begin{aligned} &\|\text{grad}_{g_m} - \text{grad}_g\|_{op} \\ &\stackrel{\text{Theorem B.17}}{=} \sup\{|\langle Y, (\text{grad}_{g_m} - \text{grad}_g)u \rangle_{L^{q'} \times L^q}| : u \in C^\infty(M), Y \in C^\infty(TM), \|u\|_{1,q} = \|Y\|_{q'} = 1\} \\ &= \sup\left\{ \left| \int_M g(Y, (A_m^{-1} - Id)\text{grad}_g u) dV_g \right| : u \in C^\infty(M), Y \in C^\infty(TM), \|u\|_{1,q} = \|Y\|_{q'} = 1 \right\} \\ &\leq \sup\left\{ \|A_m^{-1} - Id\|_\infty \int_M \|Y\|_g \|\text{grad}_g u\|_g dV_g : u \in C^\infty(M), Y \in C^\infty(TM), \|u\|_{1,q} = \|Y\|_{q'} = 1 \right\} \\ &= \sup\left\{ \|A_m^{-1} - Id\|_\infty \int_M |Y|_F |\text{grad}_g u|_F dV_g : u \in C^\infty(M), Y \in C^\infty(TM), \|u\|_{1,q} = \|Y\|_{q'} = 1 \right\} \end{aligned}$$

Now note that

$$\begin{aligned} \int_M |Y|_F |\mathbf{grad}_g u|_F dV_g &\leq \| |\mathbf{grad}_g u|_F \|_q \| |Y|_F \|_{q'} \\ &\preceq \| u \|_{1,q} \| Y \|_{q'} = 1 \end{aligned}$$

Therefore

$$\| \mathbf{grad}_{g_m} - \mathbf{grad}_g \|_{op} \preceq \| A_m^{-1} - Id \|_\infty$$

Finally, notice that by Theorem 3.2,  $\| A_m^{-1} - Id \|_\infty \rightarrow 0$  as  $m \rightarrow \infty$ .  $\square$

## 6. LINEAR CONNECTION WITH ROUGH METRIC

**Theorem 6.1.** *Let  $(M^n, g)$  be a compact Riemannian manifold. Let  $g \in W^{s,p}(T^2M)$  with  $sp > n$  and  $s \geq 1$ . Suppose  $e \in \mathbb{R}$  and  $q \in (1, \infty)$  are such that*

$$W^{s-1,p}(\mathbb{R}^n) \times W^{e+1,q}(\mathbb{R}^n) \hookrightarrow W^{e,q}(\mathbb{R}^n)$$

Also let  $X \in W^{s,p}(TM)$  where  $\tilde{s}$  and  $\tilde{p}$  have the property that

$$W^{\tilde{s},\tilde{p}}(\mathbb{R}^n) \times W^{s-1,p}(\Omega) \times W^{e+1,q}(\mathbb{R}^n) \hookrightarrow W^{e,q}(\mathbb{R}^n)$$

In particular,  $X$  can be any smooth vector field.

Suppose  $\{g_m\}$  is a sequence of smooth ( $C^\infty$ ) metrics on  $M$  such that  $g_m \rightarrow g$  in  $W^{s,p}(T^2M)$ . Then

$$(\nabla_{g_m})_X - (\nabla_g)_X \rightarrow 0 \quad \text{in } L(W^{e+1,q}(T_l^k M), W^{e,q}(T_l^k M))$$

*Proof.* In this proof we will not use the summation convention. Let  $\Lambda = \{(U_\alpha, \varphi_\alpha, \rho_\alpha)\}_{\alpha=1}^N$  be a standard total trivialization atlas for  $T_l^k(M) \rightarrow M$ . Without loss of generality we may assume that  $\Lambda$  is nice (or super nice) and GL compatible with itself. Let  $\{\psi_\alpha\}_{\alpha=1}^N$  be a partition of unity subordinate to the open cover  $\{U_\alpha\}_{\alpha=1}^N$ . Let  $\tilde{\psi}_\alpha = \frac{\psi_\alpha^3}{\sum_{\beta=1}^N \psi_\beta^3}$ . Note that  $\frac{1}{\sum_{\beta=1}^N \psi_\beta^3} \circ \varphi_\alpha^{-1} \in BC^\infty(\varphi_\alpha(U_\alpha))$ . Using techniques discussed in Appendix I, one can show that under the hypotheses of the theorem,  $(\nabla_{g_m})_X$  and  $(\nabla_g)_X$  indeed belong to  $L(W^{e+1,q}(T_l^k M), W^{e,q}(T_l^k M))$ .

$$\|(\nabla_{g_m})_X - (\nabla_g)_X\|_{L(W^{e+1,q}(T_l^k M), W^{e,q}(T_l^k M))} = \sup_{F \neq 0, F \in C^\infty} \frac{\|(\nabla_{g_m})_X F - (\nabla_g)_X F\|_{e,q}}{\|F\|_{e+1,q}}$$

We have

$$\|(\nabla_{g_m})_X F - (\nabla_g)_X F\|_{e,q} \simeq \sum_{\alpha=1}^N \sum_{j_{\tilde{r}}, i_{\tilde{r}}} \| \tilde{\psi}_\alpha [((\nabla_{g_m})_X F)_{i_1 \dots i_k}^{j_1 \dots j_l} - ((\nabla_g)_X F)_{i_1 \dots i_k}^{j_1 \dots j_l}] \circ \varphi_\alpha^{-1} \|_{W^{e,q}(\varphi_\alpha(U_\alpha))}$$

Recall that on  $U_\alpha$

$$(\nabla_{g_m})_X F = \sum_r X^r (\nabla_{g_m})_r F, \quad (\nabla_g)_X F = \sum_r X^r (\nabla_g)_r F$$

and

$$\begin{aligned}
((\nabla_{g_m})_r F)_{i_1 \dots i_k}^{j_1 \dots j_l} \circ \varphi_\alpha^{-1} &= \frac{\partial}{\partial x^r} (F_{i_1 \dots i_k}^{j_1 \dots j_l} \circ \varphi_\alpha^{-1}) \\
&+ \sum_{\hat{s}=1}^l \sum_p [F_{i_1 \dots i_k}^{j_1 \dots p \dots j_l} \circ \varphi_\alpha^{-1}] [(\Gamma_{g_m})_{rp}^{j_{\hat{s}}} \circ \varphi_\alpha^{-1}] - \sum_{\hat{s}=1}^k \sum_p [F_{i_1 \dots p \dots i_k}^{j_1 \dots j_l} \circ \varphi_\alpha^{-1}] [(\Gamma_{g_m})_{ri_{\hat{s}}}^p \circ \varphi_\alpha^{-1}] \\
((\nabla_g)_r F)_{i_1 \dots i_k}^{j_1 \dots j_l} \circ \varphi_\alpha^{-1} &= \frac{\partial}{\partial x^r} (F_{i_1 \dots i_k}^{j_1 \dots j_l} \circ \varphi_\alpha^{-1}) \\
&+ \sum_{\hat{s}=1}^l \sum_p [F_{i_1 \dots i_k}^{j_1 \dots p \dots j_l} \circ \varphi_\alpha^{-1}] [(\Gamma_g)_{rp}^{j_{\hat{s}}} \circ \varphi_\alpha^{-1}] - \sum_{\hat{s}=1}^k \sum_p [F_{i_1 \dots p \dots i_k}^{j_1 \dots j_l} \circ \varphi_\alpha^{-1}] [(\Gamma_g)_{ri_{\hat{s}}}^p \circ \varphi_\alpha^{-1}]
\end{aligned}$$

Therefore

$$\begin{aligned}
& [((\nabla_{g_m})_X F)_{i_1 \dots i_k}^{j_1 \dots j_l} - ((\nabla_g)_X F)_{i_1 \dots i_k}^{j_1 \dots j_l}] \circ \varphi_\alpha^{-1} = \\
& \sum_{\hat{s}=1}^l \sum_p \sum_r (X^r \circ \varphi_\alpha^{-1}) (F_{i_1 \dots i_k}^{j_1 \dots p \dots j_l} \circ \varphi_\alpha^{-1}) [(\Gamma_{g_m})_{rp}^{j_{\hat{s}}} \circ \varphi_\alpha^{-1} - (\Gamma_g)_{rp}^{j_{\hat{s}}} \circ \varphi_\alpha^{-1}] \\
& - \sum_{\hat{s}=1}^k \sum_p \sum_r (X^r \circ \varphi_\alpha^{-1}) (F_{i_1 \dots p \dots i_k}^{j_1 \dots j_l} \circ \varphi_\alpha^{-1}) [(\Gamma_{g_m})_{ri_{\hat{s}}}^p \circ \varphi_\alpha^{-1} - (\Gamma_g)_{ri_{\hat{s}}}^p \circ \varphi_\alpha^{-1}]
\end{aligned}$$

Thus

$$\begin{aligned}
& \|(\nabla_{g_m})_X F - (\nabla_g)_X F\|_{e,q} \simeq \\
& \sum_{\alpha=1}^N \sum_{j_{\hat{r}}, i_{\hat{r}}} \|\tilde{\psi}_\alpha \circ \varphi_\alpha^{-1}\| \left[ \sum_{\hat{s}=1}^l \sum_p \sum_r (X^r \circ \varphi_\alpha^{-1}) (F_{i_1 \dots i_k}^{j_1 \dots p \dots j_l} \circ \varphi_\alpha^{-1}) [(\Gamma_{g_m})_{rp}^{j_{\hat{s}}} \circ \varphi_\alpha^{-1} - (\Gamma_g)_{rp}^{j_{\hat{s}}} \circ \varphi_\alpha^{-1}] \right. \\
& \quad \left. - \sum_{\hat{s}=1}^k \sum_p \sum_r (X^r \circ \varphi_\alpha^{-1}) (F_{i_1 \dots p \dots i_k}^{j_1 \dots j_l} \circ \varphi_\alpha^{-1}) [(\Gamma_{g_m})_{ri_{\hat{s}}}^p \circ \varphi_\alpha^{-1} - (\Gamma_g)_{ri_{\hat{s}}}^p \circ \varphi_\alpha^{-1}] \right] \|_{W^{e,q}(\varphi_\alpha(U_\alpha))} \\
& \lesssim \sum_{\alpha=1}^N \sum_{j_{\hat{r}}, i_{\hat{r}}} \sum_{\hat{s}=1}^l \sum_p \sum_r \left[ \|(\psi_\alpha \circ \varphi_\alpha^{-1})(X^r \circ \varphi_\alpha^{-1})\|_{\hat{s}, \hat{p}} \|(\psi_\alpha \circ \varphi_\alpha^{-1})(F_{i_1 \dots i_k}^{j_1 \dots p \dots j_l} \circ \varphi_\alpha^{-1})\|_{e+1,q} \right. \\
& \quad \left. \|(\psi_\alpha \circ \varphi_\alpha^{-1})[(\Gamma_{g_m})_{rp}^{j_{\hat{s}}} \circ \varphi_\alpha^{-1} - (\Gamma_g)_{rp}^{j_{\hat{s}}} \circ \varphi_\alpha^{-1}]\|_{s-1,p} \right] \\
& + \sum_{\alpha=1}^N \sum_{j_{\hat{r}}, i_{\hat{r}}} \sum_{\hat{s}=1}^k \sum_p \sum_r \left[ \|(\psi_\alpha \circ \varphi_\alpha^{-1})(X^r \circ \varphi_\alpha^{-1})\|_{\hat{s}, \hat{p}} \|(\psi_\alpha \circ \varphi_\alpha^{-1})(F_{i_1 \dots p \dots i_k}^{j_1 \dots j_l} \circ \varphi_\alpha^{-1})\|_{e+1,q} \right. \\
& \quad \left. \|(\psi_\alpha \circ \varphi_\alpha^{-1})[(\Gamma_{g_m})_{ri_{\hat{s}}}^p \circ \varphi_\alpha^{-1} - (\Gamma_g)_{ri_{\hat{s}}}^p \circ \varphi_\alpha^{-1}]\|_{s-1,p} \right] \\
& \leq \|X\|_{W^{\hat{s}, \hat{p}}(TM)} \|F\|_{W^{e+1,q}(T_l^k(M))} \sum_{\alpha=1}^N \sum_{\hat{s}=1}^l \sum_p \sum_r \|(\psi_\alpha \circ \varphi_\alpha^{-1})[(\Gamma_{g_m})_{rp}^{j_{\hat{s}}} \circ \varphi_\alpha^{-1} - (\Gamma_g)_{rp}^{j_{\hat{s}}} \circ \varphi_\alpha^{-1}]\|_{W^{s-1,p}(\varphi_\alpha(U_\alpha))} \\
& + \|X\|_{W^{\hat{s}, \hat{p}}(TM)} \|F\|_{W^{e+1,q}(T_l^k(M))} \sum_{\alpha=1}^N \sum_{\hat{s}=1}^k \sum_p \sum_r \|(\psi_\alpha \circ \varphi_\alpha^{-1})[(\Gamma_{g_m})_{ri_{\hat{s}}}^p \circ \varphi_\alpha^{-1} - (\Gamma_g)_{ri_{\hat{s}}}^p \circ \varphi_\alpha^{-1}]\|_{W^{s-1,p}(\varphi_\alpha(U_\alpha))}
\end{aligned}$$

Therefore

$$\begin{aligned}
\frac{\|(\nabla_{g_m})_X F - (\nabla_g)_X F\|_{e,q}}{\|F\|_{e+1,q}} &\leq \sum_{\alpha=1}^N \sum_{\hat{s}=1}^l \sum_p \sum_r \|(\psi_\alpha \circ \varphi_\alpha^{-1})[(\Gamma_{g_m})_{rp}^{j_{\hat{s}}} \circ \varphi_\alpha^{-1} - (\Gamma_g)_{rp}^{j_{\hat{s}}} \circ \varphi_\alpha^{-1}]\|_{W^{s-1,p}(\varphi_\alpha(U_\alpha))} \\
&+ \sum_{\alpha=1}^N \sum_{\hat{s}=1}^k \sum_p \sum_r \|(\psi_\alpha \circ \varphi_\alpha^{-1})[(\Gamma_{g_m})_{ri_{\hat{s}}}^p \circ \varphi_\alpha^{-1} - (\Gamma_g)_{ri_{\hat{s}}}^p \circ \varphi_\alpha^{-1}]\|_{W^{s-1,p}(\varphi_\alpha(U_\alpha))}
\end{aligned}$$

Since  $g_m \rightarrow g$  in  $W^{s,p}$ , it follows from Theorem 3.3 that the right hand side goes to zero as  $m \rightarrow \infty$ .  $\square$

## 7. COVARIANT DERIVATIVE WITH ROUGH METRIC

Let  $F \in \tau_l^k(M)$ . The map

$$\begin{aligned} \nabla F : \tau^1(M) \times \cdots \times \tau^1(M) \times \chi(M) \times \cdots \times \chi(M) &\rightarrow C^\infty(M) \\ (\omega^1, \dots, \omega^l, Y_1, \dots, Y_k, X) &\mapsto (\nabla_X F)(\omega^1, \dots, \omega^l, Y_1, \dots, Y_k). \end{aligned}$$

is  $C^\infty(M)$ -multilinear and so it defines a  $\binom{k+1}{l}$ -tensor field. The tensor field  $\nabla F$  is called the (total) covariant derivative of  $F$ . Note that in any local coordinates (in this section we do not use the summation convention)

$$\begin{aligned} (\nabla F)_{i_1 \dots i_k r}^{j_1 \dots j_l} &= (\nabla_r F)_{i_1 \dots i_k}^{j_1 \dots j_l} \\ &= \frac{\partial}{\partial x^r} (F_{i_1 \dots i_k}^{j_1 \dots j_l} \circ \varphi_\alpha^{-1}) + \sum_{\tilde{s}=1}^l \sum_p F_{i_1 \dots i_k}^{j_1 \dots p \dots j_l} \circ \varphi_\alpha^{-1} (\Gamma_{g_m})_{r \tilde{s}}^{\tilde{s}} \circ \varphi_\alpha^{-1} - \sum_{\tilde{s}=1}^k \sum_p F_{i_1 \dots p \dots i_k}^{j_1 \dots j_l} \circ \varphi_\alpha^{-1} (\Gamma_{g_m})_{r i_{\tilde{s}}}^p \circ \varphi_\alpha^{-1} \end{aligned}$$

**Theorem 7.1.** *Let  $(M^n, g)$  be a compact Riemannian manifold. Let  $g \in W^{s,p}(T^2M)$  with  $sp > n$  and  $s \geq 1$ . Suppose  $e \in \mathbb{R}$  and  $q \in (1, \infty)$  are such that for balls  $\Omega \subseteq \mathbb{R}^n$  or for  $\Omega = \mathbb{R}^n$*

$$W^{s-1,p}(\Omega) \times W^{e+1,q}(\Omega) \hookrightarrow W^{e,q}(\Omega)$$

*In the case that the above multiplication property holds only for balls  $\Omega \subseteq \mathbb{R}^n$  and not  $\mathbb{R}^n$  itself, further assume that  $e$  and  $q$  are such that  $\frac{\partial}{\partial x^j} : W^{e+1,q}(\Omega) \rightarrow W^{e,q}(\Omega)$  ( $1 \leq j \leq n$ ) is continuous (see Theorem E.63).*

*Suppose  $\{g_m\}$  is a sequence of smooth ( $C^\infty$ ) metrics on  $M$  such that  $g_m \rightarrow g$  in  $W^{s,p}(T^2M)$ . Then*

$$\nabla_{g_m} \rightarrow \nabla_g \quad \text{in } L(W^{e+1,q}(T_l^k M), W^{e,q}(T_l^{k+1} M))$$

*Proof.* Let  $\Lambda = \{(U_\alpha, \varphi_\alpha, \rho_\alpha)\}_{\alpha=1}^N$  and  $\tilde{\Lambda} = \{(U_\alpha, \varphi_\alpha, \tilde{\rho}_\alpha)\}_{\alpha=1}^N$  be standard total trivialization atlases for  $T_l^k(M) \rightarrow M$  and  $T_l^{k+1}(M) \rightarrow M$ , respectively. Without loss of generality, we may assume that each of  $\Lambda$  and  $\tilde{\Lambda}$  is nice (or super nice) and GL compatible with itself. Let  $\{\psi_\alpha\}_{\alpha=1}^N$  be a partition of unity subordinate to the open cover  $\{U_\alpha\}_{\alpha=1}^N$ . Let  $\tilde{\psi}_\alpha = \frac{\psi_\alpha^2}{\sum_{\beta=1}^N \psi_\beta^2}$ . Note that  $\frac{1}{\sum_{\beta=1}^N \psi_\beta^2} \circ \varphi_\alpha^{-1} \in BC^\infty(\varphi_\alpha(U_\alpha))$ . Also, according to Example 5 in Appendix I, under the hypotheses of the theorem,  $\nabla_{g_m}$  and  $\nabla_g$  belong to  $L(W^{e+1,q}(T_l^k M), W^{e,q}(T_l^{k+1} M))$ .

$$\|\nabla_{g_m} - \nabla_g\|_{L(W^{e+1,q}(T_l^k M), W^{e,q}(T_l^{k+1} M))} = \sup_{F \neq 0, F \in C^\infty} \frac{\|\nabla_{g_m} F - \nabla_g F\|_{e,q}}{\|F\|_{e+1,q}}$$

We have

$$\begin{aligned} \|\nabla_{g_m} F - \nabla_g F\|_{e,q} &\simeq \sum_{\alpha=1}^N \sum_{j_{\tilde{r}}, i_{\tilde{r}}, r} \|\tilde{\psi}_\alpha [(\nabla_{g_m} F)_{i_1 \dots i_k r}^{j_1 \dots j_l} - (\nabla_g F)_{i_1 \dots i_k r}^{j_1 \dots j_l}] \circ \varphi_\alpha^{-1}\|_{W^{e,q}(\varphi_\alpha(U_\alpha))} \\ &= \sum_{\alpha=1}^N \sum_{j_{\tilde{r}}, i_{\tilde{r}}, r} \|\tilde{\psi}_\alpha [((\nabla_{g_m})_r F)_{i_1 \dots i_k}^{j_1 \dots j_l} - ((\nabla_g)_r F)_{i_1 \dots i_k}^{j_1 \dots j_l}] \circ \varphi_\alpha^{-1}\|_{W^{e,q}(\varphi_\alpha(U_\alpha))} \end{aligned}$$

The exact same procedure as the one given in the proof of Theorem 6.1 shows that the above expression is bounded by a constant times

$$\begin{aligned} \|F\|_{e+1,q} & \left[ \sum_{\alpha=1}^N \sum_{\mathfrak{s}=1}^l \sum_p \sum_r \left\| (\psi_\alpha \circ \varphi_\alpha^{-1}) [(\Gamma_{g_m})_{rp}^{j_{\mathfrak{s}}} \circ \varphi_\alpha^{-1} - (\Gamma_g)_{rp}^{j_{\mathfrak{s}}} \circ \varphi_\alpha^{-1}] \right\|_{W^{s-1,p}(\varphi_\alpha(U_\alpha))} \right. \\ & \left. + \sum_{\alpha=1}^N \sum_{\mathfrak{s}=1}^k \sum_p \sum_r \left\| (\psi_\alpha \circ \varphi_\alpha^{-1}) [(\Gamma_{g_m})_{r\mathfrak{s}}^p \circ \varphi_\alpha^{-1} - (\Gamma_g)_{r\mathfrak{s}}^p \circ \varphi_\alpha^{-1}] \right\|_{W^{s-1,p}(\varphi_\alpha(U_\alpha))} \right] \end{aligned}$$

Since  $g_m \rightarrow g$  in  $W^{s,p}$ , it follows from Theorem 3.3 that the right hand side divided by  $\|F\|_{e+1,q}$  goes to zero as  $m \rightarrow \infty$ .  $\square$

## 8. CONTINUITY OF TRACE

It is well known that we can associate with any  $\binom{l}{1}$  tensor field a corresponding field of endomorphisms of tangent spaces. If  $F$  is a  $\binom{l}{1}$  tensor field, then the trace of  $F$  at each point  $p \in M$  is defined as the trace of the corresponding endomorphism of  $T_p M$ . So  $\text{tr } F$  will be a scalar field on  $M$ . More generally, let  $F$  be a  $\binom{k}{l}$ -tensor field where  $k, l \geq 1$ . We can define the trace of  $F$  with respect to the pair  $(r, s)$  ( $1 \leq r \leq l, 1 \leq s \leq k$ ) as follows:  $\text{tr } F$  is a  $\binom{k-1}{l-1}$ -tensor field defined by

$$(\text{tr } F)(\omega^1, \dots, \omega^{r-1}, \omega^{r+1}, \dots, \omega^l, X_1, \dots, X_{s-1}, X_{s+1}, \dots, X_k) := \text{tr } G$$

where  $G \in T_1^1(V)$  is given by

$$G(\omega, X) := F(\omega^1, \dots, \omega^{r-1}, \omega, \omega^{r+1}, \dots, \omega^l, X_1, \dots, X_{s-1}, X, X_{s+1}, \dots, X_k).$$

Unless otherwise stated, in computing trace we assume  $(r, s) = (l, k)$ . With respect to any local coordinate chart we have

$$(\text{tr } F)_{i_1 \dots i_{k-1}}^{j_1 \dots j_{l-1}} = F_{i_1 \dots i_{k-1} m}^{j_1 \dots j_{l-1} m}.$$

**Theorem 8.1.** *Let  $M$  be a compact Riemannian manifold. Let  $e \in \mathbb{R}$  and  $q \in (1, \infty)$ . Suppose  $k, l \geq 1$ . Then  $\text{tr} : (C^\infty(M, T_l^k(M)), \|\cdot\|_{e,q}) \rightarrow W^{e,q}(T_{l-1}^{k-1}(M))$  is continuous and so it has a unique extension to a continuous operator  $\text{tr} : W^{e,q}(T_l^k(M)) \rightarrow W^{e,q}(T_{l-1}^{k-1}(M))$ .*

*Proof.* Let  $\{(U_\alpha, \varphi_\alpha, \rho_\alpha)\}_{\alpha=1}^N$  be a standard total trivialization atlas for  $T_l^k(M) \rightarrow M$  that is GL compatible with itself. Let  $\{\psi_\alpha\}_{\alpha=1}^N$  be a partition of unity subordinate to the open cover  $\{U_\alpha\}_{\alpha=1}^N$ . Note that  $T_l^k(M)$  is a bundle of rank  $n^{k+l}$ . So for each  $\alpha$ ,  $\rho_\alpha$  has  $n^{k+l}$  components which we denote by  $(\rho_\alpha)_{i_1 \dots i_k}^{j_1 \dots j_l}$ . For all  $F \in \Gamma(M, T_l^k(M))$ , we have

$$(\rho_\alpha)_{i_1 \dots i_k}^{j_1 \dots j_l} (\psi_\alpha F) = \psi_\alpha (F)_{i_1 \dots i_k}^{j_1 \dots j_l}$$



where  $F = (F_\alpha)_{i_1 \dots i_k}^{j_1 \dots j_l} \partial_{j_1} \otimes \dots \otimes \partial_{j_l} \otimes dx^{i_1} \otimes \dots \otimes dx^{i_k}$  on the coordinate chart  $(U_\alpha, \varphi_\alpha)$ . Therefore

$$\begin{aligned}
 \|\mathrm{tr} F\|_{W^{e,q}(T_l^{k-1}(M))}^q &\simeq \sum_{\alpha=1}^N \sum_{j_{\tilde{r}}, i_{\tilde{r}}} \left\| (\rho_\alpha)_{i_1 \dots i_{k-1}}^{j_1 \dots j_{l-1}} \circ (\psi_\alpha \mathrm{tr} F) \circ \varphi_\alpha^{-1} \right\|_{W^{e,q}(\varphi_\alpha(U_\alpha))}^q \\
 &= \sum_{\alpha=1}^N \sum_{j_r, i_r} \left\| \psi_\alpha((\mathrm{tr} F)_\alpha)_{i_1 \dots i_{k-1}}^{j_1 \dots j_{l-1}} \circ \varphi_\alpha^{-1} \right\|_{W^{e,q}(\varphi_\alpha(U_\alpha))}^q \\
 &= \sum_{\alpha=1}^N \sum_{j_r, i_r} \left\| \psi_\alpha(F_\alpha)_{i_1 \dots i_{k-1} m}^{j_1 \dots j_{l-1} m} \circ \varphi_\alpha^{-1} \right\|_{W^{e,q}(\varphi_\alpha(U_\alpha))}^q \\
 &\leq \sum_{\alpha=1}^N \sum_{j_r, i_r} \left\| \psi_\alpha(F_\alpha)_{i_1 \dots i_{k-1} i_k}^{j_1 \dots j_{l-1} j_l} \circ \varphi_\alpha^{-1} \right\|_{W^{e,q}(\varphi_\alpha(U_\alpha))}^q \quad (\text{this sum has more terms comparing to the last}) \\
 &= \sum_{\alpha=1}^N \sum_{j_r, i_r} \left\| (\rho_\alpha)_{i_1 \dots i_k}^{j_1 \dots j_l} \circ (\psi_\alpha F) \circ \varphi_\alpha^{-1} \right\|_{W^{e,q}(\varphi_\alpha(U_\alpha))}^q \\
 &= \|F\|_{W^{e,q}(T_l^k(M))}^q
 \end{aligned}$$

□

Note that in the above proof the trace was computed on the last pair of indices. Of course, clearly the same procedure shows that taking trace on any pair of indices is continuous.

## 9. DIVERGENCE WITH ROUGH METRIC

We begin with studying the divergence of a vector field. Then we will consider the divergence of more general tensor fields.

**Theorem 9.1.** *Let  $(M^n, g)$  be a compact Riemannian manifold. Let  $g \in W^{s,p}(T^2M)$  with  $sp > n$  and  $s \geq 1$ . Suppose  $e \in \mathbb{R}$  and  $q \in (1, \infty)$  are such that for balls  $\Omega \subseteq \mathbb{R}^n$  or for  $\Omega = \mathbb{R}^n$*

$$W^{s-1,p}(\Omega) \times W^{e+1,q}(\Omega) \hookrightarrow W^{e,q}(\Omega)$$

*In the case that the above multiplication property holds only for balls  $\Omega \subseteq \mathbb{R}^n$  and not  $\mathbb{R}^n$  itself, further assume that  $e$  and  $q$  are such that  $\frac{\partial}{\partial x^j} : W^{e+1,q}(\Omega) \rightarrow W^{e,q}(\Omega)$  ( $1 \leq j \leq n$ ) is continuous.*

*Suppose  $\{g_m\}$  is a sequence of smooth ( $C^\infty$ ) metrics on  $M$  such that  $g_m \rightarrow g$  in  $W^{s,p}(T^2M)$ . Then*

$$\mathrm{div}_{g_m} \rightarrow \mathrm{div}_g \quad \text{in } L(W^{e+1,q}(TM), W^{e,q}(M))$$

*Proof.* Let  $\Lambda = \{(U_\alpha, \varphi_\alpha, \rho_\alpha)\}_{\alpha=1}^N$  be a standard total trivialization atlas for  $TM$ . Without loss of generality we may assume that  $\Lambda$  is nice (or super nice) and GL compatible with itself. Let  $\{\psi_\alpha\}_{\alpha=1}^N$  be a partition of unity subordinate to the open cover  $\{U_\alpha\}_{\alpha=1}^N$ . Let  $\tilde{\psi}_\alpha = \frac{\psi_\alpha^2}{\sum_{\beta=1}^N \psi_\beta^2}$ . Note that  $\frac{1}{\sum_{\beta=1}^N \psi_\beta^2} \circ \varphi_\alpha^{-1} \in BC^\infty(\varphi_\alpha(U_\alpha))$ . Also, according to Example 3 in Appendix I,  $\mathrm{div}_{g_m}$  and  $\mathrm{div}_g$  belong to  $L(W^{e+1,q}(TM), W^{e,q}(M))$ . We have

$$\|\mathrm{div}_{g_m} - \mathrm{div}_g\|_{op} = \sup_{\|X\|_{e+1,q}=1, X \in C^\infty} \|(\mathrm{div}_{g_m} - \mathrm{div}_g)X\|_{W^{e,q}(M)}$$

Note that

$$\begin{aligned} \|(\operatorname{div}_{g_m} - \operatorname{div}_g)X\|_{W^{e,q}(M)} &\simeq \sum_{\alpha=1}^N \|\tilde{\psi}_\alpha((\operatorname{div}_{g_m} - \operatorname{div}_g)X) \circ \varphi_\alpha^{-1}\|_{W^{e,q}(\varphi_\alpha(U_\alpha))} \\ &= \sum_{\alpha=1}^N \|(\tilde{\psi}_\alpha \circ \varphi_\alpha^{-1})((\operatorname{div}_{g_m} X \circ \varphi_\alpha^{-1}) - (\operatorname{div}_g X \circ \varphi_\alpha^{-1}))\|_{W^{e,q}(\varphi_\alpha(U_\alpha))} \end{aligned}$$

Recall that (in what follows we will not use the summation convention)

$$\begin{aligned} \operatorname{div}_g X \circ \varphi_\alpha^{-1} &= \sum_{j=1}^n \frac{1}{\sqrt{\det g \circ \varphi_\alpha^{-1}}} \left( \frac{\partial}{\partial x^j} (\sqrt{\det g \circ \varphi_\alpha^{-1}}) (X^j \circ \varphi_\alpha^{-1}) + \frac{\partial}{\partial x^j} (X^j \circ \varphi_\alpha^{-1}) \right) \\ \operatorname{div}_{g_m} X \circ \varphi_\alpha^{-1} &= \sum_{j=1}^n \frac{1}{\sqrt{\det g_m \circ \varphi_\alpha^{-1}}} \left( \frac{\partial}{\partial x^j} (\sqrt{\det g_m \circ \varphi_\alpha^{-1}}) (X^j \circ \varphi_\alpha^{-1}) + \frac{\partial}{\partial x^j} (X^j \circ \varphi_\alpha^{-1}) \right) \end{aligned}$$

Therefore

$$\begin{aligned} \operatorname{div}_{g_m} X \circ \varphi_\alpha^{-1} - \operatorname{div}_g X \circ \varphi_\alpha^{-1} &= \\ \sum_{j=1}^n \left[ \frac{1}{\sqrt{\det g_m \circ \varphi_\alpha^{-1}}} \left( \frac{\partial}{\partial x^j} (\sqrt{\det g_m \circ \varphi_\alpha^{-1}}) \right) - \frac{1}{\sqrt{\det g \circ \varphi_\alpha^{-1}}} \left( \frac{\partial}{\partial x^j} (\sqrt{\det g \circ \varphi_\alpha^{-1}}) \right) \right] (X^j \circ \varphi_\alpha^{-1}) \end{aligned}$$

Let

$$\begin{aligned} B_m &= \frac{1}{\sqrt{\det g_m \circ \varphi_\alpha^{-1}}} \left( \frac{\partial}{\partial x^j} (\sqrt{\det g_m \circ \varphi_\alpha^{-1}}) \right) \\ B &= \frac{1}{\sqrt{\det g \circ \varphi_\alpha^{-1}}} \left( \frac{\partial}{\partial x^j} (\sqrt{\det g \circ \varphi_\alpha^{-1}}) \right) \end{aligned}$$

Since  $s > \frac{n}{p}$ ,  $W^{s,p} \times W^{s-1,p} \hookrightarrow W^{s-1,p}$ . Considering this, it follows from Lemma F.9, Theorem F.6, and Theorem H.20 that  $B_m - B \in W_{loc}^{s-1,p}$ . Also note that  $X \in W^{e+1,q}$ . So

$$\begin{aligned} (\psi_\alpha \circ \varphi_\alpha^{-1})(B_m - B) &\in W_{loc}^{s-1,p}(\varphi_\alpha(U_\alpha)) \\ (\psi_\alpha \circ \varphi_\alpha^{-1})(X^j \circ \varphi_\alpha^{-1}) &\in W_{loc}^{e+1,q}(\varphi_\alpha(U_\alpha)) \end{aligned}$$

By assumption  $W^{s-1,p} \times W^{e+1,q} \hookrightarrow W^{e,q}$ . Consequently we can write

$$\begin{aligned} \|(\operatorname{div}_{g_m} - \operatorname{div}_g)X\|_{W^{e,q}(M)} &\leq \sum_{\alpha=1}^N \sum_{j=1}^n \|(\psi_\alpha \circ \varphi_\alpha^{-1})(B_m - B)(\psi_\alpha \circ \varphi_\alpha^{-1})(X^j \circ \varphi_\alpha^{-1})\|_{W^{e,q}(\varphi_\alpha(U_\alpha))} \\ &\leq \sum_{\alpha=1}^N \sum_{j=1}^n \|(\psi_\alpha \circ \varphi_\alpha^{-1})(B_m - B)\|_{W^{s-1,p}(\varphi_\alpha(U_\alpha))} \|(\psi_\alpha \circ \varphi_\alpha^{-1})(X^j \circ \varphi_\alpha^{-1})\|_{W^{e+1,q}(\varphi_\alpha(U_\alpha))} \\ &\simeq \|(\psi_\alpha \circ \varphi_\alpha^{-1})(B_m - B)\|_{W^{s-1,p}(\varphi_\alpha(U_\alpha))} \|X\|_{W^{e+1,q}(TM)} \end{aligned}$$

By assumption  $g_m \rightarrow g$  in  $W^{s,p}$ . Therefore  $(g_m)_\alpha \rightarrow g_\alpha$  in  $W_{loc}^{s,p}$ . Consequently  $B_m \rightarrow B$  in  $W_{loc}^{s-1,p}$ . Thus  $(\psi_\alpha \circ \varphi_\alpha^{-1})B_m \rightarrow (\psi_\alpha \circ \varphi_\alpha^{-1})B$  in  $W^{s-1,p}$ .  $\square$

**Theorem 9.2.** *Let  $(M^n, g)$  be a compact Riemannian manifold. Let  $g \in W^{s,p}(T^2M)$  with  $sp > n$  and  $s \geq 1$ . Suppose  $e \in \mathbb{R}$  and  $q \in (1, \infty)$  are such that for balls  $\Omega \subseteq \mathbb{R}^n$  or for  $\Omega = \mathbb{R}^n$*

$$W^{s-1,p}(\Omega) \times W^{e+1,q}(\Omega) \hookrightarrow W^{e,q}(\Omega)$$

In the case that the above multiplication property holds only for balls  $\Omega \subseteq \mathbb{R}^n$  and not  $\mathbb{R}^n$  itself, further assume that  $e$  and  $q$  are such that  $\frac{\partial}{\partial x^j} : W^{e+1,q}(\Omega) \rightarrow W^{e,q}(\Omega)$  ( $1 \leq j \leq n$ ) is continuous.

Suppose  $\{g_m\}$  is a sequence of smooth ( $C^\infty$ ) metrics on  $M$  such that  $g_m \rightarrow g$  in  $W^{s,p}(T^2M)$ . Assume  $k \geq 0$  and  $l \geq 1$ . Then

$$\operatorname{div}_{g_m} \rightarrow \operatorname{div}_g \quad \text{in } L(W^{e+1,q}(T_l^k M), W^{e,q}(T_{l-1}^k M))$$

*Proof.* The divergence of a tensor field  $F$  is defined as the trace of the total covariant derivative of  $F$ :

$$\operatorname{div} F = \operatorname{tr}(\nabla F).$$

By Theorem 7.1

$$\nabla_{g_m} \rightarrow \nabla_g \quad \text{in } L(W^{e+1,q}(T_l^k M), W^{e,q}(T_l^{k+1} M))$$

Also by Theorem 8.1,  $\operatorname{tr} : W^{e,q}(T_l^{k+1} M) \rightarrow W^{e,q}(T_{l-1}^k M)$  is a linear continuous operator. Therefore by Theorem B.14

$$\operatorname{tr} \circ \nabla_{g_m} \rightarrow \operatorname{tr} \circ \nabla_g \quad \text{in } L(W^{e+1,q}(T_l^k M), W^{e,q}(T_{l-1}^k M))$$

□

For a general  $\binom{k}{0}$ -tensor field  $F$  ( $k \geq 1$ ),  $\nabla F$  is a  $\binom{k+1}{0}$ -tensor field and  $\operatorname{sharp}(\nabla F)$  is a  $\binom{k}{1}$ -tensor field. Divergence of  $F$  is the  $\binom{k-1}{0}$ -tensor field defined by

$$\operatorname{div} F := \operatorname{tr}(\operatorname{sharp}(\nabla F))$$

**Theorem 9.3.** Let  $(M^n, g)$  be a compact Riemannian manifold. Let  $g \in W^{s,p}(T^2M)$  with  $sp > n$  and  $s \geq 1$ . Suppose  $\{g_m\}$  is a sequence of smooth ( $C^\infty$ ) metrics on  $M$  such that  $g_m \rightarrow g$  in  $W^{s,p}(T^2M)$ . Suppose  $e \in \mathbb{R}$  and  $q \in (1, \infty)$  are such that either

$$W^{s-1,p}(\mathbb{R}^n) \times W^{e+1,q}(\mathbb{R}^n) \hookrightarrow W^{e,q}(\mathbb{R}^n)$$

$$W^{s,p}(\mathbb{R}^n) \times W^{e,q}(\mathbb{R}^n) \hookrightarrow W^{e,q}(\mathbb{R}^n)$$

or for balls  $\Omega \subseteq \mathbb{R}^n$ ,  $\frac{\partial}{\partial x^j} : W^{e+1,q}(\Omega) \rightarrow W^{e,q}(\Omega)$  ( $1 \leq j \leq n$ ) is continuous and

$$W^{s-1,p}(\Omega) \times W^{e+1,q}(\Omega) \hookrightarrow W^{e,q}(\Omega)$$

$$W^{s,p}(\Omega) \times W^{e,q}(\Omega) \hookrightarrow W^{e,q}(\Omega)$$

Assume  $k \geq 1$ . Then

$$\operatorname{div}_{g_m} \rightarrow \operatorname{div}_g \quad \text{in } L(W^{e+1,q}(T^k M), W^{e,q}(T^{k-1} M))$$

*Proof.* By Theorem 7.1

$$\nabla_{g_m} \rightarrow \nabla_g \quad \text{in } L(W^{e+1,q}(T^k M), W^{e,q}(T^{k+1} M))$$

By Theorem 4.4

$$\operatorname{sharp}_{g_m} \rightarrow \operatorname{sharp}_g \quad \text{in } L(W^{e,q}(T^{k+1} M), W^{e,q}(T_1^k M))$$

Also by Theorem 8.1,  $\operatorname{tr} : W^{e,q}(T_1^k M) \rightarrow W^{e,q}(T^{k-1} M)$  is a linear continuous operator ( $\operatorname{tr} \in L(W^{e,q}(T_1^k M), W^{e,q}(T^{k-1} M))$ ). It follows from Theorem B.14 that

$$\operatorname{tr} \circ \operatorname{sharp}_{g_m} \circ \nabla_{g_m} \rightarrow \operatorname{tr} \circ \operatorname{sharp}_g \circ \nabla_g \quad \text{in } L(W^{e+1,q}(T^k M), W^{e,q}(T^{k-1} M))$$

□

## 10. LAPLACIAN WITH ROUGH METRIC

**Theorem 10.1.** *Let  $(M^n, g)$  be a compact Riemannian manifold. Let  $g \in W^{s,p}(T^2M)$  with  $sp > n$  and  $s \geq 1$ . Suppose  $\{g_m\}$  is a sequence of smooth  $(C^\infty)$  metrics on  $M$  such that  $g_m \rightarrow g$  in  $W^{s,p}(T^2M)$ . Suppose  $e \in \mathbb{R}$  and  $q \in (1, \infty)$  are such that either*

$$\begin{aligned} W^{s,p}(\mathbb{R}^n) \times W^{e,q}(\mathbb{R}^n) &\hookrightarrow W^{e,q}(\mathbb{R}^n) \\ W^{s,p}(\mathbb{R}^n) \times W^{e-1,q}(\mathbb{R}^n) &\hookrightarrow W^{e-1,q}(\mathbb{R}^n) \end{aligned}$$

or for balls  $\Omega \subseteq \mathbb{R}^n$ ,  $\frac{\partial}{\partial x^j} : W^{e,q}(\Omega) \rightarrow W^{e-1,q}(\Omega)$  ( $1 \leq j \leq n$ ) is continuous and

$$\begin{aligned} W^{s,p}(\Omega) \times W^{e,q}(\Omega) &\hookrightarrow W^{e,q}(\Omega) \\ W^{s,p}(\Omega) \times W^{e-1,q}(\Omega) &\hookrightarrow W^{e-1,q}(\Omega) \end{aligned}$$

Then

$$\Delta_{g_m} \rightarrow \Delta_g \quad \text{in } L(W^{e+1,q}(M), W^{e-1,q}(M))$$

*Proof.* Note that  $\Delta = \text{div} \circ \text{grad}$ . By Theorem 5.1

$$\text{grad}_{g_m} \rightarrow \text{grad}_g \quad \text{in } L(W^{e+1,q}(M) \rightarrow W^{e,q}(TM))$$

Also by Theorem 9.1

$$\text{div}_{g_m} \rightarrow \text{div}_g \quad \text{in } L(W^{e,q}(TM) \rightarrow W^{e-1,q}(M))$$

Therefore it follows from Theorem B.14 that

$$\text{div}_{g_m} \circ \text{grad}_{g_m} \rightarrow \text{div}_g \circ \text{grad}_g \quad \text{in } L(W^{e+1,q}(M) \rightarrow W^{e-1,q}(M))$$

□

As an alternative, for a limited range of Sobolev spaces, we may use the technique employed in [26] to prove a similar result.

**Theorem 10.2.** *Let  $(M^n, g)$  be a compact Riemannian manifold. Let  $g \in W^{s,p}(T^2M)$  with  $sp > n$ ,  $s \geq 1$ . Suppose  $\{g_m\}$  is a sequence of smooth  $(C^\infty)$  metrics on  $M$  such that  $g_m \rightarrow g$  in  $W^{s,p}(T^2M)$ . Then*

$$\Delta_{g_m} \rightarrow \Delta_g \quad \text{in } L(W^{1,p}(M), W^{-1,p}(M))$$

*Proof.* First note that it follows from the hypotheses of the theorem that

$$W^{s,p}(\mathbb{R}^n) \times W^{1,p}(\mathbb{R}^n) \hookrightarrow W^{1,p}(\mathbb{R}^n), \quad W^{s,p}(\mathbb{R}^n) \times W^{0,p}(\mathbb{R}^n) \hookrightarrow W^{0,p}(\mathbb{R}^n)$$

So the claim of this theorem is indeed a special case of the claim of Theorem 10.1.

Let  $A_m$  denote the metric distortion tensor associated with  $g_m$ . By Theorem 3.2 we have

$$\| \sqrt{\det A_m A_m^{-1}} - Id \|_\infty \rightarrow 0, \quad A_m^{-1} \text{grad}_g = \text{grad}_{g_m}, \quad dV_{g_m} = \sqrt{\det A_m} dV_g$$

So it is enough to show that

$$\| \sqrt{\det A_m A_m^{-1}} - Id \|_\infty \rightarrow 0 \implies \| \Delta_{g_m} - \Delta_g \|_{L(W^{1,p}(M), W^{-1,p}(M))} \rightarrow 0$$

For all  $u$  and  $v$  in  $C^\infty(M)$

$$\begin{aligned}
 \langle v, \Delta_{g_m} u \rangle_{W^{1,p'} \times W^{-1,p}} &= \int_M (\Delta_{g_m} u) v \, dV_{g_m} \quad (\text{see Theorem H.29}) \\
 &= - \int_M g_m(\text{grad}_{g_m} u, \text{grad}_{g_m} v) \, dV_{g_m} \quad (\text{integration by parts}) \\
 &= - \int_M g(A_m \text{grad}_{g_m} u, \text{grad}_{g_m} v) \sqrt{\det A_m} \, dV_g \\
 &= - \int_M g(A_m A_m^{-1} \text{grad}_g u, A_m^{-1} \text{grad}_g v) \sqrt{\det A_m} \, dV_g \\
 &= - \int_M g(A_m^{-1} \text{grad}_g u, \text{grad}_g v) \sqrt{\det A_m} \, dV_g
 \end{aligned}$$

In the last equality we used the fact that  $A_m$  and  $A_m^{-1}$  are symmetric. Also

$$\langle v, \Delta_g u \rangle_{W^{1,p'} \times W^{-1,p}} = \int_M (\Delta_g u) v \, dV_g = - \int_M g(\text{grad}_g u, \text{grad}_g v) \, dV_g$$

Therefore

$$\begin{aligned}
 &\| \Delta_{g_m} - \Delta_g \|_{op} \stackrel{\text{Theorem B.17}}{=} \sup\{|\langle v, (\Delta_{g_m} - \Delta_g)u \rangle| : u, v \in C^\infty(M), \|u\|_{1,p} = \|v\|_{1,p'} = 1\} \\
 &= \sup\{ \left| - \int_M g((\sqrt{\det A_m} A_m^{-1} - Id) \text{grad}_g u, \text{grad}_g v) \, dV_g \right| : u, v \in C^\infty(M), \|u\|_{1,p} = \|v\|_{1,p'} = 1 \} \\
 &\leq \sup\{ \| \sqrt{\det A_m} A_m^{-1} - Id \|_\infty \int_M \| \text{grad}_g u \|_g \| \text{grad}_g v \|_g \, dV_g : u, v \in C^\infty(M), \|u\|_{1,p} = \|v\|_{1,p'} = 1 \} \\
 &= \sup\{ \| \sqrt{\det A_m} A_m^{-1} - Id \|_\infty \int_M |\text{grad}_g u|_F |\text{grad}_g v|_F \, dV_g : u, v \in C^\infty(M), \|u\|_{1,p} = \|v\|_{1,p'} = 1 \}
 \end{aligned}$$

Now note that

$$\begin{aligned}
 \int_M |\text{grad}_g u|_F |\text{grad}_g v|_F \, dV_g &\leq \| |\text{grad}_g u|_F \|_p \| |\text{grad}_g v|_F \|_{p'} \\
 &= \| \text{grad}_g u \|_p \| \text{grad}_g v \|_{p'} \leq \|u\|_{1,p} \|v\|_{1,p'} = 1
 \end{aligned}$$

Hence

$$\| \Delta_{g_m} - \Delta_g \|_{op} \leq \| \sqrt{\det A_m} A_m^{-1} - Id \|_\infty$$

□

## 11. CONFORMAL KILLING OPERATOR WITH ROUGH METRIC

Suppose  $(M, g)$  is a Riemannian manifold and  $\nabla$  is the corresponding Levi-Civita connection. For all vector fields  $X, Y, Z \in C^\infty(TM)$  we have

$$\begin{aligned}
 (L_X g)(Y, Z) &= X(g(Y, Z)) - g([X, Y], Z) - g(Y, [X, Z]) \\
 &= g(\nabla_X Y, Z) + g(Y, \nabla_X Z) - g([X, Y], Z) - g(Y, [X, Z]) \\
 &= g(\nabla_X Y - [X, Y], Z) + g(Y, \nabla_X Z - [X, Z]) \\
 &= g(\nabla_Y X, Z) + g(Y, \nabla_Z X).
 \end{aligned}$$

Here  $L_X$  denotes the Lie derivative with respect to the vector field  $X$ . Therefore with respect to any local coordinate chart we have

$$L_X g_{ij} = \nabla_i X_j + \nabla_j X_i.$$

It follows that  $\text{tr}(L_X g) = 2\text{div} X$ . Therefore we can decompose  $L_X g$  into the pure trace part and the trace-free part as follows:

$$L_X g = \underbrace{\left[ \frac{1}{n}(2\text{div} X)g \right]}_{\text{pure trace}} + \underbrace{\left[ L_X g - \frac{1}{n}(2\text{div} X)g \right]}_{\text{trace-free}}.$$

The *conformal Killing operator*,  $\mathcal{L}$ , is defined as follows:

$$\mathcal{L}X := \text{the trace-free part of } L_X g.$$

That is, with respect to any local chart  $(U, \varphi)$

$$(\mathcal{L}X)_{ij} = \nabla_i X_j + \nabla_j X_i - \frac{2}{n}(\text{div} X)g_{ij}.$$

Note that

$$\nabla_i X = (\partial_i X^l + X^k \Gamma_{ik}^l) \partial_l$$

Therefore

$$\begin{aligned} [\nabla_i X]_j + [\nabla_j X]_i &= g_{jl}[\nabla_i X]^l + g_{il}[\nabla_j X]^l \\ &= g_{jl}[\partial_i X^l + X^k \Gamma_{ik}^l] + g_{il}[\partial_j X^l + X^k \Gamma_{jk}^l] \end{aligned}$$

Thus

$$(\mathcal{L}X)_{ij} = g_{jl}[\partial_i X^l + X^k \Gamma_{ik}^l] + g_{il}[\partial_j X^l + X^k \Gamma_{jk}^l] - \frac{2}{n}(\text{div} X)g_{ij}. \quad (11.1)$$

**Theorem 11.1.** *Let  $(M^n, g)$  be a compact Riemannian manifold. Let  $g \in W^{s,p}(T^2 M)$  with  $sp > n$  and  $s \geq 1$ . Suppose  $e \in \mathbb{R}$  and  $q \in (1, \infty)$  are such that for balls  $\Omega \subseteq \mathbb{R}^n$  or for  $\Omega = \mathbb{R}^n$*

$$W^{s-1,p}(\Omega) \times W^{e+1,q}(\Omega) \hookrightarrow W^{e,q}(\Omega)$$

$$W^{s,p}(\Omega) \times W^{e,q}(\Omega) \hookrightarrow W^{e,q}(\Omega)$$

$$W^{s,p}(\Omega) \times W^{e+1,q}(\Omega) \hookrightarrow W^{e+1,q}(\Omega)$$

*In the case that the above multiplication properties hold only for balls  $\Omega \subseteq \mathbb{R}^n$  and not  $\mathbb{R}^n$  itself, further assume that  $e$  and  $q$  are such that  $\frac{\partial}{\partial x^j} : W^{e+1,q}(\Omega) \rightarrow W^{e,q}(\Omega)$  ( $1 \leq j \leq n$ ) is continuous. Suppose  $\{g_m\}$  is a sequence of smooth ( $C^\infty$ ) metrics on  $M$  such that  $g_m \rightarrow g$  in  $W^{s,p}(T^2 M)$ . Then*

$$\mathcal{L}_{g_m} \rightarrow \mathcal{L}_g \quad \text{in } L(W^{e+1,q}(TM), W^{e,q}(T^2 M))$$

*Proof.* In this proof we do not use the summation convention. Let  $\Lambda = \{(U_\alpha, \varphi_\alpha, \rho_\alpha)\}_{\alpha=1}^N$  and  $\tilde{\Lambda} = \{(U_\alpha, \varphi_\alpha, \tilde{\rho}_\alpha)\}_{\alpha=1}^N$  be standard total trivialization atlases for  $TM$  and  $T^2 M$ , respectively. Without loss of generality we may assume that each of  $\Lambda$  and  $\tilde{\Lambda}$  is super nice (or nice) and GL compatible with itself. Using Equation 11.1 and techniques discussed in Appendix I, one can show that under the hypotheses of the theorem,  $\mathcal{L}_{g_m}$  and  $\mathcal{L}_g$  indeed belong to  $L(W^{e+1,q}(TM), W^{e,q}(T^2 M))$ .

Let  $\{\psi_\alpha\}_{\alpha=1}^N$  be a partition of unity subordinate to the open cover  $\{U_\alpha\}_{\alpha=1}^N$ . Let  $\tilde{\psi}_\alpha = \frac{\psi_\alpha^2}{\sum_{\beta=1}^N \psi_\beta^2}$ . Note that  $\frac{1}{\sum_{\beta=1}^N \psi_\beta^2} \circ \varphi_\alpha^{-1} \in BC^\infty(\varphi_\alpha(U_\alpha))$ . We have

$$\| \mathcal{L}_{g_m} - \mathcal{L}_g \|_{op} = \sup_{\|X\|_{e+1,q} \neq 0, X \in C^\infty} \frac{\|(\mathcal{L}_{g_m} - \mathcal{L}_g)X\|_{e,q}}{\|X\|_{e+1,q}}$$

Note that

$$\|(\mathcal{L}_{g_m} - \mathcal{L}_g)X\|_{W^{e,q}(T^2M)} \simeq \sum_{\alpha=1}^N \sum_{i,j} \|\tilde{\psi}_\alpha((\mathcal{L}_{g_m} - \mathcal{L}_g)X)_{ij} \circ \varphi_\alpha^{-1}\|_{W^{e,q}(\varphi_\alpha(U_\alpha))}$$

By equation 11.1 we have

$$\begin{aligned} (\mathcal{L}_{g_m}X)_{ij} - (\mathcal{L}_gX)_{ij} &= \sum_l [(g_m)_{jl} - g_{jl}] \partial_i X^l + \sum_{k,l} [(g_m)_{jl}(\Gamma_{g_m})_{ik}^l - g_{jl}(\Gamma_g)_{ik}^l] X^k \\ &\quad + \sum_l [(g_m)_{il} - g_{il}] \partial_j X^l + \sum_{k,l} [(g_m)_{il}(\Gamma_{g_m})_{jk}^l - g_{il}(\Gamma_g)_{jk}^l] X^k - \frac{2}{n} [(\operatorname{div}_{g_m}X)(g_m)_{ij} - (\operatorname{div}_gX)g_{ij}] \end{aligned}$$

Therefore

$$\begin{aligned} \|(\mathcal{L}_{g_m} - \mathcal{L}_g)X\|_{W^{e,q}(T^2M)} &\preceq \\ &\sum_{\alpha=1}^N \sum_{i,j,k,l} \|\tilde{\psi}_\alpha[(g_m)_{jl} - g_{jl}] \partial_i X^l \circ \varphi_\alpha^{-1}\|_{e,q} \\ &\quad + \|\tilde{\psi}_\alpha[(g_m)_{jl}(\Gamma_{g_m})_{ik}^l - g_{jl}(\Gamma_g)_{ik}^l] X^k \circ \varphi_\alpha^{-1}\|_{e,q} \\ &\quad + \|\tilde{\psi}_\alpha[(g_m)_{il} - g_{il}] \partial_j X^l \circ \varphi_\alpha^{-1}\|_{e,q} + \|\tilde{\psi}_\alpha[(g_m)_{il}(\Gamma_{g_m})_{jk}^l - g_{il}(\Gamma_g)_{jk}^l] X^k \circ \varphi_\alpha^{-1}\|_{e,q} \\ &\quad + \frac{2}{n} \|\tilde{\psi}_\alpha[(\operatorname{div}_{g_m}X)(g_m)_{ij} - (\operatorname{div}_gX)g_{ij}] \circ \varphi_\alpha^{-1}\|_{e,q} \end{aligned}$$

Now we consider each summand separately:

(1)

$$\|\tilde{\psi}_\alpha[(g_m)_{jl} - g_{jl}] \partial_i X^l \circ \varphi_\alpha^{-1}\|_{e,q} \preceq \|\psi_\alpha[(g_m)_{jl} - g_{jl}] \circ \varphi_\alpha^{-1}\|_{s,p} \|\psi_\alpha \partial_i X^l \circ \varphi_\alpha^{-1}\|_{e,q}$$

Note that

$$\begin{aligned} \|\psi_\alpha \partial_i X^l \circ \varphi_\alpha^{-1}\|_{e,q} &= \|\psi_\alpha \frac{\partial}{\partial x^i} (X^l \circ \varphi_\alpha^{-1})\|_{e,q} \\ &\leq \|\frac{\partial}{\partial x^i} [(\psi_\alpha \circ \varphi_\alpha^{-1})(X^l \circ \varphi_\alpha^{-1})]\|_{e,q} + \|\frac{\partial}{\partial x^i} (\psi_\alpha \circ \varphi_\alpha^{-1})(X^l \circ \varphi_\alpha^{-1})\|_{e,q} \\ &\preceq \|\psi_\alpha X^l \circ \varphi_\alpha^{-1}\|_{e+1,q} + \|X\|_{e,q} \quad (\text{see Corollary H.18}) \\ &\preceq \|X\|_{e+1,q} \end{aligned}$$

Also

$$\|\psi_\alpha[(g_m)_{jl} - g_{jl}] \circ \varphi_\alpha^{-1}\|_{s,p} \preceq \|g_m - g\|_{s,p}$$

(2)

$$\begin{aligned} \|\tilde{\psi}_\alpha[(g_m)_{jl}(\Gamma_{g_m})_{ik}^l - g_{jl}(\Gamma_g)_{ik}^l] X^k \circ \varphi_\alpha^{-1}\|_{e,q} \\ \preceq \|\psi_\alpha[(g_m)_{jl}(\Gamma_{g_m})_{ik}^l - g_{jl}(\Gamma_g)_{ik}^l] \circ \varphi_\alpha^{-1}\|_{s-1,p} \|\psi_\alpha X^k \circ \varphi_\alpha^{-1}\|_{e+1,q} \\ \preceq \|\psi_\alpha[(g_m)_{jl}(\Gamma_{g_m})_{ik}^l - g_{jl}(\Gamma_g)_{ik}^l] \circ \varphi_\alpha^{-1}\|_{s-1,p} \|X\|_{e+1,q} \end{aligned}$$

(3)

$$\begin{aligned} \|\tilde{\psi}_\alpha[(g_m)_{il} - g_{il}] \partial_j X^l \circ \varphi_\alpha^{-1}\|_{e,q} &\preceq \|\psi_\alpha[(g_m)_{il} - g_{il}] \circ \varphi_\alpha^{-1}\|_{s,p} \|\psi_\alpha \partial_j X^l \circ \varphi_\alpha^{-1}\|_{e,q} \\ &\preceq \|g_m - g\|_{s,p} \|X\|_{e+1,q} \quad (\text{see the procedure in item (1)}) \end{aligned}$$

(4)

$$\begin{aligned}
& \|\tilde{\psi}_\alpha[(g_m)_{il}(\Gamma_{g_m})_{jk}^l - g_{il}(\Gamma_g)_{jk}^l]X^k \circ \varphi_\alpha^{-1}\|_{e,q} \\
& \leq \|\psi_\alpha[(g_m)_{il}(\Gamma_{g_m})_{jk}^l - g_{il}(\Gamma_g)_{jk}^l] \circ \varphi_\alpha^{-1}\|_{s-1,p} \|\psi_\alpha X^k \circ \varphi_\alpha^{-1}\|_{e+1,q} \\
& \leq \|\psi_\alpha[(g_m)_{il}(\Gamma_{g_m})_{jk}^l - g_{il}(\Gamma_g)_{jk}^l] \circ \varphi_\alpha^{-1}\|_{s-1,p} \|X\|_{e+1,q}
\end{aligned}$$

(5)

$$\begin{aligned}
& \|\tilde{\psi}_\alpha[(\operatorname{div}_{g_m} X)(g_m)_{ij} - (\operatorname{div}_g X)g_{ij}] \circ \varphi_\alpha^{-1}\|_{e,q} = \\
& \|\tilde{\psi}_\alpha[(\operatorname{div}_{g_m} X)(g_m)_{ij} - (\operatorname{div}_g X)(g_m)_{ij} + (\operatorname{div}_g X)(g_m)_{ij} - (\operatorname{div}_g X)g_{ij}] \circ \varphi_\alpha^{-1}\|_{e,q} \\
& \leq \|(\operatorname{div}_{g_m} X) - (\operatorname{div}_g X)\|_{e,q} \|\tilde{\psi}_\alpha(g_m)_{ij} \circ \varphi_\alpha^{-1}\|_{s,p} + \|\operatorname{div}_g X\|_{e,q} \|\tilde{\psi}_\alpha((g_m)_{ij} - g_{ij}) \circ \varphi_\alpha^{-1}\|_{s,p} \\
& \leq \|(\operatorname{div}_{g_m}) - (\operatorname{div}_g)\|_{op} \|X\|_{e+1,q} \|g_m\|_{s,p} + \|\operatorname{div}_g\|_{op} \|X\|_{e+1,q} \|g_m - g\|_{s,p}
\end{aligned}$$

Consequently we have

$$\begin{aligned}
\|\mathcal{L}_{g_m} - \mathcal{L}_g\|_{op} &= \sup_{\|X\|_{e+1,q} \neq 0, X \in C^\infty} \frac{\|(\mathcal{L}_{g_m} - \mathcal{L}_g)X\|_{e,q}}{\|X\|_{e+1,q}} \leq \sum_{\alpha=1}^N \sum_{i,j,k,l} (2 + \|\operatorname{div}_g\|_{op}) \|g_m - g\|_{s,p} \\
&+ \|\psi_\alpha[(g_m)_{jl}(\Gamma_{g_m})_{ik}^l - g_{jl}(\Gamma_g)_{ik}^l] \circ \varphi_\alpha^{-1}\|_{s-1,p} + \|\psi_\alpha[(g_m)_{il}(\Gamma_{g_m})_{jk}^l - g_{il}(\Gamma_g)_{jk}^l] \circ \varphi_\alpha^{-1}\|_{s-1,p} \\
&+ \|(\operatorname{div}_{g_m}) - (\operatorname{div}_g)\|_{op} \|g_m\|_{s,p}
\end{aligned}$$

Now note that

- According to Example 3 in Appendix I, under the hypotheses of this theorem,  $\operatorname{div}_g : W^{e+1,q}(TM) \rightarrow W^{e,q}(M)$  is a continuous linear operator. Therefore  $\|\operatorname{div}_g\|_{op}$  is a finite number.
- By assumption  $\|g_m - g\|_{s,p} \rightarrow 0$ .
- As a consequence of Theorem 3.3 we have

$$\begin{aligned}
(g_m)_{jl} \circ \varphi_\alpha^{-1} &\rightarrow g_{jl} \circ \varphi_\alpha^{-1} \quad \text{in } W_{loc}^{s,p}(\varphi_\alpha(U_\alpha)) \\
(\Gamma_{g_m})_{ik}^l \circ \varphi_\alpha^{-1} &\rightarrow (\Gamma_g)_{ik}^l \circ \varphi_\alpha^{-1} \quad \text{in } W_{loc}^{s-1,p}(\varphi_\alpha(U_\alpha))
\end{aligned}$$

Since  $W_{loc}^{s,p} \times W_{loc}^{s-1,p} \hookrightarrow W_{loc}^{s-1,p}$  we get

$$(g_m)_{jl}(\Gamma_{g_m})_{ik}^l \circ \varphi_\alpha^{-1} \rightarrow g_{jl}(\Gamma_g)_{ik}^l \circ \varphi_\alpha^{-1} \quad \text{in } W_{loc}^{s-1,p}(\varphi_\alpha(U_\alpha))$$

which implies that

$$\|\psi_\alpha[(g_m)_{jl}(\Gamma_{g_m})_{ik}^l - g_{jl}(\Gamma_g)_{ik}^l] \circ \varphi_\alpha^{-1}\|_{s-1,p} \rightarrow 0$$

Similarly

$$\|\psi_\alpha[(g_m)_{il}(\Gamma_{g_m})_{jk}^l - g_{il}(\Gamma_g)_{jk}^l] \circ \varphi_\alpha^{-1}\|_{s-1,p} \rightarrow 0$$

- It follows from Example 3 in Appendix I and Theorem 9.1 that

$$\operatorname{div}_{g_m} \rightarrow \operatorname{div}_g \quad \text{in } L(W^{e+1,q}(TM), W^{e,q}(M))$$

Also since  $g_m \rightarrow g$  in  $W^{s,p}(T^2M)$ ,  $\|g_m\|_{s,p}$  is bounded.

Thus  $\|\mathcal{L}_{g_m} - \mathcal{L}_g\|_{op} \rightarrow 0$  as  $m \rightarrow \infty$ . □

## 12. VECTOR LAPLACIAN WITH ROUGH METRIC

$\operatorname{div} \mathcal{L}$  is sometimes called *vector Laplacian* and is denoted by  $\Delta_L$ .



**Theorem 12.1.** *Let  $(M^n, g)$  be a compact Riemannian manifold. Let  $g \in W^{s,p}(T^2M)$  with  $sp > n$  and  $s \geq 1$ . Suppose  $e \in \mathbb{R}$  and  $q \in (1, \infty)$  are such that for balls  $\Omega \subseteq \mathbb{R}^n$  or for  $\Omega = \mathbb{R}^n$*

$$W^{s-1,p}(\Omega) \times W^{e+1,q}(\Omega) \hookrightarrow W^{e,q}(\Omega)$$

$$W^{s,p}(\Omega) \times W^{e,q}(\Omega) \hookrightarrow W^{e,q}(\Omega)$$

$$W^{s,p}(\Omega) \times W^{e+1,q}(\Omega) \hookrightarrow W^{e+1,q}(\Omega)$$

$$W^{s-1,p}(\Omega) \times W^{e,q}(\Omega) \hookrightarrow W^{e-1,q}(\Omega)$$

$$W^{s,p}(\Omega) \times W^{e-1,q}(\Omega) \hookrightarrow W^{e-1,q}(\Omega)$$

*In the case that the above multiplication properties hold only for balls  $\Omega \subseteq \mathbb{R}^n$  and not  $\mathbb{R}^n$  itself, further assume that  $e$  and  $q$  are such that  $\frac{\partial}{\partial x^j} : W^{e+1,q}(\Omega) \rightarrow W^{e,q}(\Omega)$  and  $\frac{\partial}{\partial x^j} : W^{e,q}(\Omega) \rightarrow W^{e-1,q}(\Omega)$  ( $1 \leq j \leq n$ ) are continuous.*

*Suppose  $\{g_m\}$  is a sequence of smooth ( $C^\infty$ ) metrics on  $M$  such that  $g_m \rightarrow g$  in  $W^{s,p}(T^2M)$ . Then*

$$(\Delta_L)_{g_m} \rightarrow (\Delta_L)_g \quad \text{in } L(W^{e+1,q}(TM), W^{e-1,q}(T^1M))$$

*Proof.* By Theorem 11.1

$$\mathcal{L}_{g_m} \rightarrow \mathcal{L}_g \quad \text{in } L(W^{e+1,q}(TM) \rightarrow W^{e,q}(T^2M))$$

Also by Theorem 9.3

$$\text{div}_{g_m} \rightarrow \text{div}_g \quad \text{in } L(W^{e,q}(T^2M) \rightarrow W^{e-1,q}(T^1M))$$

Therefore it follows from Theorem B.14 that

$$\text{div}_{g_m} \circ \mathcal{L}_{g_m} \rightarrow \text{div}_g \circ \mathcal{L}_g \quad \text{in } L(W^{e+1,q}(TM) \rightarrow W^{e-1,q}(T^1M))$$

□

### 13. CURVATURE WITH ROUGH METRIC

Let  $(M^n, g)$  be a Riemannian manifold. The **Riemannian curvature tensor** is the covariant 4-tensor field defined by

$$\text{Rm}(X, Y, Z, W) = g(\nabla_X \nabla_Y Z - \nabla_Y \nabla_X Z - \nabla_{[X,Y]} Z, W)$$

With respect to any local chart  $(U, \varphi)$  we have  $[\partial_i, \partial_j] = 0$  and

$$\begin{aligned} \nabla_i \nabla_j \partial_k &= \nabla_i (\Gamma_{jk}^r \partial_r) = \partial_i (\Gamma_{jk}^r) \partial_r + \Gamma_{jk}^r \Gamma_{ir}^l \partial_l \\ &= [\partial_i \Gamma_{jk}^p + \Gamma_{jk}^r \Gamma_{ir}^p] \partial_p \end{aligned}$$

Therefore by subtracting the same expression with  $i$  and  $j$  interchanged we get

$$\nabla_i \nabla_j \partial_k - \nabla_j \nabla_i \partial_k = [\partial_i \Gamma_{jk}^p - \partial_j \Gamma_{ik}^p + \Gamma_{jk}^r \Gamma_{ir}^p - \Gamma_{ik}^r \Gamma_{jr}^p] \partial_p$$

Subsequently

$$\begin{aligned} R_{ijkl} &= \text{Rm}(\partial_i, \partial_j, \partial_k, \partial_l) = g(\nabla_i \nabla_j \partial_k - \nabla_j \nabla_i \partial_k, \partial_l) \\ &= g_{pl} [\partial_i \Gamma_{jk}^p - \partial_j \Gamma_{ik}^p + \Gamma_{jk}^r \Gamma_{ir}^p - \Gamma_{ik}^r \Gamma_{jr}^p] \end{aligned}$$

The **Ricci tensor** is the covariant 2-tensor field defined by

$$\text{Ric} = \text{tr}(\text{sharp}_g \text{Rm})$$

where the trace is on the leftmost covariant component and the only contravariant component of  $\text{sharp}_g \text{Rm}$ . With respect to any local coordinate chart

$$\text{Ric}_{ij} := g^{km} R_{kijm}$$

The **scalar curvature**  $\text{Scal}$  is the function defined as the trace of the Ricci tensor

$$\text{Scal} := \text{tr}(\text{sharp}_g \text{Ric})$$

**Theorem 13.1.** *Let  $(M^n, g)$  be a compact Riemannian manifold. Let  $g \in W^{s,p}(T^2M)$  with  $sp > n$ ,  $s \geq 1$ , and  $n \geq 2$ . Then  $\text{Rm}$  belongs to  $W^{s-2,p}(T^4M)$ ,  $\text{Ric}$  belongs to  $W^{s-2,p}(T^2M)$ , and  $\text{Scal}$  belongs to  $W^{s-2,p}(M)$ .*

*Proof.* Let  $\{(U_\alpha, \varphi_\alpha)\}_{1 \leq \alpha \leq N}$  be an atlas for  $M$ . By Theorem H.15 it is enough to show that for each  $1 \leq \alpha \leq N$  and  $1 \leq i, j, k, l \leq n$

$$\text{Rm}_{ijkl} \circ \varphi_\alpha^{-1} \in W_{loc}^{s-2,p}(\varphi_\alpha(U_\alpha))$$

Recall that

$$\text{Rm}_{ijkl} \circ \varphi_\alpha^{-1} = g_{pl} [\partial_i \Gamma_{jk}^p - \partial_j \Gamma_{ik}^p + \Gamma_{jk}^r \Gamma_{ir}^p - \Gamma_{ik}^r \Gamma_{jr}^p] \circ \varphi_\alpha^{-1}$$

By Corollary H.19, Corollary H.22, and Theorem F.6 we have

$$g_{pl} \circ \varphi_\alpha^{-1} \in W_{loc}^{s,p}(\varphi_\alpha(U_\alpha)), \quad \partial_i \Gamma_{jk}^p \circ \varphi_\alpha^{-1}, \partial_j \Gamma_{ik}^p \circ \varphi_\alpha^{-1} \in W_{loc}^{s-2,p}(\varphi_\alpha(U_\alpha))$$

Also considering Lemma F.9, since  $W^{s-1,p} \times W^{s-1,p} \hookrightarrow W^{s-2,p}$ , we have

$$\Gamma_{jk}^r \Gamma_{ir}^p \circ \varphi_\alpha^{-1} \in W_{loc}^{s-2,p}(\varphi_\alpha(U_\alpha)), \quad \Gamma_{ik}^r \Gamma_{jr}^p \circ \varphi_\alpha^{-1} \in W_{loc}^{s-2,p}(\varphi_\alpha(U_\alpha))$$

Finally, since  $W^{s,p} \times W^{s-2,p} \hookrightarrow W^{s-2,p}$ ,

$$g_{pl} [\partial_i \Gamma_{jk}^p - \partial_j \Gamma_{ik}^p + \Gamma_{jk}^r \Gamma_{ir}^p - \Gamma_{ik}^r \Gamma_{jr}^p] \circ \varphi_\alpha^{-1} \in W_{loc}^{s-2,p}(\varphi_\alpha(U_\alpha))$$

So  $\text{Rm} \in W^{s-2,p}(T^4M)$ .

Since  $W^{s,p} \times W^{s-2,p} \hookrightarrow W^{s-2,p}$ , it follows from Theorem 4.3 that  $\text{sharp}_g : W^{s-2,p}(T^4M) \rightarrow W^{s-2,p}(T_1^3M)$  is well defined and continuous. Also by Theorem 8.1,  $\text{tr} : W^{s-2,p}(T_1^3M) \rightarrow W^{s-2,p}(T^2M)$  is well defined and continuous. Therefore  $\text{Ric} = \text{tr}(\text{sharp}_g \text{Rm})$  belongs to  $W^{s-2,p}(T^2M)$ .

The same argument shows that  $\text{Scal} := \text{tr}(\text{sharp}_g \text{Ric})$  must belong to  $W^{s-2,p}(M)$ .  $\square$

**Theorem 13.2.** *Let  $(M^n, g)$  be a compact Riemannian manifold. Let  $g \in W^{s,p}(T^2M)$  with  $sp > n$ ,  $s \geq 1$ , and  $n \geq 2$ . Suppose  $\{g_m\}$  is a sequence of smooth ( $C^\infty$ ) metrics on  $M$  such that  $g_m \rightarrow g$  in  $W^{s,p}(T^2M)$ . Then*

$$\text{Rm}_{g_m} \rightarrow \text{Rm}_g \quad \text{in } W^{s-2,p}(T^4M)$$

*Proof.* In this proof we will not use the summation convention. Let  $\{(U_\alpha, \varphi_\alpha)\}_{1 \leq \alpha \leq N}$  be a super nice atlas for  $M$  that is GL compatible with itself and  $\{\psi_\alpha\}$  be a subordinate partition of unity. We have

$$\begin{aligned} \|\text{Rm}_{g_m} - \text{Rm}_g\|_{s-2,p} &\simeq \sum_{\alpha=1}^N \sum_{i,j,k,l} \|\psi_\alpha(\text{Rm}_{g_m} - \text{Rm}_g)_{ijkl} \circ \varphi_\alpha^{-1}\|_{W^{s-2,p}(\varphi_\alpha(U_\alpha))} \\ &\leq \sum_{\alpha=1}^N \sum_{i,j,k,l,p,r} \|\psi_\alpha((g_m)_{pl} \partial_i (\Gamma_{g_m})_{jk}^p - g_{pl} \partial_i (\Gamma_g)_{jk}^p) \circ \varphi_\alpha^{-1}\|_{W^{s-2,p}(\varphi_\alpha(U_\alpha))} \\ &\quad + \|\psi_\alpha((g_m)_{pl} \partial_j (\Gamma_{g_m})_{ik}^p - g_{pl} \partial_j (\Gamma_g)_{ik}^p) \circ \varphi_\alpha^{-1}\|_{W^{s-2,p}(\varphi_\alpha(U_\alpha))} \\ &\quad + \|\psi_\alpha((\Gamma_{g_m})_{jk}^r (\Gamma_{g_m})_{ir}^p - \Gamma_{jk}^r \Gamma_{ir}^p) \circ \varphi_\alpha^{-1}\|_{W^{s-2,p}(\varphi_\alpha(U_\alpha))} \\ &\quad + \|\psi_\alpha((\Gamma_{g_m})_{ik}^r (\Gamma_{g_m})_{jr}^p - \Gamma_{ik}^r \Gamma_{jr}^p) \circ \varphi_\alpha^{-1}\|_{W^{s-2,p}(\varphi_\alpha(U_\alpha))} \end{aligned}$$

We consider each term separately:

- (1) By Theorem 3.3  $(\Gamma_{g_m})_{jk}^p \circ \varphi_\alpha^{-1} \rightarrow (\Gamma_g)_{jk}^p \circ \varphi_\alpha^{-1}$  in  $W_{loc}^{s-1,p}$  and  $(g_m)_{pl} \circ \varphi_\alpha^{-1} \rightarrow g_{pl} \circ \varphi_\alpha^{-1}$  in  $W_{loc}^{s,p}$ . It follows from Theorem F.6 that  $\partial_i(\Gamma_{g_m})_{jk}^p \circ \varphi_\alpha^{-1} \rightarrow \partial_i(\Gamma_g)_{jk}^p \circ \varphi_\alpha^{-1}$  in  $W_{loc}^{s-2,p}$  and subsequently since  $W^{s,p} \times W^{s-2,p} \hookrightarrow W^{s-2,p}$  we get

$$(g_m)_{pl} \partial_i(\Gamma_{g_m})_{jk}^p \circ \varphi_\alpha^{-1} \rightarrow g_{pl} \partial_i(\Gamma_g)_{jk}^p \circ \varphi_\alpha^{-1} \quad \text{in } W_{loc}^{s-2,p}(\varphi_\alpha(U_\alpha))$$

Therefore

$$\|\psi_\alpha((g_m)_{pl} \partial_i(\Gamma_{g_m})_{jk}^p - g_{pl} \partial_i(\Gamma_g)_{jk}^p) \circ \varphi_\alpha^{-1}\|_{W^{s-2,p}(\varphi_\alpha(U_\alpha))} \rightarrow 0 \quad \text{as } m \rightarrow \infty$$

- (2) Interchanging the roles of  $i$  and  $j$  in the above argument shows that

$$\|\psi_\alpha((g_m)_{pl} \partial_j(\Gamma_{g_m})_{ik}^p - g_{pl} \partial_j(\Gamma_g)_{ik}^p) \circ \varphi_\alpha^{-1}\|_{W^{s-2,p}(\varphi_\alpha(U_\alpha))} \rightarrow 0 \quad \text{as } m \rightarrow \infty$$

- (3) By Theorem 3.3

$$(\Gamma_{g_m})_{jk}^r \circ \varphi_\alpha^{-1} \rightarrow (\Gamma_g)_{jk}^r \circ \varphi_\alpha^{-1}, \quad (\Gamma_{g_m})_{ir}^p \circ \varphi_\alpha^{-1} \rightarrow (\Gamma_g)_{ir}^p \circ \varphi_\alpha^{-1} \quad \text{in } W_{loc}^{s-1,p}$$

Since  $W^{s-1,p} \times W^{s-1,p} \hookrightarrow W^{s-2,p}$  we obtain

$$(\Gamma_{g_m})_{jk}^r (\Gamma_{g_m})_{ir}^p \circ \varphi_\alpha^{-1} \rightarrow (\Gamma_g)_{jk}^r (\Gamma_g)_{ir}^p \circ \varphi_\alpha^{-1} \quad \text{in } W_{loc}^{s-2,p}$$

Therefore

$$\|\psi_\alpha((\Gamma_{g_m})_{jk}^r (\Gamma_{g_m})_{ir}^p - \Gamma_{jk}^r \Gamma_{ir}^p) \circ \varphi_\alpha^{-1}\|_{W^{s-2,p}(\varphi_\alpha(U_\alpha))} \rightarrow 0 \quad \text{as } m \rightarrow \infty$$

- (4) Interchanging the roles of  $i$  and  $j$  in the above argument shows that

$$\|\psi_\alpha((\Gamma_{g_m})_{ik}^r (\Gamma_{g_m})_{jr}^p - \Gamma_{ik}^r \Gamma_{jr}^p) \circ \varphi_\alpha^{-1}\|_{W^{s-2,p}(\varphi_\alpha(U_\alpha))} \rightarrow 0 \quad \text{as } m \rightarrow \infty$$

Hence

$$\|\mathbf{Rm}_{g_m} - \mathbf{Rm}_g\|_{s-2,p} \rightarrow 0$$

□

**Theorem 13.3.** *Let  $(M^n, g)$  be a compact Riemannian manifold. Let  $g \in W^{s,p}(T^2M)$  with  $sp > n$ ,  $s \geq 1$ , and  $n \geq 2$ . Suppose  $\{g_m\}$  is a sequence of smooth  $(C^\infty)$  metrics on  $M$  such that  $g_m \rightarrow g$  in  $W^{s,p}(T^2M)$ . Then*

$$\mathbf{Ric}_{g_m} \rightarrow \mathbf{Ric}_g \quad \text{in } W^{s-2,p}(T^2M)$$

*Proof.* By Theorem 13.2,  $\mathbf{Rm}_{g_m} \rightarrow \mathbf{Rm}_g$  in  $W^{s-2,p}(T^4M)$ . Also it follows from the hypotheses of the theorem that  $W^{s,p} \times W^{s-2,p} \rightarrow W^{s-2,p}$ . Thus by Theorem 4.4

$$\text{sharp}_{g_m} \rightarrow \text{sharp}_g \quad \text{in } L(W^{s-2,p}(T^4M), W^{s-2,p}(T_1^3M))$$

Consequently

$$\text{sharp}_{g_m}(\mathbf{Rm}_{g_m}) \rightarrow \text{sharp}_g(\mathbf{Rm}_g) \quad \text{in } W^{s-2,p}(T_1^3M)$$

Now it follows from Theorem 8.1 that

$$\text{tr sharp}_{g_m}(\mathbf{Rm}_{g_m}) \rightarrow \text{tr sharp}_g(\mathbf{Rm}_g) \quad \text{in } W^{s-2,p}(T^2M)$$

That is

$$\mathbf{Ric}_{g_m} \rightarrow \mathbf{Ric}_g \quad \text{in } W^{s-2,p}(T^2M)$$

□

**Theorem 13.4.** *Let  $(M^n, g)$  be a compact Riemannian manifold. Let  $g \in W^{s,p}(T^2M)$  with  $sp > n$ ,  $s \geq 1$ , and  $n \geq 2$ . Suppose  $\{g_m\}$  is a sequence of smooth  $(C^\infty)$  metrics on  $M$  such that  $g_m \rightarrow g$  in  $W^{s,p}(T^2M)$ . Then*

$$\mathbf{Scal}_{g_m} \rightarrow \mathbf{Scal}_g \quad \text{in } W^{s-2,p}(M)$$

*Proof.* By Theorem 13.3,  $\text{Ric}_{g_m} \rightarrow \text{Ric}_g$  in  $W^{s-2,p}(T^2M)$ . Also it follows from the hypotheses of the theorem that  $W^{s,p} \times W^{s-2,p} \rightarrow W^{s-2,p}$ . Thus by Theorem 4.4

$$\text{sharp}_{g_m} \rightarrow \text{sharp}_g \quad \text{in } L(W^{s-2,p}(T^2M), W^{s-2,p}(T_1^1M))$$

Consequently

$$\text{sharp}_{g_m}(\text{Ric}_{g_m}) \rightarrow \text{sharp}_g(\text{Ric}_g) \quad \text{in } W^{s-2,p}(T_1^1M)$$

Now it follows from Theorem 8.1 that

$$\text{tr sharp}_{g_m}(\text{Rm}_{g_m}) \rightarrow \text{tr sharp}_g(\text{Rm}_g) \quad \text{in } W^{s-2,p}(M)$$

That is

$$\text{Scal}_{g_m} \rightarrow \text{Scal}_g \quad \text{in } W^{s-2,p}(M)$$

□

#### ACKNOWLEDGMENTS

MH was supported in part by NSF Awards 1262982, 1318480, and 1620366. AB was supported by NSF Award 1262982.

#### APPENDIX A. REVIEW OF SOME RESULTS FROM LINEAR ALGEBRA

In this appendix we summarize a collection of definitions and results from linear algebra that play an important role in our study of function spaces and differential operators on manifolds.

There are several ways to construct new vector spaces from old ones: subspaces, products, direct sums, quotients, etc. The ones that are particularly important for the study of Sobolev spaces of sections of vector bundles are the vector space of linear maps between two given vector spaces, the tensor product of vector spaces, and the vector space of all densities on a given vector space which we briefly review here in order to set the notations straight.

- Let  $V$  and  $W$  be two vector spaces. The collection of all linear maps from  $V$  to  $W$  is a new vector space which we denote by  $\text{Hom}(V, W)$ . In particular,  $\text{Hom}(V, \mathbb{R})$  is the (algebraic) dual of  $V$ . If  $V$  and  $W$  are finite-dimensional, then  $\text{Hom}(V, W)$  is a vector space whose dimension is equal to the product of dimensions of  $V$  and  $W$ . Indeed, if we choose a basis for  $V$  and a basis for  $W$ , then  $\text{Hom}(V, W)$  is isomorphic with the space of matrices with  $\dim W$  rows and  $\dim V$  columns.
- Let  $U$ ,  $V$ , and  $W$  be 3 vector spaces. Roughly speaking, the tensor product of  $U$  and  $V$  (denoted by  $U \otimes V$ ) is the unique vector space (up to isomorphism of vector spaces) such that  $\text{Hom}(U \otimes V, W)$  is isomorphic to the collection of bilinear maps from  $U \times V$  to  $W$ . Informally  $U \otimes V$  consists of finite linear combinations of symbols  $u \otimes v$ , where  $u \in U$  and  $v \in V$ . It is assumed that these symbols satisfy the following identities:

$$\begin{aligned} (u_1 + u_2) \otimes v - u_1 \otimes v - u_2 \otimes v &= 0 \\ u \otimes (v_1 + v_2) - u \otimes v_1 - u \otimes v_2 &= 0 \\ \alpha(u \otimes v) - (\alpha u) \otimes v &= 0 \\ \alpha(u \otimes v) - u \otimes (\alpha v) &= 0 \end{aligned}$$

for all  $u, u_1, u_2 \in U$ ,  $v, v_1, v_2 \in V$  and  $\alpha \in \mathbb{R}$ . These identities simply say that the map

$$\otimes : U \times V \rightarrow U \otimes V, \quad (u, v) \mapsto u \otimes v$$

is a bilinear map. The image of this map spans  $U \otimes V$ .

**Definition A.1.** Let  $U$  and  $V$  be two vector spaces. Tensor product is a vector space  $U \otimes V$  together with a bilinear map  $\otimes : U \times V \rightarrow U \otimes V$ ,  $(u, v) \mapsto u \otimes v$  such that given any bilinear map  $b : U \times V \rightarrow W$ , there is a unique linear map  $\bar{b} : U \otimes V \rightarrow W$  with  $\bar{b}(u \otimes v) = b(u, v)$ . That is the following diagram commutes:

$$\begin{array}{ccc} U \otimes V & & \\ \uparrow \otimes & \searrow b & \\ U \times V & \xrightarrow{b} & W \end{array}$$

The most useful property of tensor products for us is the following property:

$$\text{Hom}(V, W) \cong V^* \otimes W$$

Indeed, the following map is an isomorphism of vector spaces:

$$F : V^* \otimes W \rightarrow \text{Hom}(V, W), \quad \underbrace{F(v^* \otimes w)}_{\text{an element of } \text{Hom}(V, W)}(v) = \underbrace{[v^*(v)]}_{\text{a real number}} w$$

It is useful to obtain an expression for the inverse of  $F$  too. That is, given  $T \in \text{Hom}(V, W)$ , we want to find an expression for the corresponding element of  $V^* \otimes W$ . To this end, let  $\{e_i\}_{1 \leq i \leq n}$  be a basis for  $V$  and  $\{e^i\}_{1 \leq i \leq n}$  denote the corresponding dual basis. Let  $\{s_a\}_{1 \leq a \leq r}$  be a basis for  $W$ . Then  $\{e^i \otimes s_a\}$  is a basis for  $V^* \otimes W$ . Suppose  $\sum_{i,a} R_i^a e^i \otimes s_a$  is the element of  $V^* \otimes W$  that corresponds to  $T$ . We have

$$\begin{aligned} F\left(\sum_{i,a} R_i^a e^i \otimes s_a\right) = T &\implies \forall u \in V \quad \sum_{i,a} R_i^a F[e^i \otimes s_a](u) = T(u) \\ &\implies \forall u \in V \quad \sum_{i,a} R_i^a e^i(u) s_a = T(u) \end{aligned}$$

In particular, for all  $1 \leq j \leq n$

$$T(e_j) = \sum_{i,a} R_i^a \underbrace{e^i(e_j)}_{\delta_j^i} s_a = \sum_a R_j^a s_a$$

That is,  $R_i^a$  is the entry in the  $a^{\text{th}}$  row and  $i^{\text{th}}$  column of the matrix of the linear transformation  $T$ .

- Let  $V$  be an  $n$ -dimensional vector space. A density on  $V$  is a function  $\mu : \underbrace{V \times \cdots \times V}_{n \text{ copies}} \rightarrow \mathbb{R}$  with the property that

$$\mu(Tv_1, \cdots, Tv_n) = |\det T| \mu(v_1, \cdots, v_n)$$

for all  $T \in \text{Hom}(V, V)$ .

We denote the collection of all densities on  $V$  by  $\mathcal{D}(V)$ . It can be shown that  $\mathcal{D}(V)$  is a one dimensional vector space under the obvious vector space operations. Indeed, if  $(e_1, \cdots, e_n)$  is a basis for  $V$ , then each element  $\mu \in \mathcal{D}(V)$  is uniquely determined by its value at  $(e_1, \cdots, e_n)$  because for any  $(v_1, \cdots, v_n) \in V^{\times n}$ , we have  $\mu(v_1, \cdots, v_n) = |\det T| \mu(e_1, \cdots, e_n)$  where  $T : V \rightarrow V$  is the linear transformation defined by  $T(e_i) = v_i$  for all  $1 \leq i \leq n$ . Thus

$$F : \mathcal{D}(V) \rightarrow \mathbb{R}, \quad F(\mu) = \mu(e_1, \cdots, e_n)$$

will be an isomorphism of vector spaces.

Moreover, if  $\omega \in \Lambda^n(V)$  where  $\Lambda^n(V)$  is the collection of all alternating covariant  $n$ -tensors, then  $|\omega|$  belongs to  $\mathcal{D}(V)$ . Thus if  $\omega$  is any nonzero element of  $\Lambda^n(V)$ , then  $\{|\omega|\}$  will be a basis for  $\mathcal{D}(V)$  ([33], Page 428).

**Theorem A.2** (Riesz Representation Theorem for Finite Inner Product Spaces). *Let  $(V, \langle \cdot, \cdot \rangle)$  be a finite dimensional (real) inner product space and let  $L : V \rightarrow \mathbb{R}$  be a linear function. Then there exists  $z \in V$  such that*

$$\forall y \in V \quad L(y) = \langle z, y \rangle$$

**Theorem A.3.** *Let  $(V, \langle \cdot, \cdot \rangle)$  be a finite dimensional (real) inner product space. If  $B : V \times V \rightarrow \mathbb{R}$  is a bilinear form, then there exists a unique linear transformation  $T : V \rightarrow V$  such that*

$$\forall x, y \in V \quad B(x, y) = \langle T(x), y \rangle$$

*Moreover if  $B$  is positive definite, then  $T$  is bijective. (Recall that a symmetric bilinear form  $B$  is called positive definite if  $B(x, x) > 0$  for all nonzero  $x$ .)*

## APPENDIX B. REVIEW OF SOME RESULTS FROM ANALYSIS AND TOPOLOGY

### B.1. Euclidean Space.

**Theorem B.1** (Exhaustion by Compact Sets). [23] *Let  $\Omega$  be a nonempty open subset of  $\mathbb{R}^n$ . There exists a sequence of compact subsets  $(K_j)_{j \in \mathbb{N}}$  such that  $\bigcup_{j \in \mathbb{N}} \overset{\circ}{K}_j = \Omega$  and*

$$K_1 \subseteq \overset{\circ}{K}_2 \subseteq K_2 \subseteq \cdots \subseteq \overset{\circ}{K}_j \subseteq K_j \subseteq \cdots$$

*Moreover, as a direct consequence, if  $K$  is any compact subset of the open set  $\Omega$ , then there exists an open set  $V$  such that  $K \subseteq V \subseteq \bar{V} \subseteq \Omega$ .*

**Theorem B.2.** [23] *Let  $\Omega$  be a nonempty open subset of  $\mathbb{R}^n$ . Let  $\{K_j\}_{j \in \mathbb{N}}$  be an exhaustion of  $\Omega$  by compact sets. Define*

$$V_0 = \overset{\circ}{K}_4, \quad \forall j \in \mathbb{N} \quad V_j = \overset{\circ}{K}_{j+4} \setminus K_j$$

*Then*

- (1) *Each  $V_j$  is an open bounded set and  $\Omega = \bigcup_j V_j$ .*
- (2) *The cover  $\{V_j\}_{j \in \mathbb{N}_0}$  is **locally finite** in  $\Omega$ , that is, each compact subset of  $\Omega$  has nonempty intersection with only a finite number of the  $V_j$ 's.*
- (3) *There is a family of functions  $\psi_j \in C_c^\infty(\Omega)$  taking values in  $[0, 1]$  such that  $\text{supp } \psi_j \subseteq V_j$  and*

$$\sum_{j \in \mathbb{N}_0} \psi_j(x) = 1 \quad \text{for all } x \in \Omega$$

Let  $\Omega$  be a non empty open set in  $\mathbb{R}^n$  and  $m \in \mathbb{N}_0$ . Here is a list of several useful function spaces on  $\Omega$ :

$$C(\Omega) = \{f : \Omega \rightarrow \mathbb{R} : f \text{ is continuous}\}$$

$$C^m(\Omega) = \{f : \Omega \rightarrow \mathbb{R} : \forall |\alpha| \leq m \quad \partial^\alpha f \in C(\Omega)\} \quad (C^0(\Omega) = C(\Omega))$$

$$BC(\Omega) = \{f : \Omega \rightarrow \mathbb{R} : f \text{ is continuous and bounded on } \Omega\}$$

$$BC^m(\Omega) = \{f \in C^m(\Omega) : \forall |\alpha| \leq m \quad \partial^\alpha f \text{ is bounded on } \Omega\}$$

$$BC(\bar{\Omega}) = \{f : \Omega \rightarrow \mathbb{R} : f \in BC(\Omega) \text{ and } f \text{ is **uniformly continuous** on } \Omega\}$$

$$BC^m(\bar{\Omega}) = \{f : \Omega \rightarrow \mathbb{R} : f \in BC^m(\Omega), \forall |\alpha| \leq m \quad \partial^\alpha f \text{ is uniformly continuous on } \Omega\}$$

$$C^\infty(\Omega) = \bigcap_{m \in \mathbb{N}_0} C^m(\Omega), \quad BC^\infty(\Omega) = \bigcap_{m \in \mathbb{N}_0} BC^m(\Omega), \quad BC^\infty(\bar{\Omega}) = \bigcap_{m \in \mathbb{N}_0} BC^m(\bar{\Omega})$$

**Remark B.3.** [2] *If  $g : \Omega \rightarrow \mathbb{R}$  is in  $BC(\bar{\Omega})$ , then it possesses a unique, bounded, continuous extension to the closure  $\bar{\Omega}$  of  $\Omega$ .*

**Notation :** Let  $\Omega$  be a nonempty open set in  $\mathbb{R}^n$ . The collection of all compact sets in  $\Omega$  is denoted by  $\mathcal{K}(\Omega)$ .

**Remark B.4.** *If  $\mathcal{F}(\Omega)$  is any function space on  $\Omega$  and  $K \in \mathcal{K}(\Omega)$ , then  $\mathcal{F}_K(\Omega)$  denotes the collection of elements in  $\mathcal{F}(\Omega)$  whose support is inside  $K$ . Also*

$$\mathcal{F}_c(\Omega) = \mathcal{F}_{comp}(\Omega) = \bigcup_{K \in \mathcal{K}(\Omega)} \mathcal{F}_K(\Omega)$$

Let  $0 < \lambda \leq 1$ . A function  $F : \Omega \subseteq \mathbb{R}^n \rightarrow \mathbb{R}^k$  is called  **$\lambda$ -Holder continuous** if there exists a constant  $L$  such that

$$|F(x) - F(y)| \leq L|x - y|^\lambda \quad \forall x, y \in \Omega$$

Clearly a  $\lambda$ -Holder continuous function on  $\Omega$  is uniformly continuous on  $\Omega$ . 1-Holder continuous functions are also called **Lipschitz continuous** functions or simply Lipschitz functions. We define

$$\begin{aligned} BC^{m,\lambda}(\Omega) &= \{f : \Omega \rightarrow \mathbb{R} : \forall |\alpha| \leq m \quad \partial^\alpha f \text{ is } \lambda\text{-Holder continuous and bounded}\} \\ &= \{f \in BC^m(\Omega) : \forall |\alpha| \leq m \quad \partial^\alpha f \text{ is } \lambda\text{-Holder continuous}\} \\ &= \{f \in BC^m(\bar{\Omega}) : \forall |\alpha| \leq m \quad \partial^\alpha f \text{ is } \lambda\text{-Holder continuous}\} \end{aligned}$$

and

$$BC^{\infty,\lambda}(\Omega) := \bigcap_{m \in \mathbb{N}_0} BC^{m,\lambda}(\Omega)$$

**Remark B.5.** *Let  $F : \Omega \subseteq \mathbb{R}^n \rightarrow \mathbb{R}^k$  ( $F = (F^1, \dots, F^k)$ ). Then*

$$F \text{ is Lipschitz} \iff \forall 1 \leq i \leq k \quad F^i \text{ is Lipschitz}$$

*Indeed, for each  $i$*

$$|F^i(x) - F^i(y)| \leq \sqrt{\sum_{j=1}^k |F^j(x) - F^j(y)|^2} = |F(x) - F(y)| \leq L|x - y|$$

*which shows that if  $F$  is Lipschitz so will be its components. Also if for each  $i$ , there exists  $L_i$  such that*

$$|F^i(x) - F^i(y)| \leq L_i|x - y|$$

Then

$$\sum_{j=1}^k |F^j(x) - F^j(y)|^2 \leq nL^2|x - y|^2$$

where  $L = \max\{L_1, \dots, L_k\}$ . This proves that if each component of  $F$  is Lipschitz so is  $F$  itself.

**Theorem B.6.** [23]

(1) There exists a function  $h \in C_c^\infty(\mathbb{R}^n)$  such that

$$h \geq 0, \quad \int_{\mathbb{R}^n} h(x)dx = 1, \quad \text{supph} \subseteq \bar{B}(0, 1)$$

Moreover, if for all  $j \in \mathbb{N}$  we let  $h_j(x) := j^n h(jx)$ , then for each  $j$

$$h_j \in C_c^\infty(\mathbb{R}^n), \quad h_j \geq 0, \quad \int_{\mathbb{R}^n} h_j(x)dx = 1, \quad \text{supph}_j \subseteq \bar{B}(0, \frac{1}{j})$$

(2) There exists a function  $\chi \in C_c^\infty(\mathbb{R}^n)$  such that  $0 \leq \chi(x) \leq 1$  for all  $x \in \mathbb{R}^n$  and

$$\chi(x) = \begin{cases} 1 & \text{if } |x| \leq 1 \\ 0 & \text{if } |x| \geq 2 \end{cases}$$

Moreover, if for all  $j \in \mathbb{N}$  we let  $\chi_j(x) := \chi(\frac{x}{j})$ , then for each  $j$ ,  $0 \leq \chi_j(x) \leq 1$  for all  $x \in \mathbb{R}^n$  and

$$\chi_j(x) = \begin{cases} 1 & \text{if } |x| \leq j \\ 0 & \text{if } |x| \geq 2j \end{cases}$$

Also since for any multi-index  $\alpha$ ,  $\partial^\alpha \chi_j(x) = j^{-|\alpha|}(\partial^\alpha \chi)(\frac{x}{j})$  we have

$$\forall j \quad \sup_{x \in \mathbb{R}^n} |\partial^\alpha \chi_j(x)| \leq C_{|\alpha|}$$

where  $C_{|\alpha|} = \sup_{x \in \mathbb{R}^n, |\beta| \leq |\alpha|} |\partial^\beta \chi(x)|$ .

**Theorem B.7.** ([1], Page 15) Let  $A \subseteq \mathbb{R}^n$  be a nonempty (Lebesgue) measurable set and  $f \in L^1(A)$ . Then for all measurable sets  $B$  contained in  $A$  we have  $f \in L^1(B)$ . Moreover, if  $f(x) \geq 0$  for all  $x \in A$ , then  $\int_B f(x)dx \leq \int_A f(x)dx$ .

**Theorem B.8** ([18], Page 74). Suppose  $\Omega$  is an open set in  $\mathbb{R}^n$  and  $G : \Omega \rightarrow G(\Omega) \subseteq \mathbb{R}^n$  is a  $C^1$ -diffeomorphism. If  $f$  is a Lebesgue measurable function on  $G(\Omega)$ , then  $f \circ G$  is Lebesgue measurable on  $\Omega$ . If  $f \geq 0$  or  $f \in L^1(G(\Omega))$ , then

$$\int_{G(\Omega)} f(x)dx = \int_{\Omega} f \circ G(x) |\det G'(x)| dx$$

**Theorem B.9** ([18], Page 79). If  $f$  is a nonnegative measurable function on  $\mathbb{R}^n$  such that  $f(x) = g(|x|)$  for some function  $g$  on  $(0, \infty)$ , then

$$\int f(x)dx = \sigma(S^{n-1}) \int_0^\infty g(r)r^{n-1} dr$$

where  $\sigma(S^{n-1})$  is the surface area of  $(n-1)$ -sphere.

**Theorem B.10.** ([4], Section 12.11) Suppose  $U$  is an open set in  $\mathbb{R}^n$  and  $f : U \rightarrow \mathbb{R}$  is differentiable. Let  $x$  and  $y$  be two points in  $U$  and suppose the line segment joining  $x$  and  $y$  is contained in  $U$ . Then there exists a point  $z$  on the line joining  $x$  to  $y$  such that

$$f(y) - f(x) = \nabla f(z) \cdot (y - x)$$



As a consequence, if  $U$  is **convex** and all first order partial derivatives of  $f$  are bounded, then  $f$  is Lipschitz on  $U$ .

**Warning:** Suppose  $f \in BC^\infty(U)$ . By the above item, if  $U$  is convex, then  $f$  is Lipschitz. However, if  $U$  is not convex, then  $f$  is not necessarily Lipschitz. For example, let  $U = \cup_{n=0}^\infty (n, n+1)$  and define

$$f : U \rightarrow \mathbb{R}, \quad f(x) = (-1)^n, \quad \forall x \in (n, n+1)$$

Clearly all derivatives of  $U$  are equal to zero, so  $f \in BC^\infty(U)$ . But  $f$  is not uniformly continuous and thus it is not Lipschitz. Indeed, for any  $1 > \delta > 0$ , we can let  $x = 2 - \delta/4$  and  $y = 2 + \delta/4$ . Clearly  $|x - y| < \delta$ , however,  $|f(x) - f(y)| = 2$ .

Of course if  $f \in C_c^\infty(U)$ , then  $f$  can be extended by zero to a function in  $C_c^\infty(\mathbb{R}^n)$ . Since  $\mathbb{R}^n$  is convex, we may conclude that the extension by zero of  $f$  is Lipschitz which implies that  $f : U \rightarrow \mathbb{R}$  is Lipschitz. So  $C_c^\infty(U) \subseteq BC^{\infty,1}(U)$ . Also we have the following theorem.

**Theorem B.11.** *Let  $U \subseteq \mathbb{R}^n$  and  $V \subseteq \mathbb{R}^k$  be two nonempty open sets and let  $T : U \rightarrow V$  ( $T = (T^1, \dots, T^k)$ ) be a  $C^1$  map (that is for each  $1 \leq i \leq k$ ,  $T^i \in C^1(U)$ ). Suppose  $B \subseteq U$  is a bounded set such that  $B \subseteq \bar{B} \subseteq U$ . Then  $T : B \rightarrow V$  is Lipschitz.*

*Proof.* By Remark B.5 it is enough to show that each  $T^i$  is Lipschitz on  $B$ . Fix a function  $\varphi \in C_c^\infty(\mathbb{R}^n)$  such that  $\varphi = 1$  on  $\bar{B}$  and  $\varphi = 0$  on  $\mathbb{R}^n \setminus U$ . Then  $\varphi T^i$  can be viewed as an element of  $C_c^\infty(\mathbb{R}^n)$ . Therefore it is Lipschitz ( $\mathbb{R}^n$  is convex) and there exists a constant  $L$ , which may depend on  $\varphi$ ,  $B$  and  $T^i$ , such that

$$|\varphi T^i(x) - \varphi T^i(y)| \leq L|x - y| \quad \forall x, y \in \mathbb{R}^n$$

Since  $\varphi = 1$  on  $\bar{B}$  we have it follows that

$$|T^i(x) - T^i(y)| \leq L|x - y| \quad \forall x, y \in B$$

□

## B.2. Normed Spaces.

**Theorem B.12.** ([13], Page 154) *Let  $B : V \times V \rightarrow \mathbb{R}$  be a bilinear form on a normed space  $V$  and let  $Q$  be the associated quadratic form ( $Q(x) = B(x, x)$ ). If  $B$  is symmetric and bounded, then  $\|B\| = \|Q\|$ , that is*

$$\sup \{|B(x, y)| : \|x\| = \|y\| = 1\} = \sup \{|B(x, x)| : \|x\| = 1\}$$

**Theorem B.13.** ([13], Page 155) *Let  $A$  be a bounded linear operator on a Hilbert space  $H$ . Then the bilinear functional defined by  $B(x, y) = \langle Ax, y \rangle$  is bounded and  $\|A\| = \|\varphi\|$ .*

**Theorem B.14.** *Let  $X, Y$ , and  $Z$  be normed spaces. Suppose  $A_n \rightarrow A$  in  $L(X, Y)$  and  $B_n \rightarrow B$  in  $L(Y, Z)$ . Then*

$$B_n \circ A_n \rightarrow B \circ A \quad \text{in } L(X, Z)$$

*In particular, if  $A_n \rightarrow A$  in  $L(X, Y)$  and  $B \in L(Y, Z)$ , then  $B \circ A_n \rightarrow B \circ A$ .*

**Theorem B.15.** *Let  $X$  and  $Y$  be normed spaces. Let  $A$  be a dense subspace of  $X$  and  $B$  be a dense subspace of  $Y$ . Then*

- $A \times B$  is dense in  $X \times Y$ ;

- if  $T : A \times B \rightarrow \mathbb{R}$  is a continuous bilinear map, then  $T$  has a unique extension to a continuous bilinear operator  $\tilde{T} : X \times Y \rightarrow \mathbb{R}$ .

**Theorem B.16.** [2] *Let  $X$  be a normed space and let  $M$  be a closed vector subspace of  $X$ . Then*

- (1) *If  $X$  is reflexive, then  $X$  is a Banach space.*
- (2)  *$X$  is reflexive if and only if  $X^*$  is reflexive.*
- (3) *If  $X^*$  is separable, then  $X$  is separable.*
- (4) *If  $X$  is reflexive and separable, then so is  $X^*$ .*
- (5) *If  $X$  is a reflexive Banach space, then so is  $M$ .*
- (6) *If  $X$  is a separable Banach space, then so is  $M$ .*

*Moreover, if  $X_1, \dots, X_r$  are reflexive Banach spaces, then  $X_1 \times \dots \times X_r$  equipped with the norm*

$$\|(x_1, \dots, x_r)\| = \|x_1\|_{X_1} + \dots + \|x_r\|_{X_r}$$

*is also a reflexive Banach space.*

**Theorem B.17.** *Let  $A : V \rightarrow W$  be a linear transformation between the Banach spaces  $V$  and  $W$ . Suppose  $W$  is reflexive. Then*

$$\|A\|_{op} = \sup_{\|x\|_V=1, \|y\|_{W^*}=1} |\langle y, Ax \rangle_{W^* \times W}|$$

*Proof.*

$$\begin{aligned} \|A\|_{op} &= \sup_{\|x\|_V=1} \|Ax\|_W = \sup_{\|x\|_V=1} \|Ax\|_{(W^*)^*} = \sup_{\|x\|_V=1} \sup_{\|y\|_{W^*}=1} |\langle Ax, y \rangle_{(W^*)^* \times W^*}| \\ &= \sup_{\|x\|_V=1, \|y\|_{W^*}=1} |\langle y, Ax \rangle_{W^* \times W}| \end{aligned}$$

□

**B.3. Topological Vector Spaces.** There are different, generally nonequivalent, ways to define topological vector spaces. The conventions in this appendix mainly follow Rudin's functional analysis [39]. Every single statement about topological vector spaces here is either taken directly from Rudin's functional analysis, Grubb's distributions and operators [23], excellent presentation of Reus [38], and Treves' topological vector spaces [42] or is a direct consequence of statements in the aforementioned references. Therefore we will not give the proofs.

**Definition B.18.** *A topological vector space (TVS) is a vector space  $X$  together with a topology  $\tau$  with the following properties:*

- i) *For all  $x \in X$ , the singleton  $\{x\}$  is a closed set.*
- ii) *The maps*

$$(x, y) \mapsto x + y \quad (\text{from } X \times X \text{ into } X)$$

$$(\lambda, x) \mapsto \lambda x \quad (\text{from } \mathbb{R} \times X \text{ into } X)$$

*are continuous where  $X \times X$  and  $\mathbb{R} \times X$  are equipped with the product topology.*

**Definition B.19.** *Suppose  $(X, \tau)$  is a topological vector space and  $Y \subseteq X$ .*

- *$Y$  is said to be **convex** if for all  $y_1, y_2 \in Y$  and  $t \in (0, 1)$  it is true that  $ty_1 + (1-t)y_2 \in Y$ .*

- $Y$  is said to be **balanced** if for all  $y \in Y$  and  $|\lambda| \leq 1$  it holds that  $\lambda y \in Y$ . In particular, any balanced set contains the origin.
- We say  $Y$  is **bounded** if for any neighborhood  $U$  of the origin (i.e. any open set containing the origin), there exists  $t > 0$  such that  $Y \subseteq tU$ .

**Theorem B.20** (Important Properties of a TVS).

- Every topological vector space is Hausdorff.
- If  $(X, \tau)$  is a topological vector space, then
  - (1) for all  $a \in X$ :  $E \in \tau \iff a + E \in \tau$  (that is  $\tau$  is **translation invariant**)
  - (2) for all  $\lambda \in \mathbb{R} \setminus \{0\}$ :  $E \in \tau \iff \lambda E \in \tau$  (that is  $\tau$  is **scale invariant**)
  - (3) if  $A \subseteq X$  is convex and  $x \in X$ , then so is  $A + x$
  - (4) if  $\{A_i\}_{i \in I}$  is a family of convex subsets of  $X$ , then  $\bigcap_{i \in I} A_i$  is convex.

**Note :** Some authors do not include condition (i) in the definition of topological vector spaces. In that case, a topological vector space will not necessarily be Hausdorff.

**Definition B.21.** Let  $(X, \tau)$  be a topological space.

- A collection  $\mathcal{B} \subseteq \tau$  is said to be a **basis** for  $\tau$ , if every element of  $\tau$  is a union of elements in  $\mathcal{B}$ .
- Let  $p \in X$ . If  $\gamma \subseteq \tau$  is such that each element of  $\gamma$  contains  $p$  and every neighborhood of  $p$  (i.e. every open set containing  $p$ ) is contained in at least one element of  $\gamma$ , then we say  $\gamma$  is a **local base at  $p$** . If  $X$  is a vector space, then the local base  $\gamma$  is said to be convex if each element of  $\gamma$  is a convex set.
- $(X, \tau)$  is called **first countable** if each point has a countable local base.
- $(X, \tau)$  is called **second countable** if there is a countable basis for  $\tau$ .

**Theorem B.22.** Let  $(X, \tau)$  be a topological space and suppose for all  $x \in X$ ,  $\gamma_x$  is a local base at  $x$ . Then  $\mathcal{B} := \bigcup_{x \in X} \gamma_x$  is a basis for  $\tau$ .

**Theorem B.23.** Let  $X$  be a vector space and suppose  $\tau$  is a translation invariant topology on  $X$ . Then for all  $x_1, x_2 \in X$  we have

the collection  $\gamma_{x_1}$  is a local base at  $x_1 \iff$  the collection  $\{A + (x_2 - x_1)\}_{A \in \gamma_{x_1}}$  is a local base at  $x_2$

**Remark B.24.** Let  $X$  be a vector space and suppose  $\tau$  is a translation invariant topology on  $X$ . As a direct consequence of the previous theorems the topology  $\tau$  is uniquely determined by giving a local base  $\gamma_{x_0}$  at some point  $x_0 \in X$ .

**Definition B.25.** Let  $(X, \tau)$  be a topological vector space.  $X$  is said to be **metrizable** if there exists a metric  $d : X \times X \rightarrow [0, \infty)$  whose induced topology is  $\tau$ . In this case we say that the metric  $d$  is compatible with the topology  $\tau$ .

**Theorem B.26.** Let  $(X, \tau)$  be a topological vector space. Then

- $X$  is metrizable  $\iff$  there exists a metric  $d$  on  $X$  such that for all  $x \in X$ ,  $\{B(x, \frac{1}{n})\}_{n \in \mathbb{N}}$  is a local base at  $x$ .
  - A metric  $d$  on  $X$  is compatible with  $\tau \iff$  for all  $x \in X$ ,  $\{B(x, \frac{1}{n})\}_{n \in \mathbb{N}}$  is a local base at  $x$ .
- $(B(x, \frac{1}{n})$  is the open ball of radius  $\frac{1}{n}$  centered at  $x$ )

**Definition B.27.** Let  $X$  be a vector space and  $d$  be a metric on  $X$ .  $d$  is said to be translation invariant provided that

$$\forall x, y, a \in X \quad d(x + a, y + a) = d(x, y)$$

**Remark B.28.** Let  $(X, \tau)$  be a topological vector space and suppose  $d$  is a translation invariant metric on  $X$ . Then the following statements are equivalent

- (1) for all  $x \in X$ ,  $\{B(x, \frac{1}{n})\}_{n \in \mathbb{N}}$  is a local base at  $x$
- (2) there exists  $x_0 \in X$  such that  $\{B(x_0, \frac{1}{n})\}_{n \in \mathbb{N}}$  is a local base at  $x_0$

Therefore  $d$  is compatible with  $\tau$  if and only if  $\{B(0, \frac{1}{n})\}_{n \in \mathbb{N}}$  is a local base at the origin.

**Theorem B.29.** Let  $(X, \tau)$  be a topological vector space. Then  $(X, \tau)$  is metrizable if and only if it has a countable local base at the origin. Moreover, if  $(X, \tau)$  is metrizable, then one can find a translation invariant metric that is compatible with  $\tau$ .

**Definition B.30.** Let  $(X, \tau)$  be a topological vector space and let  $\{x_n\}$  be a sequence in  $X$ .

- We say that  $\{x_n\}$  converges to a point  $x \in X$  provided that

$$\forall U \in \tau, x \in U \quad \exists N \quad \forall n \geq N \quad x_n \in U$$

- We say that  $\{x_n\}$  is a Cauchy sequence provided that

$$\forall U \in \tau, 0 \in U \quad \exists N \quad \forall m, n \geq N \quad x_n - x_m \in U$$

**Theorem B.31.** Let  $(X, \tau)$  be a topological vector space,  $\{x_n\}$  be a sequence in  $X$ , and  $x, y \in X$ . Also suppose  $\gamma$  is a local base at the origin. The following statements are equivalent:

- (1)  $x_n \rightarrow x$
- (2)  $(x_n - x) \rightarrow 0$
- (3)  $x_n + y \rightarrow x + y$
- (4)  $\forall V \in \gamma \quad \exists N \quad \forall n \geq N \quad x_n - x \in V$

Moreover  $\{x_n\}$  is a Cauchy sequence if and only if

$$\forall V \in \gamma \quad \exists N \quad \forall n, m \geq N \quad x_n - x_m \in V$$

**Remark B.32.** In contrast with properties like continuity of a function and convergence of a sequence which depend only on the topology of the space, the property of being a Cauchy sequence is not a topological property. Indeed, it is easy to construct examples of two metrics  $d_1$  and  $d_2$  on a vector space  $X$  that induce the same topology (i.e. the metrics are equivalent) but have different collection of Cauchy sequences. However, it can be shown that if  $d_1$  and  $d_2$  are two translation invariant metrics that induce the same topology on  $X$ , then the Cauchy sequences of  $(X, d_1)$  will be exactly the same as the Cauchy sequences of  $(X, d_2)$ .

**Theorem B.33.** Let  $(X, \tau)$  be a metrizable topological vector space and  $d$  be a translation invariant metric on  $X$  that is compatible with  $\tau$ . Let  $\{x_n\}$  be a sequence in  $X$ . The following statements are equivalent:

- (1)  $\{x_n\}$  is a Cauchy sequence in the topological vector space  $(X, \tau)$ .
- (2)  $\{x_n\}$  is a Cauchy sequence in the metric space  $(X, d)$ .

**Definition B.34.** Let  $(X, \tau)$  be a topological vector space. We say  $(X, \tau)$  is **locally convex** if it has a convex local base at the origin.

Note that, as a consequence of theorems (B.20) and (B.23), the following statements are equivalent:

- (1)  $(X, \tau)$  is a locally convex topological vector space.
- (2) There exists  $p \in \mathcal{P}$  with a convex local base at  $p$ .
- (3) For every  $p \in \mathcal{P}$  there exists a convex local base at  $p$ .

**Definition B.35.** Let  $(X, \tau)$  be a metrizable locally convex topological vector space. Let  $d$  be a translation invariant metric on  $X$  that is compatible with  $\tau$ . We say that  $X$  is **complete** if and only if the metric space  $(X, d)$  is a complete metric space. A complete metrizable locally convex topological vector space is called a **Frechet space**.

**Remark B.36.** Our previous remark about Cauchy sequences shows that the above definition of completeness is independent of the chosen translation invariant metric  $d$ . Indeed one can show that the locally convex topological vector space  $(X, \tau)$  is complete in the above sense if and only if every Cauchy net in  $(X, \tau)$  is convergent.

**Definition B.37.** A **seminorm** on a vector space  $X$  is a real-valued function  $p : X \rightarrow \mathbb{R}$  such that

- i.  $\forall x, y \in X \quad p(x + y) \leq p(x) + p(y)$
- ii.  $\forall x \in X \quad \forall \alpha \in \mathbb{R} \quad p(\alpha x) = |\alpha|p(x)$

If  $\mathcal{P}$  is a family of seminorms on  $X$ , then we say  $\mathcal{P}$  is **separating** provided that for all  $x \neq 0$  there exists at least one  $p \in \mathcal{P}$  such that  $p(x) \neq 0$  (that is if  $p(x) = 0$  for all  $p \in \mathcal{P}$ , then  $x = 0$ ).

**Theorem B.38.** Suppose  $\mathcal{P}$  is a separating family of seminorms on a vector space  $X$ . For all  $p \in \mathcal{P}$  and  $n \in \mathbb{N}$  let

$$V(p, n) := \left\{ x \in X : p(x) < \frac{1}{n} \right\}$$

Also let  $\gamma$  be the collection of all finite intersections of  $V(p, n)$ 's. That is,

$$A \in \gamma \iff \exists k \in \mathbb{N}, \exists p_1, \dots, p_k \in \mathcal{P}, \exists n_1, \dots, n_k \in \mathbb{N} \text{ such that } A = \bigcap_{i=1}^k V(p_i, n_i)$$

Then each element of  $\gamma$  is a convex balanced subset of  $X$ . Moreover, there exists a unique topology  $\tau$  on  $X$  that satisfies both of the following properties:

- (1)  $\tau$  is translation invariant (that is, if  $U \in \tau$  and  $a \in X$ , then  $a + U \in \tau$ ).
- (2)  $\gamma$  is a local base at the origin for  $\tau$ .

This unique topology is called the **natural topology** induced by the family of seminorms  $\mathcal{P}$ . Furthermore, if  $X$  is equipped with the natural topology  $\tau$ , then

- i)  $(X, \tau)$  is a locally convex topological vector space.
- ii) every  $p \in \mathcal{P}$  is a continuous function from  $X$  to  $\mathbb{R}$ .

**Theorem B.39.** Suppose  $\mathcal{P}$  is a separating family of seminorms on a vector space  $X$ . Let  $\tau$  be the natural topology induced by  $\mathcal{P}$ . Then

- (1)  $\tau$  is the smallest topology on  $X$  that is translation invariant and with respect to which every  $p \in \mathcal{P}$  is continuous.
- (2)  $\tau$  is the smallest topology on  $X$  with respect to which addition is continuous and every  $p \in \mathcal{P}$  is continuous.

**Theorem B.40.** Let  $X$  and  $Y$  be two vector spaces and suppose  $\mathcal{P}$  and  $\mathcal{Q}$  are two separating families of seminorms on  $X$  and  $Y$ , respectively. Equip  $X$  and  $Y$  with the corresponding natural topologies. Then

(1) A sequence  $x_n$  converges to  $x$  in  $X$  if and only if for all  $p \in \mathcal{P}$ ,  $p(x_n - x) \rightarrow 0$ .

(2) A linear operator  $T : X \rightarrow Y$  is continuous if and only if

$$\forall q \in \mathcal{Q} \quad \exists c > 0, k \in \mathbb{N}, p_1, \dots, p_k \in \mathcal{P} \quad \text{such that} \quad \forall x \in X \quad |q \circ T(x)| \leq c \max_{1 \leq i \leq k} p_i(x)$$

(3) A linear operator  $T : X \rightarrow \mathbb{R}$  is continuous if and only if

$$\exists c > 0, k \in \mathbb{N}, p_1, \dots, p_k \in \mathcal{P} \quad \text{such that} \quad \forall x \in X \quad |T(x)| \leq c \max_{1 \leq i \leq k} p_i(x)$$

**Theorem B.41.** Let  $X$  be a Frechet space and let  $Y$  be a topological vector space. When  $T$  is a linear map of  $X$  into  $Y$ , the following two properties are equivalent

(1)  $T$  is continuous.

(2)  $x_n \rightarrow 0$  in  $X \implies Tx_n \rightarrow 0$  in  $Y$ .

**Theorem B.42.** Let  $\mathcal{P} = \{p_k\}_{k \in \mathbb{N}}$  be a **countable** separating family of seminorms on a vector space  $X$ . Let  $\tau$  be the corresponding natural topology. Then the locally convex topological vector space  $(X, \tau)$  is metrizable and the following translation invariant metric on  $X$  is compatible with  $\tau$ :

$$d(x, y) = \sum_{k=1}^{\infty} \frac{1}{2^k} \frac{p_k(x - y)}{1 + p_k(x - y)}$$

Let  $(X, \tau)$  be a topological vector space. Consider the topological dual of  $X$ ,

$$X^* := \{f : X \rightarrow \mathbb{R} : f \text{ is linear and continuous}\}$$

There are several ways to topologize  $X^*$ : the weak\* topology, the topology of convex compact convergence, the topology of compact convergence, and the strong topology (see [42], Chapter 19). Here we describe the weak\* topology and the strong topology on  $X^*$ .

**Definition B.43.** Let  $(X, \tau)$  be a topological vector space.

- The **weak\* topology** on  $X^*$  is the natural topology induced by the family of seminorms  $\{p_x\}_{x \in X}$  where

$$\forall x \in X \quad p_x : X^* \rightarrow \mathbb{R}, \quad p_x(f) := |f(x)|$$

A sequence  $\{f_m\}$  converges to  $f$  in  $X^*$  with respect to the weak\* topology if and only if  $f_m(x) \rightarrow f(x)$  in  $\mathbb{R}$  for all  $x \in X$ .

- The **strong topology** on  $X^*$  is the natural topology induced by the family of seminorms  $\{p_B\}_{B \subseteq X \text{ bounded}}$  where for any bounded subset  $B$  of  $X$

$$p_B : X^* \rightarrow \mathbb{R} \quad p_B(f) := \sup\{|f(x)| : x \in B\}$$

(it can be shown that for any bounded subset  $B$  of  $X$  and  $f \in X^*$ ,  $f(B)$  is a bounded subset of  $\mathbb{R}$ )

**Remark B.44.**

(1) If  $X$  is a normed space, then the topology induced by the norm

$$\forall f \in X^* \quad \|f\|_{op} = \sup_{\|x\|_X=1} |f(x)|$$

on  $X^*$  is the same as the strong topology on  $X^*$  ([42], Page 198).

(2) In this manuscript we always consider the topological dual of a topological vector space with the strong topology. Of course it is worth mentioning that for many of the spaces that we will consider (including  $X = \mathcal{E}(\Omega)$  or  $X = D(\Omega)$  where  $\Omega$  is an open subset of  $\mathbb{R}^n$ ) a sequence in  $X^*$  converges with respect to the weak\* topology if and only if it converges with respect to the strong topology (for more details on this see the definition and properties of **Montel spaces** in section 34.4, page 356 of [42]).

The following theorem, which is easy to prove, will later be used in the proof of completeness of Sobolev spaces of sections of vector bundles.

**Theorem B.45** ([38], Page 160). *If  $X$  and  $Y$  are topological vector spaces and  $I : X \rightarrow Y$  and  $P : Y \rightarrow X$  are continuous linear maps such that  $P \circ I = id_X$ , then  $I : X \rightarrow I(X) \subseteq Y$  is a linear topological isomorphism and  $I(X)$  is closed in  $Y$ .*

Now we briefly review the relationship between the dual of a product of topological vector spaces and the product of the dual spaces. This will play an important role in our discussion of local representations of distributions in vector bundles in later sections.

Let  $X_1, \dots, X_r$  be topological vector spaces. Recall that the product topology on  $X_1 \times \dots \times X_r$  is the smallest topology such that the projection maps

$$\pi_k : X_1 \times \dots \times X_r \rightarrow X_k, \quad \pi_k(x_1, \dots, x_r) = x_k$$

are continuous for all  $1 \leq k \leq r$ . It can be shown that if each  $X_k$  is a locally convex topological vector space whose topology is induced by a family of seminorms  $\mathcal{P}_k$ , then  $X_1 \times \dots \times X_r$  equipped with the product topology is a locally convex topological vector space whose topology is induced by the following family of seminorms

$$\{p_1 \circ \pi_1 + \dots + p_r \circ \pi_r : p_k \in \mathcal{P}_k \forall 1 \leq k \leq r\}$$

**Theorem B.46** ([38], Page 164). *Let  $X_1, \dots, X_r$  be locally convex topological vector spaces. Equip  $X_1 \times \dots \times X_r$  and  $X_1^* \times \dots \times X_r^*$  with the product topology. The mapping  $\tilde{L} : X_1^* \times \dots \times X_r^* \rightarrow (X_1 \times \dots \times X_r)^*$  defined by*

$$\tilde{L}(u_1, \dots, u_r) = u_1 \circ \pi_1 + \dots + u_r \circ \pi_r$$

*is a linear topological isomorphism. Its inverse is*

$$L(v) = (v \circ i_1, \dots, v \circ i_r)$$

*where for all  $1 \leq k \leq r$ ,  $i_k : X_k \rightarrow X_1 \times \dots \times X_r$  is defined by*

$$i_k(z) = (0, \dots, 0, \underbrace{z}_{k^{th} \text{ position}}, 0, \dots, 0)$$

The notion of adjoint operator, which frequently appears in the future sections, is introduced in the following theorem.

**Theorem B.47** ([38], Page 163). *Let  $X$  and  $Y$  be locally convex topological vector spaces and suppose  $T : X \rightarrow Y$  is a continuous linear map. Then*

(1) *the map*

$$T^* : Y^* \rightarrow X^* \quad \langle T^*y, x \rangle_{X^* \times X} = \langle y, Tx \rangle_{Y^* \times Y}$$

*is well defined, linear, and continuous. ( $T^*$  is called the **adjoint** of  $T$ .)*

(2) *If  $T(X)$  is dense in  $Y$ , then  $T^* : Y^* \rightarrow X^*$  is injective.*

**Remark B.48.** *In the subsequent sections we will focus heavily on certain function spaces on domains  $\Omega$  in the Euclidean space. For approximation purposes, it is always desirable to have  $D(\Omega)(= C_c^\infty(\Omega))$  as a dense subspace of our function spaces. However, there is another, may be more profound, reason for being interested in having  $D(\Omega)$  as a dense subspace. It is important to note that we would like to use the term “function spaces” for topological vector spaces that can be continuously embedded in  $D'(\Omega)$  (see Appendix D for the definition of  $D'(\Omega)$ ) so that concepts such as differentiation will be meaningful for the elements of our function spaces. Given a function space  $A(\Omega)$  it is usually helpful to consider its dual too. In order to be able to view the dual of  $A(\Omega)$  as a function space we need to ensure that  $[A(\Omega)]^*$  can be viewed as a subspace of  $D'(\Omega)$ . To this end, according to the above theorem, we just need to ensure that  $D(\Omega)$  is dense in  $A(\Omega)$ . To further illustrate the importance of this point let’s consider a concrete example. Let  $\Omega$  be a domain with smooth boundary in  $\mathbb{R}^n$ . In Appendix E we will introduce function spaces denoted by  $\tilde{W}^{s,p}(\bar{\Omega})$  which are reflexive normed spaces for all  $s \in \mathbb{R}$  and  $1 < p < \infty$ . One can show that ([43], Page 332)*

$$[\tilde{W}^{s,p}(\bar{\Omega})]^* = W^{-s,p'}(\bar{\Omega})$$

*From the above facts we may conclude that  $[W^{s,p}(\bar{\Omega})]^*$  is topologically isomorphic with  $\tilde{W}^{-s,p'}(\bar{\Omega})$  as normed spaces. However, it can be shown that if  $s > \frac{1}{p}$ , then  $C_c^\infty(\Omega)$  is not dense in  $W^{s,p}(\bar{\Omega})$  ([40], Page 83). Therefore,  $[W^{s,p}(\bar{\Omega})]^*$  is not a subspace of  $D'(\Omega)$  and so cannot be considered as a function space. It is just a normed space that is isomorphic to a function space.*

Let us consider more closely two special cases of Theorem B.47.

- (1) Suppose  $Y$  is a normed space and  $H$  is a dense subspace of  $Y$ . Clearly the identity map  $i : H \rightarrow Y$  is continuous with dense image. Therefore  $i^* : Y^* \rightarrow H^*$  ( $F \mapsto F|_H$ ) is continuous and injective. Furthermore, by the Hahn-Banach theorem for all  $\varphi \in H^*$  there exists  $F \in Y^*$  such that  $F|_H = \varphi$  and  $\|F\| = \|\varphi\|$ . So the above map is indeed bijective and  $Y^*$  and  $H^*$  are isometrically isomorphic.
- (2) Suppose  $(Y, \|\cdot\|_Y)$  is a normed space,  $(X, \tau)$  is a locally convex topological vector space,  $X \subseteq Y$ , and the identity map  $i : (X, \tau) \rightarrow (Y, \|\cdot\|_Y)$  is continuous with dense image. So  $i^* : Y^* \rightarrow X^*$  ( $F \mapsto F|_X$ ) is continuous and injective and can be used to identify  $Y^*$  with a subspace of  $X^*$ .

- **Question:** Exactly what elements of  $X^*$  are in the image of  $i^*$ ? That is, which elements of  $X^*$  “belong to”  $Y^*$ ?
- **Answer:**  $\varphi \in X^*$  belongs to the image of  $i^*$  if and only if  $\varphi : (X, \|\cdot\|_Y) \rightarrow \mathbb{R}$  is continuous, that is,  $\varphi \in X^*$  belongs to the image  $i^*$  if and only if  $\sup_{x \in X \setminus \{0\}} \frac{|\varphi(x)|}{\|x\|_Y} < \infty$ .

So an element  $\varphi \in X^*$  can be considered as an element of  $Y^*$  if and only if

$$\sup_{x \in X \setminus \{0\}} \frac{|\varphi(x)|}{\|x\|_Y} < \infty.$$

Furthermore if we denote the unique corresponding element in  $Y^*$  by  $\tilde{\varphi}$  (normally we identify  $\varphi$  and  $\tilde{\varphi}$  and we use the same notation for both) then since  $X$  is dense in  $Y$

$$\|\tilde{\varphi}\|_{Y^*} = \sup_{y \in Y \setminus \{0\}} \frac{|\tilde{\varphi}(y)|}{\|y\|_Y} = \sup_{x \in X \setminus \{0\}} \frac{|\varphi(x)|}{\|x\|_Y} < \infty$$

**Remark B.49.** *To sum up, given an element  $\varphi \in X^*$  in order to show that  $\varphi$  can be considered as an element of  $Y^*$  we just need to show that  $\sup_{x \in X \setminus \{0\}} \frac{|\varphi(x)|}{\|x\|_Y} < \infty$  and in*



that case, norm of  $\varphi$  as an element of  $Y^*$  is  $\sup_{x \in X \setminus \{0\}} \frac{|\varphi(x)|}{\|x\|_Y}$ . However, it is important to notice that if  $F : Y \rightarrow \mathbb{R}$  is a linear map and  $F|_X$  is bounded, that does NOT imply that  $F \in Y^*$ . It just shows that there exists  $G \in Y^*$  such that  $G|_X = F|_X$ .

We conclude this section by a quick review of the inductive limit topology.

**Definition B.50.** Let  $X$  be a vector space and let  $\{X_\alpha\}_{\alpha \in I}$  be a family of vector subspaces of  $X$  with the property that

- for each  $\alpha \in I$ ,  $X_\alpha$  is equipped with a topology that makes it a locally convex topological vector space, and
- $\bigcup_{\alpha \in I} X_\alpha = X$ .

The **inductive limit topology** on  $X$  with respect to the family  $\{X_\alpha\}_{\alpha \in I}$  is defined to be the largest topology with respect to which

- (1)  $X$  is a locally convex topological vector space, and
- (2) all the inclusions  $X_K \subseteq X$  are continuous.

**Theorem B.51.** Let  $X$  be a vector space equipped with the inductive limit topology with respect to  $\{X_\alpha\}$  as described above. If  $Y$  is a locally convex vector space, then a linear map  $T : X \rightarrow Y$  is continuous if and only if  $T|_{X_\alpha} : X_\alpha \rightarrow Y$  is continuous for all  $\alpha \in I$ .

**Theorem B.52.** Let  $X$  be a vector space and let  $\{X_j\}_{j \in \mathbb{N}_0}$  be a nested family of vector subspaces of  $X$ :

$$X_0 \subsetneq X_1 \subsetneq \cdots \subsetneq X_j \subsetneq \cdots$$

Suppose each  $X_j$  is equipped with a topology that makes it a locally convex topological vector space. Equip  $X$  with the inductive limit topology with respect to  $\{X_j\}$ . Then the following topologies on  $X^{\times r}$  are equivalent (=they are the same)

- (1) The product topology
- (2) The inductive limit topology with respect to the family  $\{X_j^{\times r}\}$ . (For each  $j$ ,  $X_j^{\times r}$  is equipped with the product topology)

As a consequence, if  $Y$  is a locally convex vector space, then a linear map  $T : X^{\times r} \rightarrow Y$  is continuous if and only if  $T|_{X_j^{\times r}} : X_j^{\times r} \rightarrow Y$  is continuous for all  $j \in \mathbb{N}_0$ .

## APPENDIX C. REVIEW OF SOME RESULTS FROM DIFFERENTIAL GEOMETRY

The main purpose of this section is to set the notations and terminology straight. To this end we cite the definitions of several basic terms and a number of basic properties that we will frequently use. The main reference for the majority of the definitions is the invaluable book by Jack Lee ([33]).

**C.1. Smooth Manifolds.** Suppose  $M$  is a topological space. We say that  $M$  is a topological manifold of dimension  $n$  if it is Hausdorff, second-countable, and locally Euclidean in the sense that each point of  $M$  has a neighborhood that is homeomorphic to an open subset of  $\mathbb{R}^n$ . It is easy to see that the following statements are equivalent ([33], Page 3):

- (1) Each point of  $M$  has a neighborhood that is homeomorphic to an open subset of  $\mathbb{R}^n$ .
- (2) Each point of  $M$  has a neighborhood that is homeomorphic to an open ball in  $\mathbb{R}^n$ .
- (3) Each point of  $M$  has a neighborhood that is homeomorphic to  $\mathbb{R}^n$ .

By a **coordinate chart** (or just **chart**) on  $M$  we mean a pair  $(U, \varphi)$ , where  $U$  is an open subset of  $M$  and  $\varphi : U \rightarrow \hat{U}$  is a homeomorphism from  $U$  to an open subset  $\hat{U} = \varphi(U) \subseteq \mathbb{R}^n$ .  $U$  is called a **coordinate domain** or a **coordinate neighborhood** of each of its points and  $\varphi$  is called a **coordinate map**. An **atlas for  $M$**  is a collection of charts whose domains cover  $M$ . Two charts  $(U, \varphi)$  and  $(V, \psi)$  are said to be **smoothly compatible** if either  $U \cap V = \emptyset$  or the transition map  $\psi \circ \varphi^{-1}$  is a  $C^\infty$  diffeomorphism. An atlas  $\mathcal{A}$  is called a **smooth atlas** if any two charts in  $\mathcal{A}$  are smoothly compatible with each other. A smooth atlas  $\mathcal{A}$  on  $M$  is **maximal** if it is not properly contained in any larger smooth atlas. A **smooth structure** on  $M$  is a maximal smooth atlas. A **smooth manifold** is a pair  $(M, \mathcal{A})$ , where  $M$  is a topological manifold and  $\mathcal{A}$  is a smooth structure on  $M$ . Any chart  $(U, \varphi)$  contained in the given maximal smooth atlas is called a **smooth chart**.

**Remark C.1.**

- Clearly if  $(U, \varphi)$  is a smooth chart and  $V$  is an open subset of  $U$ , then  $(V, \psi)$  where  $\psi = \varphi|_V$  is also a smooth chart (i.e. it belongs to the same maximal atlas).
- Every smooth atlas  $\mathcal{A}$  for  $M$  is contained in a unique maximal smooth atlas, called the **smooth structure determined by  $\mathcal{A}$** .
- If  $M$  is a compact smooth manifold, then there exists a smooth atlas with finitely many elements that determines the smooth structure of  $M$  (this is immediate from the definition of compactness).

**Definition C.2.**

- We say that a smooth atlas for a smooth manifold  $M$  is a **geometrically Lipschitz (GL) smooth atlas** if the image of each coordinate domain in the atlas under the corresponding coordinate map is a nonempty bounded open set with Lipschitz boundary.
- We say that a smooth atlas for a smooth manifold  $M^n$  is a **generalized geometrically Lipschitz (GGL) smooth atlas** if the image of each coordinate domain in the atlas under the corresponding coordinate map is the entire  $\mathbb{R}^n$  or a nonempty bounded open set with Lipschitz boundary.
- We say that a smooth atlas for a smooth manifold  $M^n$  is a **nice smooth atlas** if the image of each coordinate domain in the atlas under the corresponding coordinate map is a ball in  $\mathbb{R}^n$ .
- We say that a smooth atlas for a smooth manifold  $M^n$  is a **super nice smooth atlas** if the image of each coordinate domain in the atlas under the corresponding coordinate map is the entire  $\mathbb{R}^n$ .
- We say that two smooth atlases  $\{(U_\alpha, \varphi_\alpha)\}_{\alpha \in I}$  and  $\{(\tilde{U}_\beta, \tilde{\varphi}_\beta)\}_{\beta \in J}$  for a smooth manifold  $M$  are **geometrically Lipschitz compatible (GLC) smooth atlases** provided that each atlas is GGL and moreover for all  $\alpha \in I$  and  $\beta \in J$  with  $U_\alpha \cap \tilde{U}_\beta \neq \emptyset$ ,  $\varphi_\alpha(U_\alpha \cap \tilde{U}_\beta)$  and  $\tilde{\varphi}_\beta(U_\alpha \cap \tilde{U}_\beta)$  are nonempty bounded open sets with Lipschitz boundary or the entire  $\mathbb{R}^n$ .

Clearly every super nice smooth atlas is also a GGL smooth atlas; every nice smooth atlas is also a GL smooth atlas, and every GL smooth atlas is also a GGL smooth atlas. Also note that two arbitrary GL smooth atlases are not necessarily GLC smooth atlases because the intersection of two Lipschitz domains is not necessarily Lipschitz (see e.g.

[6], pages 115-117).

Given a smooth atlas  $\{(U_\alpha, \varphi_\alpha)\}$  for a compact manifold  $M$ , it is not necessarily possible to construct a new atlas  $\{(U_\alpha, \tilde{\varphi}_\alpha)\}$  such that this new atlas is nice; for instance if  $U_\alpha$  is not connected we cannot find  $\tilde{\varphi}_\alpha$  such that  $\tilde{\varphi}_\alpha(U_\alpha) = \mathbb{R}^n$  (or any ball in  $\mathbb{R}^n$ ). However, as the following lemma states it is always possible to find a refinement that is nice.

**Lemma C.3.** *Suppose  $\{(U_\alpha, \varphi_\alpha)\}_{1 \leq \alpha \leq N}$  is a smooth atlas for a compact smooth manifold  $M$ . Then there exists a finite open cover  $\{V_\beta\}_{1 \leq \beta \leq L}$  of  $M$  such that*

$$\forall \beta \quad \exists 1 \leq \alpha(\beta) \leq N \text{ s.t. } V_\beta \subseteq U_{\alpha(\beta)}, \quad \varphi_{\alpha(\beta)}(V_\beta) \text{ is a ball in } \mathbb{R}^n$$

Therefore  $\{(V_\beta, \varphi_{\alpha(\beta)}|_{V_\beta})\}_{1 \leq \beta \leq L}$  is a nice smooth atlas.

*Proof.* For each  $1 \leq \alpha \leq N$  and  $p \in U_\alpha$ , there exists  $r_{\alpha p} > 0$  such that  $B_{r_{\alpha p}}(\varphi_\alpha(p)) \subseteq \varphi_\alpha(U_\alpha)$ . Let  $V_{\alpha p} := \varphi_\alpha^{-1}(B_{r_{\alpha p}}(\varphi_\alpha(p)))$ .  $\bigcup_{1 \leq \alpha \leq N} \bigcup_{p \in U_\alpha} V_{\alpha p}$  is an open cover of  $M$  and so it has a finite subcover  $\{V_{\alpha_1 p_1}, \dots, V_{\alpha_L p_L}\}$ . Let  $V_\beta = V_{\alpha_\beta p_\beta}$ . Clearly,  $V_\beta \subseteq U_{\alpha_\beta}$  and  $\varphi_{\alpha_\beta}(V_\beta)$  is a ball in  $\mathbb{R}^n$ .  $\square$

**Remark C.4.** *Every open ball in  $\mathbb{R}^n$  is  $C^\infty$ -diffeomorphic to  $\mathbb{R}^n$ . Also compositions of diffeomorphisms is a diffeomorphism. Therefore existence of a finite nice smooth atlas on a compact smooth manifold (which is guaranteed by the above lemma) implies the existence of a finite super nice smooth atlas.*

**Lemma C.5.** *Let  $M$  be a compact manifold. Let  $\{U_\alpha\}_{1 \leq \alpha \leq N}$  be an open cover of  $M$ . Suppose  $C$  is a closed set in  $M$  (so  $C$  is compact) which is contained in  $U_\beta$  for some  $1 \leq \beta \leq N$ . Then there exists an open cover  $\{A_\alpha\}_{1 \leq \alpha \leq N}$  of  $M$  such that  $C \subseteq A_\beta \subseteq \bar{A}_\beta \subseteq U_\beta$  and  $A_\alpha \subseteq \bar{A}_\alpha \subseteq U_\alpha$  for all  $\alpha \neq \beta$ .*

*Proof.* Without loss of generality we may assume that  $\beta = 1$ . For each  $1 \leq \alpha \leq N$  and  $p \in U_\alpha$ , there exists  $r_{\alpha p} > 0$  such that  $B_{2r_{\alpha p}}(\varphi_\alpha(p)) \subseteq \varphi_\alpha(U_\alpha)$ . Let  $V_{\alpha p} := \varphi_\alpha^{-1}(B_{r_{\alpha p}}(\varphi_\alpha(p)))$ . Clearly  $p \in V_{\alpha p} \subseteq \bar{V}_{\alpha p} \subseteq U_\alpha$ . Since  $M$  is compact, the open cover  $\bigcup_{1 \leq \alpha \leq N} \bigcup_{p \in U_\alpha} V_{\alpha p}$  of  $M$  has a finite subcover  $\mathcal{A}$ . For each  $1 \leq \alpha \leq N$  let  $E_\alpha = \{p \in U_\alpha : V_{\alpha p} \in \mathcal{A}\}$  and

$$I_1 = \{\alpha : E_\alpha \neq \emptyset\}$$

If  $\alpha \in I_1$ , we let  $W_\alpha = \bigcup_{p \in E_\alpha} V_{\alpha p}$ . For  $\alpha \notin I_1$  choose one point  $p \in U_\alpha$  and let  $W_\alpha = V_{\alpha p}$ .

$C$  is compact so  $\varphi_1(C)$  is a compact set inside the open set  $\varphi_1(U_1)$ . Therefore there exists an open set  $B$  such that

$$\varphi_1(C) \subseteq B \subseteq \bar{B} \subseteq \varphi_1(U_1)$$

Let  $W = \varphi_1^{-1}(B)$ . Clearly  $C \subseteq W \subseteq \bar{W} \subseteq U_\alpha$ . Now Let

$$\begin{aligned} A_1 &= W \bigcup W_1 \\ A_\alpha &= W_\alpha \quad \forall \alpha > 1 \end{aligned}$$

Clearly  $A_1$  contains  $W$  which contains  $C$ . Also union of  $A_\alpha$ 's contains  $\bigcup_{\alpha=1}^N \bigcup_{p \in E_\alpha} V_{\alpha p}$  which is equal to  $M$ . Closure of a union of sets is a subset of the union of closures of those sets. Therefore for each  $\alpha$ ,  $\bar{A}_\alpha \subseteq U_\alpha$ .  $\square$

**Theorem C.6** (Exhaustion by Compact Sets for Manifolds). *Let  $M$  be a smooth manifold. There exists a sequence of compact subsets  $(K_j)_{j \in \mathbb{N}}$  such that  $\bigcup_{j \in \mathbb{N}} \overset{\circ}{K}_j = M$ ,  $\overset{\circ}{K}_{j+1} \setminus K_j \neq \emptyset$  for all  $j$  and*

$$K_1 \subseteq \overset{\circ}{K}_2 \subseteq K_2 \subseteq \cdots \subseteq \overset{\circ}{K}_j \subseteq K_j \subseteq \cdots$$

**Definition C.7.** *A  $C^\infty$  partition of unity on a manifold is a collection of nonnegative  $C^\infty$  functions  $\{\psi_\alpha : M \rightarrow \mathbb{R}\}_{\alpha \in A}$  such that*

- (i) *the collection of supports,  $\{\text{supp } \psi_\alpha\}_{\alpha \in A}$  is locally finite.*
- (ii)  $\sum \psi_\alpha = 1$ .

*Given an open cover  $\{U_\alpha\}_{\alpha \in A}$  of  $M$ , we say that a partition of unity  $\{\psi_\alpha\}_{\alpha \in A}$  is subordinate to the open cover  $\{U_\alpha\}$  if  $\text{supp } \psi_\alpha \subseteq U_\alpha$  for every  $\alpha \in A$ .*

**Theorem C.8.** ([47], Page 146) *Let  $M$  be a **compact** manifold and  $\{U_\alpha\}_{\alpha \in A}$  an open cover of  $M$ . There exists a  $C^\infty$  partition of unity  $\{\psi_\alpha\}_{\alpha \in A}$  subordinate to  $\{U_\alpha\}_{\alpha \in A}$ . (Notice that the index sets are the same.)*

**Theorem C.9.** ([47], Page 347) *Let  $\{U_\alpha\}_{\alpha \in A}$  be an open cover of a manifold  $M$ .*

- (i) *There is a  $C^\infty$  partition of unity  $\{\varphi_k\}_{k=1}^\infty$  with every  $\varphi_k$  **having compact support** such that for each  $k$ ,  $\text{supp } \varphi_k \subseteq U_\alpha$  for some  $\alpha \in A$ .*
- (ii) *If we do not require compact support, then there is a  $C^\infty$  partition of unity  $\{\psi_\alpha\}_{\alpha \in A}$  subordinate to  $\{U_\alpha\}_{\alpha \in A}$ .*

**Remark C.10.** *Let  $M$  be a compact Riemannian manifold. Suppose  $\{U_\alpha\}_{\alpha \in A}$  is an open cover of  $M$  and  $\{\psi_\alpha\}_{\alpha \in A}$  is a partition of unity subordinate to  $\{U_\alpha\}_{\alpha \in A}$ .*

- *For all  $m \in \mathbb{N}$ ,  $\{\tilde{\psi}_\alpha = \frac{\psi_\alpha^m}{\sum_{\alpha \in A} \psi_\alpha^m}\}$  is another partition of unity subordinate to  $\{U_\alpha\}_{\alpha \in A}$ .*
- *If  $\{V_\beta\}_{\beta \in B}$  is an open cover of  $M$  and  $\{\xi_\beta\}$  is a partition of unity subordinate to  $\{V_\beta\}_{\beta \in B}$ , then  $\{\psi_\alpha \xi_\beta\}_{(\alpha, \beta) \in A \times B}$  is a partition of unity subordinate to the open cover  $\{U_\alpha \cap V_\beta\}_{(\alpha, \beta) \in A \times B}$ .*

**Lemma C.11.** *Let  $M$  be a compact manifold. Suppose  $\{U_\alpha\}_{1 \leq \alpha \leq N}$  is an open cover of  $M$ . Suppose  $C$  is a closed set in  $M$  (so  $C$  is compact) which is contained in  $U_\beta$  for some  $1 \leq \beta \leq N$ . Then there exists a partition of unity  $\{\psi_\alpha\}_{1 \leq \alpha \leq N}$  subordinate to  $\{U_\alpha\}_{1 \leq \alpha \leq N}$  such that  $\psi_\beta = 1$  on  $C$ .*

*Proof.* We follow the argument in [15]. Without loss of generality we may assume  $\beta = 1$ . We can construct a partition of unity with the desired property as follows: Let  $A_\alpha$  be a collection of open sets that covers  $M$  and such that  $C \subseteq A_1 \subseteq \bar{A}_1 \subseteq U_1$  and for  $\alpha > 1$ ,  $A_\alpha \subseteq \bar{A}_\alpha \subseteq U_\alpha$  (see Lemma C.5). Let  $\eta_\alpha \in C_c^\infty(U_\alpha)$  be such that  $0 \leq \eta_\alpha \leq 1$  and  $\eta_\alpha = 1$  on a neighborhood of  $\bar{A}_\alpha$ . Of course  $\sum_{\alpha=1}^N \eta_\alpha$  is not necessarily equal to 1 for all  $x \in M$ . However, if we define  $\psi_1 = \eta_1$  and for  $\alpha > 1$

$$\psi_\alpha = \eta_\alpha (1 - \eta_1) \cdots (1 - \eta_{\alpha-1})$$

by induction one can easily show that for  $1 \leq l \leq N$

$$1 - \sum_{\alpha=1}^l \psi_\alpha = (1 - \eta_1) \cdots (1 - \eta_l)$$

In particular,

$$1 - \sum_{\alpha=1}^N \psi_\alpha = (1 - \eta_1) \cdots (1 - \eta_N) = 0$$

since for each  $x \in M$  there exists  $\alpha$  such that  $x \in A_\alpha$  and so  $\eta_\alpha(x) = 1$ . Consequently  $\sum_{\alpha=1}^N \psi_\alpha = 1$ .  $\square$

**C.2. Vector Bundles, Basic Definitions.** Let  $M$  be a smooth manifold. A **(smooth real) vector bundle** of rank  $r$  over  $M$  is a smooth manifold  $E$  together with a surjective smooth map  $\pi : E \rightarrow M$  such that

- (1) for each  $x \in M$ ,  $E_x = \pi^{-1}(x)$  is an  $r$ -dimensional (real) vector space.
- (2) for each  $x \in M$ , there exists a neighborhood  $U$  of  $x$  in  $M$  and a smooth map  $\rho = (\rho^1, \dots, \rho^r)$  from  $E|_U := \pi^{-1}(U)$  onto  $\mathbb{R}^r$  such that
  - for every  $x \in U$ ,  $\rho|_{E_x} : E_x \rightarrow \mathbb{R}^r$  is an isomorphism of vector spaces
  - $\Phi = (\pi|_{E_U}, \rho) : E_U \rightarrow U \times \mathbb{R}^r$  is a diffeomorphism.

We denote the projection onto the last  $r$  components by  $\pi'$ . So  $\pi' \circ \Phi = \rho$ . The expressions "E is a vector bundle over M", or "E → M is a vector bundle", or "π : E → M is a vector bundle" are all considered to be equivalent in this manuscript. We refer to both  $\Phi : E_U \rightarrow U \times \mathbb{R}^r$  and  $\rho : E_U \rightarrow \mathbb{R}^r$  as a (smooth) **local trivialization** of  $E$  over  $U$  (it will be clear from the context which one we are referring to). We say that  $E|_U$  is trivial. The pair  $(U, \rho)$  (or  $(U, \Phi)$ ) is sometimes called a **vector bundle chart**. It is easy to see that if  $(U, \rho)$  is a vector bundle chart and  $\emptyset \neq V \subseteq U$  is open, then  $(V, \rho|_{E_V})$  is also a vector bundle chart for  $E$ . Moreover if  $V$  is any nonempty open subset of  $M$ , then  $E_V$  is a vector bundle over the manifold  $V$ . We say that a triple  $(U, \varphi, \rho)$  is a **total trivialization triple** of the vector bundle  $\pi : E \rightarrow M$  provided that  $(U, \varphi)$  is a smooth coordinate chart and  $\rho = (\rho^1, \dots, \rho^r) : E_U \rightarrow \mathbb{R}^r$  is a trivialization of  $E$  over  $U$ . A collection  $\{(U_\alpha, \varphi_\alpha, \rho_\alpha)\}$  is called a **total trivialization atlas** for the vector bundle  $E \rightarrow M$  provided that for each  $\alpha$ ,  $(U_\alpha, \varphi_\alpha, \rho_\alpha)$  is a total trivialization triple and  $\{(U_\alpha, \varphi_\alpha)\}$  is a smooth atlas for  $M$ . The following theorems show that any vector bundle has a total trivialization atlas.

**Lemma C.12.** ([48], Page 77) *Let  $E$  be a vector bundle over an  $n$ -dimensional smooth manifold  $M$  ( $M$  does not need to be compact). Then  $M$  can be covered by  $n + 1$  open sets  $V_0, \dots, V_n$  where the restriction  $E|_{V_i}$  is trivial.*

**Theorem C.13.** *Let  $E$  be a vector bundle of rank  $r$  over an  $n$ -dimensional smooth manifold  $M$ . Then  $E \rightarrow M$  has a total trivialization atlas. In particular, if  $M$  is compact, then it has a total trivialization atlas that consists of only finitely many total trivialization triples.*

*Proof.* Let  $V_0, \dots, V_n$  be an open cover of  $M$  such that  $E$  is trivial over  $V_\beta$  with the mapping  $\rho_\beta : E_{V_\beta} \rightarrow \mathbb{R}^r$ . Let  $\{(U_\alpha, \varphi_\alpha)\}_{\alpha \in I}$  be a smooth atlas for  $M$  (if  $M$  is compact, the index set  $I$  can be chosen to be finite). For all  $\alpha \in I$  and  $0 \leq \beta \leq n$  let  $W_{\alpha\beta} = U_\alpha \cap V_\beta$ . Let  $J = \{(\alpha, \beta) : W_{\alpha\beta} \neq \emptyset\}$ . Clearly  $\{(W_{\alpha\beta}, \varphi_{\alpha\beta}, \rho_{\alpha\beta})\}_{(\alpha, \beta) \in J}$  where  $\varphi_{\alpha\beta} = \varphi_\alpha|_{W_{\alpha\beta}}$  and  $\rho_{\alpha\beta} = \rho_\beta|_{\pi^{-1}(W_{\alpha\beta})}$  is a total trivialization atlas for  $E \rightarrow M$ .  $\square$

**Definition C.14.**

- We say that a total trivialization triple  $(U, \varphi, \rho)$  is **geometrically Lipschitz (GL)** provided that  $\varphi(U)$  is a nonempty bounded open set with Lipschitz boundary. A total trivialization atlas is called **geometrically Lipschitz** if each of its total trivialization triples is GL.
- We say that a total trivialization triple  $(U, \varphi, \rho)$  is **nice** provided that  $\varphi(U)$  is equal to a ball in  $\mathbb{R}^n$ . A total trivialization atlas is called **nice** if each of its total trivialization triples is nice.

- We say that a total trivialization triple  $(U, \varphi, \rho)$  is **super nice** provided that  $\varphi(U)$  is equal to  $\mathbb{R}^n$ . A total trivialization atlas is called **super nice** if each of its total trivialization triples is super nice.
- A total trivialization atlas is called **generalized geometrically Lipschitz (GGL)** if each of its total trivialization triples is GL or super nice.
- We say that two total trivialization atlases  $\{(U_\alpha, \varphi_\alpha, \rho_\alpha)\}_{\alpha \in I}$  and  $\{(\tilde{U}_\beta, \tilde{\varphi}_\beta, \tilde{\rho}_\beta)\}_{\beta \in J}$  are **geometrically Lipschitz compatible (GLC)** if the corresponding atlases  $\{(U_\alpha, \varphi_\alpha)\}_{\alpha \in I}$  and  $\{(\tilde{U}_\beta, \tilde{\varphi}_\beta)\}_{\beta \in J}$  are GLC.

**Theorem C.15.** *Let  $E$  be a vector bundle of rank  $r$  over an  $n$ -dimensional compact smooth manifold  $M$ . Then  $E$  has a nice total trivialization atlas (and a super nice total trivialization atlas) that consists of only finitely many total trivialization triples.*

*Proof.* By Theorem C.13,  $E \rightarrow M$  has a finite total trivialization atlas  $\{(U_\alpha, \varphi_\alpha, \rho_\alpha)\}$ . By Lemma C.3 (and Remark C.4) there exists a finite open cover  $\{V_\beta\}_{1 \leq \beta \leq L}$  of  $M$  such that

$$\begin{aligned} \forall \beta \quad \exists 1 \leq \alpha(\beta) \leq N \text{ s.t. } \quad V_\beta \subseteq U_{\alpha(\beta)}, \quad \varphi_{\alpha(\beta)}(V_\beta) \text{ is a ball in } \mathbb{R}^n \\ (\text{or } \forall \beta \quad \exists 1 \leq \alpha(\beta) \leq N \text{ s.t. } \quad V_\beta \subseteq U_{\alpha(\beta)}, \quad \varphi_{\alpha(\beta)}(V_\beta) = \mathbb{R}^n) \end{aligned}$$

and thus  $\{(V_\beta, \varphi_{\alpha(\beta)}|_{V_\beta})\}_{1 \leq \beta \leq L}$  is a nice (resp. super nice) smooth atlas. Now clearly  $\{(V_\beta, \varphi_{\alpha(\beta)}|_{V_\beta}, \rho_{\alpha(\beta)}|_{E_{V_\beta}})\}_{1 \leq \beta \leq L}$  is a nice (resp. super nice) total trivialization atlas.  $\square$

**Theorem C.16.** *Let  $E$  be a vector bundle of rank  $r$  over an  $n$ -dimensional compact smooth manifold  $M$ . Then  $E$  admits a finite total trivialization atlas that is GL compatible with itself. In fact, there exists a total trivialization atlas  $\{(U_\alpha, \varphi_\alpha, \rho_\alpha)\}_{1 \leq \alpha \leq N}$  such that*

- for all  $1 \leq \alpha \leq N$ ,  $\varphi_\alpha(U_\alpha)$  is bounded with Lipschitz continuous boundary, and,
- for all  $1 \leq \alpha, \beta \leq N$ ,  $U_\alpha \cap U_\beta$  is either empty or else  $\varphi_\alpha(U_\alpha \cap U_\beta)$  and  $\varphi_\beta(U_\alpha \cap U_\beta)$  are bounded with Lipschitz continuous boundary.

*Proof.* The proof of this theorem is based on the argument presented in the proof of Lemma 3.1 in [29]. Equip  $M$  with a smooth Riemannian metric  $g$ . Let  $r_{inj}$  denote the injectivity radius of  $M$  which is strictly positive because  $M$  is compact. Let  $V_0, \dots, V_n$  be an open cover of  $M$  such that  $E$  is trivial over  $V_\beta$  with the mapping  $\rho_\beta : E_{V_\beta} \rightarrow \mathbb{R}^r$ . For every  $x \in M$  choose  $0 \leq i(x) \leq n$  such that  $x \in V_{i(x)}$ . For all  $x \in M$  let  $r_x$  be a positive number less than  $\frac{r_{inj}}{2}$  such that  $\exp_x(B_{r_x}) \subseteq V_{i(x)}$  where  $B_{r_x}$  denotes the open ball in  $T_x M$  of radius  $r_x$  (with respect to the inner product induced by the Riemannian metric  $g$ ) and  $\exp_x : T_x M \rightarrow M$  denotes the exponential map at  $x$ . For every  $x \in M$  define the normal coordinate chart centered at  $x$ ,  $(U_x, \varphi_x)$ , as follows:

$$U_x = \exp_x(B_{r_x}), \quad \varphi_x := \lambda_x^{-1} \circ \exp_x^{-1} : U_x \rightarrow \mathbb{R}^n,$$

where  $\lambda_x : \mathbb{R}^n \rightarrow T_x M$  is an isomorphism defined by  $\lambda_x(y^1, \dots, y^n) = y^i E_{ix}$ ; Here  $\{E_{ix}\}_{i=1}^n$  is an arbitrary but fixed orthonormal basis for  $T_x M$ . It is well-known that (see e.g. [32])

- $\varphi_x(x) = (0, \dots, 0)$
- $g_{ij}(x) = \delta_{ij}$  where  $g_{ij}$  denotes the components of the metric with respect to the normal coordinate chart  $(U_x, \varphi_x)$ .
- $E_{ix} = \partial_i|_x$  where  $\{\partial_i\}_{1 \leq i \leq n}$  is the coordinate basis induced by  $(U_x, \varphi_x)$ .

As a consequence of the previous items, it is easy to show that if  $X \in T_x M$  ( $X = X^i \partial_i$ ), then the Euclidean norm of  $X$  will be equal to the norm of  $X$  with respect to the metric  $g$ , that is  $|X|_g = |X|$  where

$$|X|_g = \sqrt{(X^1)^2 + \cdots + (X^n)^2} \quad |X|_g = \sqrt{g(X, X)}$$

Consequently, for every  $x \in M$ ,  $\varphi_x(U_x)$  will be a ball in the Euclidean space, in particular,  $\{(U_x, \varphi_x)\}_{x \in M}$  is a GL atlas. The proof of Lemma 3.1 in [29] in part shows that the atlas  $\{(U_x, \varphi_x)\}_{x \in M}$  is GL compatible with itself. Since  $M$  is compact there exists  $x_1, \dots, x_N \in M$  such that  $\{U_{x_j}\}_{1 \leq j \leq N}$  also covers  $M$ .

Now clearly  $\{(U_{x_j}, \varphi_{x_j}, \rho_{i(x_j)}|_{U_{x_j}})\}_{1 \leq j \leq N}$  is a total trivialization atlas for  $E$  that is GL compatible with itself.  $\square$

**Corollary C.17.** *Let  $E$  be a vector bundle of rank  $r$  over an  $n$ -dimensional compact smooth manifold  $M$ . Then  $E$  admits a finite super nice total trivialization atlas that is GL compatible with itself.*

*Proof.* Let  $\{(U_\alpha, \varphi_\alpha, \rho_\alpha)\}_{1 \leq \alpha \leq N}$  be the total trivialization atlas that was constructed above. For each  $\alpha$ ,  $\varphi_\alpha(U_\alpha)$  is a ball in the Euclidean space and so it is diffeomorphic to  $\mathbb{R}^n$ ; let  $\xi_\alpha : \varphi_\alpha(U_\alpha) \rightarrow \mathbb{R}^n$  be such a diffeomorphism. We let  $\tilde{\varphi}_\alpha := \xi_\alpha \circ \varphi_\alpha : U_\alpha \rightarrow \mathbb{R}^n$ . A composition of diffeomorphisms is a diffeomorphism, so for all  $1 \leq \alpha, \beta \leq N$ ,  $\tilde{\varphi}_\alpha \circ \tilde{\varphi}_\beta^{-1} : \tilde{\varphi}_\beta(U_\alpha \cap U_\beta) \rightarrow \tilde{\varphi}_\alpha(U_\alpha \cap U_\beta)$  is a diffeomorphism. So  $\{(U_\alpha, \tilde{\varphi}_\alpha, \rho_\alpha)\}_{1 \leq \alpha \leq N}$  is clearly a smooth super nice total trivialization atlas. Moreover, if  $1 \leq \alpha, \beta \leq N$  are such that  $U_\alpha \cap U_\beta$  is nonempty, then  $\tilde{\varphi}_\alpha(U_\alpha \cap U_\beta)$  is  $\mathbb{R}^n$  or a bounded open set with Lipschitz continuous boundary. The reason is that  $\tilde{\varphi}_\alpha = \xi_\alpha \circ \varphi_\alpha$ , and  $\varphi_\alpha(U_\alpha \cap U_\beta)$  is  $\mathbb{R}^n$  or Lipschitz,  $\xi_\alpha$  is a diffeomorphism and being equal to  $\mathbb{R}^n$  or Lipschitz is a property that is preserved under diffeomorphisms. Therefore  $\{(U_\alpha, \tilde{\varphi}_\alpha, \rho_\alpha)\}_{1 \leq \alpha \leq N}$  is a finite super nice total trivialization atlas that is GL compatible with itself.  $\square$

A **section** of  $E$  is a map  $u : M \rightarrow E$  such that  $\pi \circ u = Id_M$ . The collection of all sections of  $E$  is denoted by  $\Gamma(M, E)$ . A section  $u \in \Gamma(M, E)$  is said to be smooth if it is smooth as a map from the smooth manifold  $M$  to the smooth manifold  $E$ . The collection of all smooth sections of  $E \rightarrow M$  is denoted by  $C^\infty(M, E)$ . Note that if  $\{(U_\alpha, \varphi_\alpha, \rho_\alpha)\}_{\alpha \in I}$  is a total trivialization atlas for the vector bundle  $E \rightarrow M$  of rank  $r$ , then for  $u \in \Gamma(M, E)$  we have

$$u \in C^\infty(M, E) \iff \forall \alpha \in I, \forall 1 \leq l \leq r \quad \rho_\alpha^l \circ u \circ \varphi_\alpha^{-1} \in C^\infty(\varphi_\alpha(U_\alpha))$$

A local section of  $E$  over an open set  $U \subseteq M$  is a map  $u : U \rightarrow E$  where  $u$  has the property that  $\pi \circ u = Id_U$  (that is,  $u$  is a section of the vector bundle  $E_U \rightarrow U$ ). We denote the collection of all local sections on  $U$  by  $\Gamma(U, E)$  or  $\Gamma(U, E_U)$ .

**Remark C.18.** *As a consequence of  $\rho|_{E_x} : E_x \rightarrow \mathbb{R}^r$  being an isomorphism, if  $u$  is a section of  $E|_U \rightarrow U$  and  $f : U \rightarrow \mathbb{R}$  is a function, then  $\rho(fu) = f\rho(u)$ . In particular  $\rho(0) = 0$ .*

Given a total trivialization triple  $(U, \varphi, \rho)$  we have the following commutative diagram

$$\begin{array}{ccc} E|_U & \xrightarrow{(\varphi \circ \pi, \rho^j)} & \varphi(U) \times \mathbb{R} \\ \downarrow \pi & & \downarrow \tilde{\pi} \\ U & \xrightarrow{\varphi} & \varphi(U) \subseteq \mathbb{R}^n \end{array}$$

If  $s$  is a section of  $E|_U \rightarrow U$ , then by definition the push forward of  $s$  by  $\rho^j$  (the  $j^{\text{th}}$  component of  $\rho$ ) is a section of  $\varphi(U) \times \mathbb{R} \rightarrow \varphi(U)$  which is defined by

$$\rho_*^j(s) = \rho^j \circ s \circ \varphi^{-1}$$

Let  $E \rightarrow M$  be a vector bundle of rank  $r$  and  $U \subseteq M$  be an open set. A **(smooth) local frame** for  $E$  over  $U$  is an ordered  $r$ -tuple  $(s_1, \dots, s_r)$  of smooth local sections over  $U$  such that for each  $x \in U$ ,  $(s_1(x), \dots, s_r(x))$  is a basis for  $E_x$ . Given any vector bundle chart  $(V, \rho)$ , we can define the associated local frame on  $V$  as follows:

$$\forall 1 \leq l \leq r \quad \forall x \in V \quad s_l(x) = \rho|_{E_x}^{-1}(e_l)$$

where  $(e_1, \dots, e_r)$  is the standard basis of  $\mathbb{R}^r$ . The following theorem states the converse of this observation is also true.

**Theorem C.19.** ([33], Page 258) *Let  $E \rightarrow M$  be a vector bundle of rank  $r$  and let  $(s_1, \dots, s_r)$  be a (smooth) local frame over an open set  $U \subseteq M$ . Then  $(U, \rho)$  is a vector bundle chart where the map  $\rho : E_U \rightarrow \mathbb{R}^r$  is defined by*

$$\forall x \in U, \forall u \in E_x \quad \rho(u) = u^1 e_1 + \dots + u^r e_r$$

where  $u = u^1 s_1(x) + \dots + u^r s_r(x)$ .

**Theorem C.20.** ([33], Page 260) *Let  $E \rightarrow M$  be a vector bundle of rank  $r$  and let  $(s_1, \dots, s_r)$  be a (smooth) local frame over an open set  $U \subseteq M$ . If  $f \in \Gamma(M, E)$ , then  $f$  is smooth on  $U$  if and only if its component functions with respect to  $(s_1, \dots, s_r)$  are smooth.*

A (smooth) **fiber metric** on a vector bundle  $E$  is a (smooth) function which assigns to each  $x \in M$  an inner product

$$\langle \cdot, \cdot \rangle_E : E_x \times E_x \rightarrow \mathbb{R}$$

Note that the smoothness of the fiber metric means that for all  $u, v \in C^\infty(M, E)$  the mapping

$$M \rightarrow \mathbb{R}, \quad x \mapsto \langle u(x), v(x) \rangle_E$$

is smooth. One can show that every (smooth) vector bundle can be equipped with a (smooth) fiber metric ([41], Page 72).

**Remark C.21.** *If  $(M, g)$  is a Riemannian manifold, then  $g$  can be viewed as a fiber metric on the tangent bundle. The metric  $g$  induces fiber metrics on all tensor bundles; it can be shown that [32] if  $(M, g)$  is a Riemannian manifold, then there exists a unique inner product on each fiber of  $T_l^k(M)$  with the property that for all  $x \in M$ , if  $\{e_i\}$  is an orthonormal basis of  $T_x M$  with dual basis  $\{\eta^i\}$ , then the corresponding basis of  $T_l^k(T_x M)$  is orthonormal. When there is no ambiguity, we denote this inner product by  $\langle \cdot, \cdot \rangle_F$  and the corresponding norm by  $|\cdot|_F$ . If  $A$  and  $B$  are two tensor fields, then with respect to any local frame*

$$\langle A, B \rangle_F = g^{i_1 r_1} \dots g^{i_k r_k} g_{j_1 s_1} \dots g_{j_l s_l} A_{i_1 \dots i_k}^{j_1 \dots j_l} B_{r_1 \dots r_k}^{s_1 \dots s_l}$$

**Theorem C.22.** *Let  $\pi : E \rightarrow M$  be a vector bundle with rank  $r$  equipped with a fiber metric  $\langle \cdot, \cdot \rangle_E$ . Then given any total trivialization triple  $(U, \varphi, \rho)$ , there exists a smooth map  $\tilde{\rho} : E_U \rightarrow \mathbb{R}^r$  such that with respect to the new total trivialization triple  $(U, \varphi, \tilde{\rho})$  the fiber metric trivializes on  $U$ , that is*

$$\forall x \in U \quad \forall u, v \in E_x \quad \langle u, v \rangle_E = u^1 v^1 + \dots + u^r v^r$$

where for each  $1 \leq l \leq r$ ,  $u^l$  and  $v^l$  denote the  $l^{\text{th}}$  component of  $u$  and  $v$ , respectively (with respect to the local frame associated with the bundle chart  $(U, \tilde{\rho})$ ).



*Proof.* Let  $(t_1, \dots, t_r)$  be the local frame on  $U$  associated with the vector bundle chart  $(U, \rho)$ . That is

$$\forall x \in U, \forall 1 \leq l \leq r \quad t_l(x) = \rho|_{E_x}^{-1}(e_l)$$

Now we apply the Gram-Schmidt algorithm to the local frame  $(t_1, \dots, t_r)$  to construct an orthonormal frame  $(s_1, \dots, s_r)$  where

$$\forall 1 \leq l \leq r \quad s_l = \frac{t_l - \sum_{j=1}^{l-1} \langle t_l, s_j \rangle_E s_j}{|t_l - \sum_{j=1}^{l-1} \langle t_l, s_j \rangle_E s_j|}$$

$s_l : U \rightarrow E$  is smooth because

- (1) smooth local sections over  $U$  form a module over the ring  $C^\infty(U)$ ,
- (2) the function  $x \mapsto \langle t_l(x), s_j(x) \rangle_E$  from  $U$  to  $\mathbb{R}$  is smooth,
- (3) Since  $\text{Span}\{s_1, \dots, s_{l-1}\} = \text{Span}\{t_1, \dots, t_{l-1}\}$ ,  $t_l - \sum_{j=1}^{l-1} \langle t_l, s_j \rangle_E s_j$  is nonzero on  $U$  and  $x \mapsto |t_l(x) - \sum_{j=1}^{l-1} \langle t_l(x), s_j(x) \rangle_E s_j(x)|$  as a function from  $U$  to  $\mathbb{R}$  is nonzero on  $U$  and it is a composition of smooth functions.

Thus for each  $l$ ,  $s_l$  is a linear combination of elements of the  $C^\infty(U)$ -module of smooth local sections over  $U$ , and so it is a smooth local section over  $U$ . Now we let  $(U, \tilde{\rho})$  be the associated vector bundle chart described in Theorem C.19. For all  $x \in U$  and for all  $u, v \in E_x$  we have

$$\langle u, v \rangle_E = \langle u^l s_l, v^j s_j \rangle_E = u^l v^j \langle s_l, s_j \rangle_E = u^l v^j \delta_{lj} = u^1 v^1 + \dots + u^r v^r.$$

□

**Corollary C.23.** *As a consequence of Theorem C.22, Theorem C.16, and Theorem C.15 every vector bundle on a compact manifold equipped with a fiber metric admits a nice finite total trivialization atlas (and a super nice finite total trivialization atlas and a finite total trivialization atlas that is GL compatible with itself) such that the fiber metric is trivialized with respect to each total trivialization triple in the atlas.*

**Lemma C.24.** ([33], Page 252) *Let  $\pi : E \rightarrow M$  be a smooth vector bundle of rank  $r$  over  $M$ . Suppose  $\Phi : \pi^{-1}(U) \rightarrow U \times \mathbb{R}^r$  and  $\Psi : \pi^{-1}(V) \rightarrow V \times \mathbb{R}^r$  are two smooth local trivializations of  $E$  with  $U \cap V \neq \emptyset$ . There exists a smooth map  $\tau : U \cap V \rightarrow GL(r, \mathbb{R})$  such that the composition*

$$\Phi \circ \Psi^{-1} : (U \cap V) \times \mathbb{R}^r \rightarrow (U \cap V) \times \mathbb{R}^r$$

*has the form*

$$\Phi \circ \Psi^{-1}(p, v) = (p, \tau(p)v)$$

**C.3. Standard Total Trivialization Triples.** Let  $M^n$  be a smooth manifold and  $\pi : E \rightarrow M$  be a vector bundle of rank  $r$ . For certain vector bundles there are standard methods to associate with any given smooth coordinate chart  $(U, \varphi = (x^i))$  a total trivialization triple  $(U, \varphi, \rho)$ . We call such a total trivialization triple the **standard total trivialization** associated with  $(U, \varphi)$ . Usually this is done by first associating with  $(U, \varphi)$  a local frame for  $E_U$  and then applying Theorem C.19 to construct a total trivialization triple.

- $E = T_l^k(M)$ : The collection of the following tensor fields on  $U$  form a local frame for  $E_U$  associated with  $(U, \varphi = (x^i))$

$$\frac{\partial}{\partial x^{i_1}} \otimes \dots \otimes \frac{\partial}{\partial x^{i_l}} \otimes dx^{j_1} \otimes \dots \otimes dx^{j_k}$$

So given any atlas  $\{(U_\alpha, \varphi_\alpha)\}$  of a manifold  $M^n$ , there is a corresponding total trivialization atlas for the tensor bundle  $T_l^k(M)$ , namely  $\{(U_\alpha, \varphi_\alpha, \rho_\alpha)\}$  where for each  $\alpha$ ,  $\rho_\alpha$  has  $n^{k+l}$  components which we denote by  $(\rho_\alpha)_{i_1 \dots i_k}^{j_1 \dots j_l}$ . For all  $F \in \Gamma(M, T_l^k(M))$ , we have

$$(\rho_\alpha)_{i_1 \dots i_k}^{j_1 \dots j_l}(F) = (F_\alpha)_{i_1 \dots i_k}^{j_1 \dots j_l}$$

Here  $(F_\alpha)_{i_1 \dots i_k}^{j_1 \dots j_l}$  denotes the components of  $F$  with respect to the standard frame for  $T_l^k U_\alpha$  described above. When there is no possibility of confusion, we may write  $F_{i_1 \dots i_k}^{j_1 \dots j_l}$  instead of  $(F_\alpha)_{i_1 \dots i_k}^{j_1 \dots j_l}$ .

- $E = \Lambda^k(M)$  The collection of the following forms on  $U$  form a local frame for  $E_U$  associated with  $(U, \varphi = (x^i))$

$$dx^{j_1} \wedge \dots \wedge dx^{j_k} \quad ((j_1, \dots, j_k) \text{ is increasing})$$

- $E = \mathcal{D}(M)$  (the density bundle) The density bundle over  $M$  is the vector bundle whose fiber over each  $x \in M$  is  $\mathcal{D}(T_x M)$ . More precisely, if we let

$$\mathcal{D}(M) = \coprod_{x \in M} \mathcal{D}(T_x M)$$

then  $\mathcal{D}(M)$  is a smooth vector bundle of rank 1 over  $M$  ([33], Page 429). Indeed, for every smooth chart  $(U, \varphi = (x^i))$ ,  $|dx^1 \wedge \dots \wedge dx^n|$  on  $U$  is a local frame for  $\mathcal{D}(M)|_U$ . We denote the corresponding trivialization by  $\rho_{\mathcal{D}, \varphi}$ , that is, given  $\mu \in \mathcal{D}(T_y M)$ , there exists a number  $a$  such that

$$\mu = a(|dx^1 \wedge \dots \wedge dx^n|_y)$$

and  $\rho_{\mathcal{D}, \varphi}$  sends  $\mu$  to  $a$ . Sometimes we write  $\mathcal{D}$  instead of  $\mathcal{D}(M)$  if  $M$  is clear from the context. Also when there is no possibility of confusion we may write  $\rho_{\mathcal{D}}$  instead of  $\rho_{\mathcal{D}, \varphi}$ .

**Remark C.25** (Integration of densities on manifolds). *Elements of  $C_c(M, \mathcal{D})$  can be integrated over  $M$ . Indeed, for  $\mu \in C_c(M, \mathcal{D})$  we may consider two cases*

- **Case 1:** *There exists a smooth chart  $(U, \varphi)$  such that  $\text{supp} \mu \subseteq U$ .*

$$\int_M \mu := \int_{\varphi(U)} \rho_{\mathcal{D}, \varphi} \circ \mu \circ \varphi^{-1} dV$$

- **Case 2:** *If  $\mu$  is an arbitrary element of  $C_c(M, \mathcal{D})$ , then we consider a smooth atlas  $\{U_\alpha, \varphi_\alpha\}_{\alpha \in I}$  and a partition of unity  $\{\psi_\alpha\}_{\alpha \in I}$  subordinate to  $\{U_\alpha\}$  and we let*

$$\int_M \mu := \sum_{\alpha \in I} \int_M \psi_\alpha \mu$$

*It can be shown that the above definitions are independent of the choices (charts and partition of unity) involved ([33], Pages 431 and 432).*

## C.4. Constructing New Bundles From Old Ones.

### C.4.1. Hom Bundle, Dual Bundle, Functional Dual Bundle.

- The construction  $\text{Hom}(\cdot, \cdot)$  can be applied fiberwise to a pair of vector bundles  $E$  and  $\tilde{E}$  over a manifold  $M$  to give a new vector bundle denoted by  $\text{Hom}(E, \tilde{E})$ . The fiber of  $\text{Hom}(E, \tilde{E})$  at any given point  $p \in M$  is the vector space  $\text{Hom}(E_p, \tilde{E}_p)$ . Clearly if  $\text{rank } E = r$  and  $\text{rank } \tilde{E} = \tilde{r}$ , then  $\text{rank } \text{Hom}(E, \tilde{E}) = r\tilde{r}$ .

If  $\{(U_\alpha, \varphi_\alpha, \rho_\alpha)\}$  and  $\{(U_\alpha, \varphi_\alpha, \tilde{\rho}_\alpha)\}$  are total trivialization atlases for the vector bundles  $\pi : E \rightarrow M$  and  $\tilde{\pi} : \tilde{E} \rightarrow M$ , respectively, then  $\{(U_\alpha, \varphi_\alpha, \hat{\rho}_\alpha)\}$  will be a total trivialization atlas for  $\pi_{\text{Hom}} : \text{Hom}(E, \tilde{E}) \rightarrow M$  where

$$\hat{\rho}_\alpha : \pi_{\text{Hom}}^{-1}(U_\alpha) \rightarrow \text{Hom}(\mathbb{R}^r, \mathbb{R}^r) \cong \mathbb{R}^{r^2}, \quad A \mapsto [\tilde{\rho}_\alpha|_{E_{\tilde{\pi}(A)}}] \circ A \circ [\rho_\alpha|_{E_{\pi(A)}}]^{-1}$$

- Let  $\pi : E \rightarrow M$  be a vector bundle. The **dual bundle**  $E^*$  is defined by  $E^* = \text{Hom}(E, \tilde{E} = M \times \mathbb{R})$ .
- Let  $\pi : E \rightarrow M$  be a vector bundle. The **functional dual bundle**  $E^\vee$  is defined by  $E^\vee = \text{Hom}(E, \mathcal{D})$  where  $\mathcal{D}$  denotes the density bundle of  $M$  (see [38]). Let's describe explicitly what the standard total trivialization triples of this bundle are. Let  $(U, \varphi, \rho)$  be a total trivialization triple for  $E$ . We can associate with this triple the total trivialization triple  $(U, \varphi, \rho^\vee)$  for  $E^\vee$  where  $\rho^\vee : E^\vee \rightarrow \mathbb{R}^r$  is defined as follows: for  $x \in U$ ,  $L_x \in \text{Hom}(E_x, \mathcal{D}_x)$  is mapped to  $\rho_{\mathcal{D}, \varphi} \circ L_x \circ (\rho|_{E_x})^{-1} \in (\mathbb{R}^r)^* \simeq \mathbb{R}^r$ . Note that  $(\mathbb{R}^r)^* \simeq \mathbb{R}^r$  under the following isomorphism

$$(\mathbb{R}^r)^* \rightarrow \mathbb{R}^r, \quad u \mapsto u(e_1)e_1 + \cdots + u(e_r)e_r$$

That is  $u$  as an element of  $\mathbb{R}^r$  is the vector whose components are  $(u(e_1), \dots, u(e_r))$ . In particular if  $z = z_1e_1 + \cdots + z_re_r$  is an arbitrary vector in  $\mathbb{R}^r$ , then

$$u(z) = u(z_1e_1 + \cdots + z_re_r) = z_1u(e_1) + \cdots + z_ru(e_r) = z \cdot u$$

where on the LHS  $u$  is viewed as an element of  $(\mathbb{R}^r)^*$  and on the RHS  $u$  is viewed as an element of  $\mathbb{R}^r$ .

**C.4.2. Tensor Product Of Bundles.** Let  $\pi : E \rightarrow M$  and  $\tilde{\pi} : \tilde{E} \rightarrow M$  be two vector bundles. Then  $E \otimes \tilde{E}$  is a new vector bundle whose fiber at  $p \in M$  is  $E_p \otimes \tilde{E}_p$ . If  $\{(U_\alpha, \varphi_\alpha, \rho_\alpha)\}$  and  $\{(U_\alpha, \varphi_\alpha, \tilde{\rho}_\alpha)\}$  are total trivialization atlases for the vector bundles  $\pi : E \rightarrow M$  and  $\tilde{\pi} : \tilde{E} \rightarrow M$ , respectively, then  $\{(U_\alpha, \varphi_\alpha, \hat{\rho}_\alpha)\}$  will be a total trivialization atlas for  $\pi_{\text{tensor}} : E \otimes \tilde{E} \rightarrow M$  where

$$\hat{\rho}_\alpha : \pi_{\text{tensor}}^{-1}(U_\alpha) \rightarrow (\mathbb{R}^r \otimes \mathbb{R}^r) \cong \mathbb{R}^{r^2}, \quad a \mapsto \rho_\alpha|_{E_{\pi(a)}}(a) \otimes \tilde{\rho}_\alpha|_{E_{\tilde{\pi}(a)}}(a)$$

It can be shown that  $E \otimes \tilde{E} \cong \text{Hom}(E^*, \tilde{E})$  (isomorphism of vector bundles over  $M$ ).

**Remark C.26** (Fiber Metric on Tensor Product). *Consider the inner product spaces  $(U, \langle \cdot, \cdot \rangle_U)$  and  $(V, \langle \cdot, \cdot \rangle_V)$ . We can turn the tensor product of  $U$  and  $V$ ,  $U \otimes V$  into an inner product space by defining*

$$\langle u_1 \otimes v_1, u_2 \otimes v_2 \rangle_{U \otimes V} = \langle u_1, u_2 \rangle_U \langle v_1, v_2 \rangle_V$$

and extending by linearity. As a consequence, if  $E$  is a vector bundle (on a Riemannian manifold  $(M, g)$ ) equipped with a fiber metric  $\langle \cdot, \cdot \rangle_E$ , then there is a natural fiber metric on the bundle  $(T^*M)^{\otimes k}$  and subsequently on the bundle  $(T^*M)^{\otimes k} \otimes E$ . If  $F = F_{i_1 \dots i_k}^a dx^{i_1} \otimes \cdots \otimes dx^{i_k} \otimes s_a$  and  $G = G_{j_1 \dots j_k}^b dx^{j_1} \otimes \cdots \otimes dx^{j_k} \otimes s_b$  are two local sections of this bundle on a domain  $U$  of a chart, then at any point in  $U$  we have

$$\begin{aligned} \langle F, G \rangle_E &= F_{i_1 \dots i_k}^a G_{j_1 \dots j_k}^b \langle dx^{i_1}, dx^{j_1} \rangle_{T^*M} \cdots \langle dx^{i_k}, dx^{j_k} \rangle_{T^*M} \langle s_a, s_b \rangle_E \\ &= g^{i_1 j_1} \cdots g^{i_k j_k} h_{ab} F_{i_1 \dots i_k}^a G_{j_1 \dots j_k}^b \end{aligned}$$

where  $h_{ab} := \langle s_a, s_b \rangle_E$ .

### C.5. Connection on Vector Bundles, Covariant Derivative.

C.5.1. *Basic Definitions.* Let  $\pi : E \rightarrow M$  be a vector bundle.

**Definition C.27.** A *connection* in  $E$  is a map

$$\nabla : C^\infty(M, TM) \times C^\infty(M, E) \rightarrow C^\infty(M, E), \quad (X, u) \mapsto \nabla_X u$$

satisfying the following properties:

(1)  $\nabla_X u$  is linear over  $C^\infty(M)$  in  $X$

$$\forall f, g \in C^\infty(M) \quad \nabla_{fX_1 + gX_2} u = f\nabla_{X_1} u + g\nabla_{X_2} u$$

(2)  $\nabla_X u$  is linear over  $\mathbb{R}$  in  $u$ :

$$\forall a, b \in \mathbb{R} \quad \nabla_X (au_1 + bu_2) = a\nabla_X u_1 + b\nabla_X u_2$$

(3)  $\nabla$  satisfies the following product rule

$$\forall f \in C^\infty(M) \quad \nabla_X (fu) = f\nabla_X u + (Xf)u$$

A **metric connection** in a real vector bundle  $E$  with a fiber metric is a connection  $\nabla$  such that

$$\forall X \in C^\infty(M, TM), \forall u, v \in C^\infty(M, E) \quad X\langle u, v \rangle_E = \langle \nabla_X u, v \rangle_E + \langle u, \nabla_X v \rangle_E$$

Here is a list of useful facts about connections:

- ([30], Page 183) Using a partition of unity, one can show that any real vector bundle with fiber metric admits a metric connection
- ([33], Page 50) If  $\nabla$  is a connection in a bundle  $E$ ,  $X \in C^\infty(M, TM)$ ,  $u \in C^\infty(M, E)$ , and  $p \in M$ , then  $\nabla_X u|_p$  depends only on the values of  $u$  in a neighborhood of  $p$  and the value of  $X$  at  $p$ . More precisely, if  $u = \tilde{u}$  on a neighborhood of  $p$  and  $X_p = \tilde{X}_p$ , then  $\nabla_X u|_p = \nabla_{\tilde{X}} \tilde{u}|_p$ .
- ([33], Page 53) If  $\nabla$  is a connection in  $TM$ , then there exists a unique connection in each tensor bundle  $T_l^k(M)$ , also denoted by  $\nabla$ , such that the following conditions are satisfied:
  - (1) On the tangent bundle,  $\nabla$  agrees with the given connection.
  - (2) On  $T^0(M)$ ,  $\nabla$  is given by ordinary differentiation of functions, that is, for all real-valued smooth functions  $f : M \rightarrow \mathbb{R}$ :  $\nabla_X f = Xf$ .
  - (3)  $\nabla_X (F \otimes G) = (\nabla_X F) \otimes G + F \otimes (\nabla_X G)$ .
  - (4) If  $\text{tr}$  denotes the trace on any pair of indices, then  $\nabla_X (\text{tr} F) = \text{tr}(\nabla_X F)$ .
 This connection satisfies the following additional property: for any  $T \in C^\infty(M, T_l^k(M))$ , vector fields  $Y_i$ , and differential 1-forms  $\omega^j$ ,

$$\begin{aligned} (\nabla_X T)(\omega^1, \dots, \omega^l, Y_1, \dots, Y_k) &= X(T(\omega^1, \dots, \omega^l, Y_1, \dots, Y_k)) \\ &\quad - \sum_{j=1}^l T(\omega^1, \dots, \nabla_X \omega^j, \dots, \omega^l, Y_1, \dots, Y_k) \\ &\quad - \sum_{i=1}^k T(\omega^1, \dots, \omega^l, Y_1, \dots, \nabla_X Y_i, \dots, Y_k). \end{aligned}$$

**Definition C.28.** Let  $\nabla$  be a connection in  $\pi : E \rightarrow M$ . We define the corresponding **covariant derivative** on  $E$ , also denoted  $\nabla$ , as follows

$$\nabla : C^\infty(M, E) \rightarrow C^\infty(M, \text{Hom}(TM, E)) \cong C^\infty(M, T^*M \otimes E), \quad u \mapsto \nabla u$$

where for all  $p \in M$ ,  $\nabla u(p) : T_p M \rightarrow E_p$  is defined by

$$X \mapsto \nabla_X u|_p$$

**Remark C.29.** Let  $\nabla$  be a connection in  $TM$ . As it was discussed  $\nabla$  induces a connection in any tensor bundle  $E = T_l^k(M)$ , also denoted by  $\nabla$ . Some authors (including Lee in [33], Page 53) define the corresponding covariant derivative on  $E = T_l^k(M)$  as follows:

$$\nabla : C^\infty(M, T_l^k(M)) \rightarrow C^\infty(M, T_l^{k+1}(M)), \quad F \mapsto \nabla F$$

where

$$\nabla F(\omega^1, \dots, \omega^l, Y_1, \dots, Y_k, X) = (\nabla_X F)(\omega^1, \dots, \omega^l, Y_1, \dots, Y_k)$$

This definition agrees with the previous definition of covariant derivative that we had for general vector bundles because

$$T^*M \otimes T_l^k M \cong T^*M \otimes \underbrace{T^*M \otimes \dots \otimes T^*M}_{k \text{ factors}} \otimes \underbrace{TM \otimes \dots \otimes TM}_{l \text{ factors}} \cong T_l^{k+1} M$$

Therefore

$$C^\infty(M, \text{Hom}(TM, T_l^k M)) \cong C^\infty(M, T^*M \otimes T_l^k M) \cong C^\infty(M, T_l^{k+1} M)$$

More concretely we have the following one-to-one correspondence between  $C^\infty(M, \text{Hom}(TM, T_l^k M))$  and  $C^\infty(M, T_l^{k+1} M)$ :

(1) Given  $u \in C^\infty(M, T_l^{k+1} M)$ , the corresponding element  $\mathfrak{u} \in C^\infty(M, \text{Hom}(TM, T_l^k M))$  is given by

$$\forall p \in M \quad \tilde{u}(p) : T_p M \rightarrow T_l^k(T_p M), \quad X \mapsto u(p)(\dots, \dots, X)$$

(2) Given  $\tilde{u} \in C^\infty(M, \text{Hom}(TM, T_l^k M))$ , the corresponding element  $u \in C^\infty(M, T_l^{k+1} M)$  is given by

$$\forall p \in M \quad u(p)(\omega^1, \dots, \omega^l, Y_1, \dots, Y_k, X) = [\tilde{u}(p)(X)](\omega^1, \dots, \omega^l, Y_1, \dots, Y_k)$$

**C.5.2. Covariant Derivative on Tensor Product of Bundles.** ([36], Page 87) If  $E$  and  $\tilde{E}$  are vector bundles over  $M$  with covariant derivatives  $\nabla^E : C^\infty(M, E) \rightarrow C^\infty(M, T^*M \otimes E)$  and  $\nabla^{\tilde{E}} : C^\infty(M, \tilde{E}) \rightarrow C^\infty(M, T^*M \otimes \tilde{E})$ , respectively, then there is a uniquely determined covariant derivative

$$\nabla^{E \otimes \tilde{E}} : C^\infty(M, E \otimes \tilde{E}) \rightarrow C^\infty(M, T^*M \otimes E \otimes \tilde{E})$$

such that

$$\nabla^{E \otimes \tilde{E}}(u \otimes \tilde{u}) = \nabla^E u \otimes \tilde{u} + \nabla^{\tilde{E}} \tilde{u} \otimes u$$

The above sum makes sense because of the following isomorphisms:

$$(T^*M \otimes E) \otimes \tilde{E} \cong T^*M \otimes E \otimes \tilde{E} \cong T^*M \otimes \tilde{E} \otimes E \cong (T^*M \otimes \tilde{E}) \otimes E$$

**Remark C.30.** Recall that for tensor fields covariant derivative can be considered as a map from  $C^\infty(M, T_l^k M) \rightarrow C^\infty(M, T_l^{k+1} M)$ . Using this, we can give a second description of covariant derivative on  $E \otimes \tilde{E}$  when  $E = T_l^k M$ . In this new description we have

$$\nabla^{T_l^k M \otimes \tilde{E}} : C^\infty(M, T_l^k M \otimes \tilde{E}) \rightarrow C^\infty(M, T_l^{k+1} M \otimes \tilde{E})$$

Indeed, for  $F \in C^\infty(M, T_l^k M)$  and  $u \in C^\infty(M, \tilde{E})$

$$\nabla^{T_l^k M \otimes \tilde{E}}(F \otimes u) = \underbrace{(\nabla^{T_l^k M} F)}_{T_l^{k+1} M} \otimes u + \underbrace{F \otimes \nabla^{\tilde{E}} u}_{\underbrace{T_l^k M \otimes T^*M \otimes \tilde{E}}_{T_l^{k+1} M \otimes \tilde{E}}}$$

In particular, if  $f \in C^\infty(M)$  and  $u \in C^\infty(M, E)$  we have  $\nabla^E(fu) \in C^\infty(M, T^*M \otimes E)$  and it is equal to

$$\nabla^E(fu) = df \otimes u + f\nabla^E u$$

**C.5.3. Higher Order Covariant Derivatives.** Let  $\pi : E \rightarrow M$  be a vector bundle. Let  $\nabla^E$  be a connection in  $E$  and  $\nabla$  be a connection in  $TM$  which induces a connection in  $T^*M$ . We have the following chain

$$\begin{aligned} C^\infty(M, E) &\xrightarrow{\nabla^E} C^\infty(M, T^*M \otimes E) \xrightarrow{\nabla^{T^*M \otimes E}} C^\infty(M, (T^*M)^{\otimes 2} \otimes E) \xrightarrow{\nabla^{(T^*M)^{\otimes 2} \otimes E}} \dots \\ &\dots \xrightarrow{\nabla^{(T^*M)^{\otimes (k-1)} \otimes E}} C^\infty(M, (T^*M)^{\otimes k} \otimes E) \xrightarrow{\nabla^{(T^*M)^{\otimes k} \otimes E}} \dots \end{aligned}$$

In what follows we denote all the maps in the above chain by  $\nabla^E$ . That is, for any  $k \in \mathbb{N}_0$  we consider  $\nabla^E$  as a map from  $C^\infty(M, (T^*M)^{\otimes k} \otimes E)$  to  $C^\infty(M, (T^*M)^{\otimes (k+1)} \otimes E)$ . So

$$(\nabla^E)^k : C^\infty(M, E) \rightarrow C^\infty(M, (T^*M)^{\otimes k} \otimes E)$$

As an example let's consider  $(\nabla^E)^k(fu)$  where  $f \in C^\infty(M)$  and  $u \in C^\infty(M, E)$ . We have

$$\begin{aligned} \nabla^E(fu) &= df \otimes u + f\nabla^E u \\ (\nabla^E)^2(fu) &= \nabla^{T^*M \otimes E} [df \otimes u + f\nabla^E u] \\ &= [\nabla^{T^*M}(df) \otimes u + df \otimes \nabla^E u] + [df \otimes \nabla^E u + f(\nabla^E)^2 u] \\ &= \sum_{j=0}^2 \binom{2}{j} (\nabla^{T^*M})^j f \otimes (\nabla^E)^{2-j} u \end{aligned}$$

In general, we can show by induction that

$$(\nabla^E)^k(fu) = \sum_{j=0}^k \binom{k}{j} (\nabla^{T^*M})^j f \otimes (\nabla^E)^{k-j} u$$

where  $(\nabla^{T^*M})^0 = Id$ .

**C.5.4. Three Useful Rules, Two Important Observations.** Let  $\pi : E \rightarrow M$  and  $\tilde{\pi} : \tilde{E} \rightarrow M$  be two vector bundles over  $M$  with ranks  $r$  and  $\tilde{r}$ , respectively. Let  $\nabla$  be a connection in  $TM$  (which automatically induces a connection in all tensor bundles),  $\nabla^E$  be a connection in  $E$  and  $\nabla^{\tilde{E}}$  be a connection in  $\tilde{E}$ . Let  $(U, \varphi, \rho)$  be a total trivialization triple for  $E$ .

- (1)  $\{\partial_i = \varphi_*^{-1} \frac{\partial}{\partial x^i}\}_{1 \leq i \leq n}$  is a coordinate frame for  $TM$  over  $U$ .
- (2)  $\{s_a = \rho^{-1}(e_a)\}_{1 \leq a \leq r}$  is a local frame for  $E$  over  $U$ . ( $\{e_a\}_{1 \leq a \leq r}$  is the standard basis for  $\mathbb{R}^r$  where  $r = \text{rank } E$ .)
- (3) Christoffel Symbols for  $\nabla$  on  $(U, \varphi, \rho)$ :  $\nabla_{\partial_i} \partial_j = \Gamma_{ij}^k \partial_k$
- (4) Christoffel Symbols for  $\nabla^E$  on  $(U, \varphi, \rho)$ :  $\nabla_{\partial_i} s_a = (\Gamma_E)_{ia}^b s_b$

Also recall that for any 1-form  $\omega$

$$\nabla_X \omega = (X^i \partial_i \omega_k - X^i \omega_j \Gamma_{ik}^j) dx^k$$

Therefore

$$\nabla_{\partial_i} dx^j = -\Gamma_{ik}^j dx^k$$

- **Rule 1:** For all  $u \in C^\infty(M, E)$

$$\nabla^E u = dx^i \otimes \nabla_{\partial_i}^E u \quad \text{on } U$$

The reason is as follows: Recall that for all  $p \in M$ ,  $\nabla^E u(p) \in T^*M \otimes E$ . Since  $\{dx^i \otimes s_a\}$  is a local frame for  $T^*M \otimes E$  on  $U$  we have

$$\nabla^E u = R_i^a dx^i \otimes s_a = dx^i \otimes (R_i^a s_a)$$

According to what was discussed in the study of the isomorphism  $\text{Hom}(V, W) \cong V^* \otimes W$  in Appendix A we know that at any point  $p \in M$ ,  $R_i^a$  is the element in column  $i$  and row  $a$  of the matrix of  $\nabla^E u(p)$  as an element of  $\text{Hom}(T_p M, E_p)$ . Therefore

$$\nabla_{\partial_i}^E u = R_i^a s_a$$

Consequently we have  $\nabla^E u = dx^i \otimes (R_i^a s_a) = dx^i \otimes \nabla_{\partial_i}^E u$ .

- **Rule 2:** For all  $v_1 \in C^\infty(M, E)$  and  $v_2 \in C^\infty(M, \tilde{E})$

$$\nabla_{\partial_j}^{E \otimes \tilde{E}}(v_1 \otimes v_2) = (\nabla_{\partial_j}^E v_1) \otimes v_2 + v_1 \otimes (\nabla_{\partial_j}^{\tilde{E}} v_2)$$

- **Rule 3:** For all  $u \in C^\infty(M, E)$  and  $f \in C^\infty(M)$

$$\nabla^E(fu) = f\nabla^E u + df \otimes u$$

The following two examples are taken from [19].

- **Example 1:** Let  $u \in C^\infty(M, E)$ . On  $U$  we may write  $u = u^a s_a$ . We have

$$\begin{aligned} \nabla^E u &= \nabla^E(u^a s_a) \stackrel{\text{Rule 3}}{=} u^a \nabla^E s_a + du^a \otimes s_a = u^a \nabla^E s_a + (\partial_i u^a dx^i) \otimes s_a \\ &\stackrel{\text{Rule 1}}{=} u^a dx^i \otimes \nabla_{\partial_i}^E s_a + (\partial_i u^a dx^i) \otimes s_a \\ &= u^a dx^i \otimes ((\Gamma_E)_{ia}^b s_b) + (\partial_i u^a dx^i) \otimes s_a = dx^i \otimes (u^a (\Gamma_E)_{ia}^b s_b) + dx^i \otimes (\partial_i u^a s_a) \\ &= dx^i \otimes (u^b (\Gamma_E)_{ib}^a s_a) + dx^i \otimes (\partial_i u^a s_a) \\ &= [\partial_i u^a + (\Gamma_E)_{ib}^a u^b] dx^i \otimes s_a \end{aligned}$$

That is,  $\nabla^E u = (\nabla^E u)_i^a dx^i \otimes s_a$  where

$$(\nabla^E u)_i^a = \partial_i u^a + (\Gamma_E)_{ib}^a u^b$$

- **Example 2:** Let  $u \in C^\infty(M, E)$ . On  $U$  we may write  $u = u^a s_a$ . We have

$$\begin{aligned} (\nabla^E)^2 u &= \nabla^{T^*M \otimes E}([\partial_i u^a + (\Gamma_E)_{ib}^a u^b] dx^i \otimes s_a) \\ &\stackrel{\text{Rule 3}}{=} [\partial_i u^a + (\Gamma_E)_{ib}^a u^b] \nabla^{T^*M \otimes E}(dx^i \otimes s_a) + d[\partial_i u^a + (\Gamma_E)_{ib}^a u^b] \otimes (dx^i \otimes s_a) \\ &\stackrel{\text{Rule 1}}{=} [\partial_i u^a + (\Gamma_E)_{ib}^a u^b] dx^j \otimes \nabla_{\partial_j}^{T^*M \otimes E}(dx^i \otimes s_a) + d[\partial_i u^a + (\Gamma_E)_{ib}^a u^b] \otimes (dx^i \otimes s_a) \\ &\stackrel{\text{Def. of } d}{=} [\partial_i u^a + (\Gamma_E)_{ib}^a u^b] dx^j \otimes \nabla_{\partial_j}^{T^*M \otimes E}(dx^i \otimes s_a) + \partial_j [\partial_i u^a + (\Gamma_E)_{ib}^a u^b] dx^j \otimes dx^i \otimes s_a \\ &\stackrel{\text{Rule 2}}{=} [\partial_i u^a + (\Gamma_E)_{ib}^a u^b] dx^j \otimes [\nabla_{\partial_j}^{T^*M} dx^i \otimes s_a + dx^i \otimes \nabla_{\partial_j}^E s_a] + \partial_j [\partial_i u^a + (\Gamma_E)_{ib}^a u^b] dx^j \otimes dx^i \otimes s_a \\ &= [\partial_i u^a + (\Gamma_E)_{ib}^a u^b] dx^j \otimes [-\Gamma_{jk}^i dx^k \otimes s_a + dx^i \otimes (\Gamma_E)_{ja}^c s_c] + \partial_j [\partial_i u^a + (\Gamma_E)_{ib}^a u^b] dx^j \otimes dx^i \otimes s_a \\ &\stackrel{i \leftrightarrow k \text{ in the first summand}}{=} [\partial_k u^a + (\Gamma_E)_{kb}^a u^b] dx^j \otimes [-\Gamma_{ji}^k dx^i \otimes s_a + dx^k \otimes (\Gamma_E)_{ja}^c s_c] + \partial_j [\partial_i u^a + (\Gamma_E)_{ib}^a u^b] dx^j \otimes dx^i \otimes s_a \\ &= \{\partial_j [\partial_i u^a + (\Gamma_E)_{ib}^a u^b] - \Gamma_{ji}^k [\partial_k u^a + (\Gamma_E)_{kb}^a u^b]\} dx^j \otimes dx^i \otimes s_a + [\partial_k u^a + (\Gamma_E)_{kb}^a u^b] (\Gamma_E)_{ja}^c dx^j \otimes dx^k \otimes s_c \\ &\stackrel{i \leftrightarrow k \text{ in the last summand}}{=} \{\partial_j [\partial_i u^a + (\Gamma_E)_{ib}^a u^b] - \Gamma_{ji}^k [\partial_k u^a + (\Gamma_E)_{kb}^a u^b]\} dx^j \otimes dx^i \otimes s_a \\ &\quad + [\partial_i u^a + (\Gamma_E)_{ib}^a u^b] (\Gamma_E)_{ja}^c dx^j \otimes dx^i \otimes s_c \\ &\stackrel{c \leftrightarrow a \text{ in the last summand}}{=} \{\partial_j [\partial_i u^a + (\Gamma_E)_{ib}^a u^b] - \Gamma_{ji}^k [\partial_k u^a + (\Gamma_E)_{kb}^a u^b]\} dx^j \otimes dx^i \otimes s_a \\ &\quad + [\partial_i u^c + (\Gamma_E)_{ib}^c u^b] (\Gamma_E)_{ja}^c dx^j \otimes dx^i \otimes s_a \end{aligned}$$

Considering the above examples we make the following two useful observations that can be proved by induction.

- **Observation 1:** In general  $(\nabla^E)^k u = ((\nabla^E)^k u)_{i_1 \dots i_k}^a dx^{i_1} \otimes \dots \otimes dx^{i_k} \otimes s_a$  ( $1 \leq a \leq r$ ,  $1 \leq i_1, \dots, i_k \leq n$ ) where  $((\nabla^E)^k u)_{i_1 \dots i_k}^a$  is a linear combination of  $u^1 \circ \varphi^{-1}, \dots, u^r \circ \varphi^{-1}$  and their partial derivatives up to order  $k$  and the coefficients are polynomials in terms of Christoffel symbols (of the linear connection on  $M$  and connection in  $E$ ) and their derivatives (on a compact manifold these coefficients are uniformly bounded provided that the metric and the fiber metric are smooth). That is,

$$((\nabla^E)^k u)_{i_1 \dots i_k}^a \circ \varphi^{-1} = \sum_{|\eta| \leq k} \sum_{l=1}^r C_{\eta l} \partial^\eta (u^l \circ \varphi^{-1})$$

where for each  $\eta$  and  $l$ ,  $C_{\eta l}$  is a polynomial in terms of Christoffel symbols (of the linear connection on  $M$  and connection in  $E$ ) and their derivatives.

- **Observation 2:** The highest order term in  $((\nabla^E)^k u)_{i_1 \dots i_k}^a \circ \varphi^{-1}$  is  $\frac{\partial}{\partial x^{i_1}} \dots \frac{\partial}{\partial x^{i_k}} (u^a \circ \varphi^{-1})$ ; that is

$$((\nabla^E)^k u)_{i_1 \dots i_k}^a \circ \varphi^{-1} = \frac{\partial}{\partial x^{i_1}} \dots \frac{\partial}{\partial x^{i_k}} (u^a \circ \varphi^{-1}) + \text{terms that contain derivatives of order at most } k-1 \text{ of } u^l \circ \varphi^{-1} \text{ (} 1 \leq l \leq r \text{)}$$

So

$$((\nabla^E)^k u)_{i_1 \dots i_k}^a \circ \varphi^{-1} = \frac{\partial^k}{\partial x^{i_1} \dots \partial x^{i_k}} (u^a \circ \varphi^{-1}) + \sum_{|\eta| < k} \sum_{l=1}^r C_{\eta l} \partial^\eta (u^l \circ \varphi^{-1})$$

#### APPENDIX D. SOME RESULTS FROM THE THEORY OF GENERALIZED FUNCTIONS

In this section we collect some results from the theory of distributions that will be needed for our definition of function spaces on manifolds. Our main reference for this part is the exquisite exposition by Marcel De Reus ([38]).

**D.1. Distributions on Domains in Euclidean Space.** Let  $\Omega$  be a nonempty open set in  $\mathbb{R}^n$ .

(1) Recall that

- $\mathcal{K}(\Omega)$  is the collection of all compact subsets of  $\Omega$ .
- $C^\infty(\Omega)$  = the collection of all infinitely differentiable (real-valued) functions on  $\Omega$ .
- For all  $K \in \mathcal{K}(\Omega)$ ,  $C_K^\infty(\Omega) = \{\varphi \in C^\infty(\Omega) : \text{supp } \varphi \subseteq K\}$ .
- $C_c^\infty(\Omega) = \bigcup_{K \in \mathcal{K}(\Omega)} C_K^\infty(\Omega) = \{\varphi \in C^\infty(\Omega) : \text{supp } \varphi \text{ is compact in } \Omega\}$ .

(2) For all  $\varphi \in C^\infty(\Omega)$ ,  $j \in \mathbb{N}$  and  $K \in \mathcal{K}(\Omega)$  we define

$$\|\varphi\|_{j,K} := \sup\{|\partial^\alpha \varphi(x)| : |\alpha| \leq j, x \in K\}$$

(3) For all  $j \in \mathbb{N}$  and  $K \in \mathcal{K}(\Omega)$ ,  $\|\cdot\|_{j,K}$  is a seminorm on  $C^\infty(\Omega)$ . We define  $\mathcal{E}(\Omega)$  to be  $C^\infty(\Omega)$  equipped with the natural topology induced by the family of seminorms  $\{\|\cdot\|_{j,K}\}_{j \in \mathbb{N}, K \in \mathcal{K}(\Omega)}$ . It can be shown that  $\mathcal{E}(\Omega)$  is a Frechet space.

(4) For all  $K \in \mathcal{K}(\Omega)$  we define  $\mathcal{E}_K(\Omega)$  to be  $C_K^\infty(\Omega)$  equipped with the subspace topology. Since  $C_K^\infty(\Omega)$  is a closed subset of the Frechet space  $\mathcal{E}(\Omega)$ ,  $\mathcal{E}_K(\Omega)$  is also a Frechet space.



- (5) We define  $D(\Omega) = \bigcup_{K \in \mathcal{K}(\Omega)} \mathcal{E}_K(\Omega)$  equipped with the inductive limit topology with respect to the family of vector subspaces  $\{\mathcal{E}_K(\Omega)\}_{K \in \mathcal{K}(\Omega)}$ . It can be shown that if  $\{K_j\}_{j \in \mathbb{N}_0}$  is an exhaustion by compact sets of  $\Omega$ , then the inductive limit topology on  $D(\Omega)$  with respect to the family  $\{K_j\}_{j \in \mathbb{N}_0}$  is exactly the same as the inductive limit topology with respect to  $\{\mathcal{E}_K(\Omega)\}_{K \in \mathcal{K}(\Omega)}$ .

**Remark D.1.** *Let us mention a trivial but extremely useful consequence of the above description of the inductive limit topology on  $D(\Omega)$ . Suppose  $Y$  is a topological space and the mapping  $T : Y \rightarrow D(\Omega)$  is such that  $T(Y) \subseteq \mathcal{E}_K(\Omega)$  for some  $K \in \mathcal{K}(\Omega)$ . Since  $\mathcal{E}_K(\Omega) \hookrightarrow D(\Omega)$ , if  $T : Y \rightarrow \mathcal{E}_K(\Omega)$  is continuous, then  $T : Y \rightarrow D(\Omega)$  will be continuous.*

**Theorem D.2** (Convergence and Continuity for  $\mathcal{E}(\Omega)$ ). *Let  $\Omega$  be a nonempty open set in  $\mathbb{R}^n$ . Let  $Y$  be a topological vector space whose topology is induced by a family of seminorms  $\mathcal{Q}$ .*

- (1) *A sequence  $\{\varphi_m\}$  converges to  $\varphi$  in  $\mathcal{E}(\Omega)$  if and only if  $\|\varphi_m - \varphi\|_{j,K} \rightarrow 0$  for all  $j \in \mathbb{N}$  and  $K \in \mathcal{K}(\Omega)$ .*
- (2) *Suppose  $T : \mathcal{E}(\Omega) \rightarrow Y$  is a linear map. Then the followings are equivalent*
- *$T$  is continuous.*
  - *For every  $q \in \mathcal{Q}$ , there exist  $j \in \mathbb{N}$  and  $K \in \mathcal{K}(\Omega)$ , and  $C > 0$  such that*

$$\forall \varphi \in \mathcal{E}(\Omega) \quad q(T(\varphi)) \leq C \|\varphi\|_{j,K}$$

- *If  $\varphi_m \rightarrow 0$  in  $\mathcal{E}(\Omega)$ , then  $T(\varphi_m) \rightarrow 0$  in  $Y$ .*

- (3) *In particular, a linear map  $T : \mathcal{E}(\Omega) \rightarrow \mathbb{R}$  is continuous if and only if there exist  $j \in \mathbb{N}$  and  $K \in \mathcal{K}(\Omega)$ , and  $C > 0$  such that*

$$\forall \varphi \in \mathcal{E}(\Omega) \quad |T(\varphi)| \leq C \|\varphi\|_{j,K}$$

- (4) *A linear map  $T : Y \rightarrow \mathcal{E}(\Omega)$  is continuous if and only if*

$$\forall j \in \mathbb{N}, \forall K \in \mathcal{K}(\Omega) \quad \exists C > 0, k \in \mathbb{N}, q_1, \dots, q_k \in \mathcal{Q} \quad \text{such that} \quad \|T(y)\|_{j,K} \leq C \max_{1 \leq i \leq k} q_i(x)$$

**Theorem D.3** (Convergence and Continuity for  $\mathcal{E}_K(\Omega)$ ). *Let  $\Omega$  be a nonempty open set in  $\mathbb{R}^n$  and  $K \in \mathcal{K}(\Omega)$ . Let  $Y$  be a topological vector space whose topology is induced by a family of seminorms  $\mathcal{Q}$ .*

- (1) *A sequence  $\{\varphi_m\}$  converges to  $\varphi$  in  $\mathcal{E}_K(\Omega)$  if and only if  $\|\varphi_m - \varphi\|_{j,K} \rightarrow 0$  for all  $j \in \mathbb{N}$ .*
- (2) *Suppose  $T : \mathcal{E}_K(\Omega) \rightarrow Y$  is a linear map. Then the followings are equivalent*

- *$T$  is continuous.*
- *For every  $q \in \mathcal{Q}$ , there exists  $j \in \mathbb{N}$  and  $C > 0$  such that*

$$\forall \varphi \in \mathcal{E}_K(\Omega) \quad q(T(\varphi)) \leq C \|\varphi\|_{j,K}$$

- *If  $\varphi_m \rightarrow 0$  in  $\mathcal{E}_K(\Omega)$ , then  $T(\varphi_m) \rightarrow 0$  in  $Y$ .*

**Theorem D.4** (Convergence and Continuity for  $D(\Omega)$ ). *Let  $\Omega$  be a nonempty open set in  $\mathbb{R}^n$ . Let  $Y$  be a topological vector space whose topology is induced by a family of seminorms  $\mathcal{Q}$ .*

- (1) *A sequence  $\{\varphi_m\}$  converges to  $\varphi$  in  $D(\Omega)$  if and only if there is a  $K \in \mathcal{K}(\Omega)$  such that  $\text{supp } \varphi_m \subseteq K$  and  $\varphi_m \rightarrow \varphi$  in  $\mathcal{E}_K(\Omega)$ .*

- (2) *Suppose  $T : D(\Omega) \rightarrow Y$  is a linear map. Then the followings are equivalent*

- $T$  is continuous.
- For all  $K \in \mathcal{K}(\Omega)$ ,  $T : \mathcal{E}_K(\Omega) \rightarrow Y$  is continuous.
- For every  $q \in \mathcal{Q}$  and  $K \in \mathcal{K}(\Omega)$ , there exists  $j \in \mathbb{N}$  and  $C > 0$  such that

$$\forall \varphi \in \mathcal{E}_K(\Omega) \quad q(T(\varphi)) \leq C \|\varphi\|_{j,K}$$

- If  $\varphi_m \rightarrow 0$  in  $D(\Omega)$ , then  $T(\varphi_m) \rightarrow 0$  in  $Y$ .

(3) In particular, a linear map  $T : D(\Omega) \rightarrow \mathbb{R}$  is continuous if and only if for every  $K \in \mathcal{K}(\Omega)$ , there exists  $j \in \mathbb{N}$  and  $C > 0$  such that

$$\forall \varphi \in \mathcal{E}_K(\Omega) \quad |T(\varphi)| \leq C \|\varphi\|_{j,K}$$

**Remark D.5.** Let  $\Omega$  be a nonempty open set in  $\mathbb{R}^n$ . Here are two immediate consequences of the previous theorems and remark:

(1) The identity map

$$i_{D,\mathcal{E}} : D(\Omega) \rightarrow \mathcal{E}(\Omega)$$

is continuous (that is,  $D(\Omega) \hookrightarrow \mathcal{E}(\Omega)$ ).

(2) If  $T : \mathcal{E}(\Omega) \rightarrow \mathcal{E}(\Omega)$  is a continuous linear map such that  $\text{supp}(T\varphi) \subseteq \text{supp}\varphi$  for all  $\varphi \in \mathcal{E}(\Omega)$  (i.e.  $T$  is a **local** continuous linear map), then  $T$  restricts to a continuous linear map from  $D(\Omega)$  to  $D(\Omega)$ . Indeed, the assumption  $\text{supp}(T\varphi) \subseteq \text{supp}\varphi$  implies that  $T(D(\Omega)) \subseteq D(\Omega)$ . Moreover  $T : D(\Omega) \rightarrow D(\Omega)$  is continuous if and only if for  $K \in \mathcal{K}(\Omega)$   $T : \mathcal{E}_K(\Omega) \rightarrow D(\Omega)$  is continuous. Since  $T(\mathcal{E}_K(\Omega)) \subseteq \mathcal{E}_K(\Omega)$ , this map is continuous if and only if  $T : \mathcal{E}_K(\Omega) \rightarrow \mathcal{E}_K(\Omega)$  is continuous (see Remark D.1). However, since the topology of  $\mathcal{E}_K(\Omega)$  is the induced topology from  $\mathcal{E}(\Omega)$ , the continuity of the preceding map follows from the continuity of  $T : \mathcal{E}(\Omega) \rightarrow \mathcal{E}(\Omega)$ .

**Theorem D.6.** Let  $\Omega$  be a nonempty open set in  $\mathbb{R}^n$ . Let  $Y$  be a topological vector space whose topology is induced by a family of seminorms  $\mathcal{Q}$ . Suppose  $T : [D(\Omega)]^{\times r} \rightarrow Y$  is a linear map. The following are equivalent: (product spaces are equipped with the product topology)

- (1)  $T : [D(\Omega)]^{\times r} \rightarrow Y$  is continuous.
- (2) For all  $K \in \mathcal{K}(\Omega)$ ,  $T : [\mathcal{E}_K(\Omega)]^{\times r} \rightarrow Y$  is continuous.
- (3) For all  $q \in \mathcal{Q}$  and  $K \in \mathcal{K}(\Omega)$ , there exists  $j_1, \dots, j_l \in \mathbb{N}$  such that

$$\forall (\varphi_1, \dots, \varphi_r) \in [\mathcal{E}_K(\Omega)]^{\times r} \quad |q \circ T(\varphi_1, \dots, \varphi_r)| \leq C(\|\varphi_1\|_{j_1,K} + \dots + \|\varphi_r\|_{j_r,K})$$

**Theorem D.7.** Let  $\Omega$  be a nonempty open set in  $\mathbb{R}^n$ .

- (1) A set  $B \subseteq D(\Omega)$  is bounded if and only if there exists  $K \in \mathcal{K}(\Omega)$  such that  $B$  is a bounded subset of  $\mathcal{E}_K(\Omega)$  which is in turn equivalent to the following statement

$$\forall j \in \mathbb{N} \exists r_j \geq 0 \quad \text{such that} \quad \forall \varphi \in B \quad \|\varphi\|_{j,K} \leq r_j$$

- (2) If  $\{\varphi_m\}$  is a Cauchy sequence in  $D(\Omega)$ , then it converges to a function  $\varphi \in D(\Omega)$ . We say  $D(\Omega)$  is sequentially complete.

**Remark D.8.** Topological spaces whose topology is determined by knowing the convergent sequences and their limits exhibit nice properties and are of particular interest. Let us recall a number of useful definitions related to this topic:

- Let  $X$  be a topological space and let  $E \subseteq X$ . The **sequential closure** of  $E$ , denoted  $\text{scl}(E)$  is defined as follows:

$$\text{scl}(E) = \{x \in X : \text{there is a sequence } \{x_n\} \text{ in } E \text{ such that } x_n \rightarrow x\}$$

Clearly  $\text{scl}(E)$  is contained in the closure of  $E$ .

- A topological space  $X$  is called a **Frechet-Urysohn** space if for every  $E \subseteq X$  the sequential closure of  $E$  is equal to the closure of  $E$ .
- A subset  $E$  of a topological space  $X$  is said to be **sequentially closed** if  $E = scl(E)$ .
- A topological space  $X$  is said to be **sequential** if for every  $E \subseteq X$ ,  $E$  is closed if and only if  $E$  is sequentially closed. If  $X$  is a sequential topological space and  $Y$  is any topological space, then a map  $f : X \rightarrow Y$  is continuous if and only if

$$\lim_{n \rightarrow \infty} f(x_n) = f(\lim_{n \rightarrow \infty} x_n)$$

for each convergent sequence  $\{x_n\}$  in  $X$ .

The following implications hold for a topological space  $X$ :

$X$  is metrizable  $\rightarrow X$  is first countable  $\rightarrow X$  is Frechet-Urysohn  $\rightarrow X$  is sequential

As it was stated,  $\mathcal{E}$  and  $\mathcal{E}_K$  (For all  $K \in \mathcal{K}(\Omega)$ ) are Frechet and subsequently they are metrizable. However, it can be shown that  $D(\Omega)$  is not first countable and subsequently it is not metrizable. In fact, although according to Theorem D.4, the elements of the dual of  $D(\Omega)$  can be determined by knowing the convergent sequences in  $D(\Omega)$ , it can be proved that  $D(\Omega)$  is not sequential.

**Definition D.9.** Let  $\Omega$  be a nonempty open set in  $\mathbb{R}^n$ . The topological dual of  $D(\Omega)$ , denoted  $D'(\Omega)$  ( $D'(\Omega) = [D(\Omega)]^*$ ), is called the **space of distributions** on  $\Omega$ . Each element of  $D'(\Omega)$  is called a **distribution** on  $\Omega$ .

**Remark D.10.** Every function  $f \in L^1_{loc}(\Omega)$  defines a distribution  $u_f \in D'(\Omega)$  as follows

$$\forall \varphi \in D(\Omega) \quad u_f(\varphi) := \int f\varphi dx \quad (\text{D.1})$$

In particular, every function  $\varphi \in \mathcal{E}(\Omega)$  defines a distribution  $u_\varphi$ . It can be shown that the map  $j : \mathcal{E}(\Omega) \rightarrow D'(\Omega)$  which sends  $\varphi$  to  $u_\varphi$  is an injective linear continuous map ([38], Page 11). Therefore we can identify  $\mathcal{E}(\Omega)$  with a subspace of  $D'(\Omega)$ .

**Remark D.11.** Let  $\Omega \subseteq \mathbb{R}^n$  be a nonempty open set. Recall that  $f : \Omega \rightarrow \mathbb{R}$  is locally integrable ( $f \in L^1_{loc}(\Omega)$ ) if it satisfies any of the following equivalent conditions.

- (1)  $f \in L^1(K)$  for all  $K \in \mathcal{K}(\Omega)$ .
- (2) For all  $\varphi \in C^\infty_c(\Omega)$ ,  $f\varphi \in L^1(\Omega)$ .
- (3) For every nonempty open set  $V \subseteq \Omega$  such that  $\bar{V}$  is compact and contained in  $\Omega$ ,  $f \in L^1(V)$ .

(It can be shown that every locally integrable function is measurable ([13], Page 70).)

As a consequence, if we define  $\text{Func}_{reg}(\Omega)$  to be the set

$\{f : \Omega \rightarrow \mathbb{R} : u_f : D(\Omega) \rightarrow \mathbb{R} \text{ defined by Equation D.1 is well defined and continuous}\}$   
then  $\text{Func}_{reg}(\Omega) = L^1_{loc}(\Omega)$ .

**Definition D.12** (Calculus Rules for Distributions). Let  $\Omega$  be a nonempty open set in  $\mathbb{R}^n$ . Let  $u \in D'(\Omega)$ .

- For all  $\varphi \in C^\infty(\Omega)$ ,  $\varphi u$  is defined by

$$\forall \psi \in C^\infty_c(\Omega) \quad [\varphi u](\psi) := u(\varphi\psi)$$

It can be shown that  $\varphi u \in D'(\Omega)$ .

- For all multiindices  $\alpha$ ,  $\partial^\alpha u$  is defined by

$$\forall \psi \in C_c^\infty(\Omega) \quad [\partial^\alpha u](\psi) = (-1)^{|\alpha|} u(\partial^\alpha \psi)$$

It can be shown that  $\partial^\alpha u \in D'(\Omega)$ .

Also it is possible to make sense of "change of coordinates" for distributions. Let  $\Omega$  and  $\Omega'$  be two open sets in  $\mathbb{R}^n$ . Suppose  $T : \Omega \rightarrow \Omega'$  is a  $C^\infty$  diffeomorphism.  $T$  can be used to move any function on  $\Omega$  to a function on  $\Omega'$  and vice versa.

$$\begin{aligned} T^* : \text{Func}(\Omega', \mathbb{R}) &\rightarrow \text{Func}(\Omega, \mathbb{R}), & T^*(f) &= f \circ T \\ T_* : \text{Func}(\Omega, \mathbb{R}) &\rightarrow \text{Func}(\Omega', \mathbb{R}), & T_*(f) &= f \circ T^{-1} \end{aligned}$$

$T^*f$  is called the **pullback** of the function  $f$  under the mapping  $T$  and  $T_*f$  is called the **pushforward** of the function  $f$  under the mapping  $T$ . Clearly  $T^*$  and  $T_*$  are inverses of each other and  $T_* = (T^{-1})^*$ . One can show that  $T_*$  sends functions in  $L^1_{loc}(\Omega)$  to  $L^1_{loc}(\Omega')$  and furthermore  $T_*$  restricts to linear topological isomorphisms  $T_* : \mathcal{E}(\Omega) \rightarrow \mathcal{E}(\Omega')$  and  $T_* : D(\Omega) \rightarrow D(\Omega')$ . Note that for all  $f \in L^1_{loc}(\Omega)$  and  $\varphi \in C_c^\infty(\Omega')$

$$\begin{aligned} \langle u_{T_*f}, \varphi \rangle_{D'(\Omega') \times D(\Omega')} &= \int_{\Omega'} (T_*f)(y) \varphi(y) dy = \int_{\Omega} (f \circ T^{-1})(y) \varphi(y) dy \\ &= \int_{\Omega} f(x) \varphi(T(x)) |\det T'(x)| dx \\ &= \langle u_f, |\det T'(x)| \varphi(T(x)) \rangle_{D'(\Omega) \times D(\Omega')} \end{aligned}$$

The above observation motivates us to define the pushforward of any distribution  $u \in D'(\Omega)$  as follows

$$\forall \varphi \in D(\Omega') \quad \langle T_*u, \varphi \rangle_{D'(\Omega') \times D(\Omega')} := \langle u, |\det T'(x)| \varphi(T(x)) \rangle_{D'(\Omega) \times D(\Omega')}$$

It can be shown that  $T_*u : D(\Omega') \rightarrow \mathbb{R}$  is continuous and so it is in fact an element of  $D'(\Omega')$ . Similarly, the pullback  $T^* : D'(\Omega') \rightarrow D'(\Omega)$  is defined by

$$\forall \varphi \in D(\Omega) \quad \langle T^*u, \varphi \rangle_{D'(\Omega) \times D(\Omega')} := \langle u, |\det(T^{-1})'(y)| \varphi(T^{-1}(y)) \rangle_{D'(\Omega') \times D(\Omega')}$$

It can be shown that  $T^*u : D(\Omega) \rightarrow \mathbb{R}$  is continuous and so it is in fact an element of  $D'(\Omega)$ .

**Definition D.13** (Extension by Zero of a Function). *Let  $\Omega$  be an open subset of  $\mathbb{R}^n$  and  $V$  be an open subset of  $\Omega$ . We define the linear map  $\text{ext}_V^0 : \text{Func}(V, \mathbb{R}) \rightarrow \text{Func}(\Omega, \mathbb{R})$  as follows*

$$\text{ext}_V^0(f)(x) = \begin{cases} f(x) & \text{if } x \in V \\ 0 & \text{if } x \in \Omega \setminus V \end{cases}$$

$\text{ext}_V^0$  restricts to a continuous linear map  $D(V) \rightarrow D(\Omega)$ .

**Definition D.14** (Restriction of a Distribution). *Let  $\Omega$  be an open subset of  $\mathbb{R}^n$  and  $V$  be an open subset of  $\Omega$ . We define the restriction map  $\text{res}_{,V} : D'(\Omega) \rightarrow D'(V)$  as follows*

$$\langle \text{res}_{,V}u, \varphi \rangle_{D'(V) \times D(V)} := \langle u, \text{ext}_V^0 \varphi \rangle_{D'(\Omega) \times D(\Omega)}$$

This is well defined; indeed,  $\text{res}_{,V} : D'(\Omega) \rightarrow D'(V)$  is a continuous linear map as it is the adjoint of the continuous map  $\text{ext}_V^0 : D(V) \rightarrow D(\Omega)$ . Given  $u \in D'(\Omega)$ , we sometimes write  $u|_V$  instead of  $\text{res}_{,V}u$ .

**Remark D.15.** *It is easy to see that the restriction of the map  $\text{res}_{,V} : D'(\Omega) \rightarrow D'(V)$  to  $\mathcal{E}(\Omega)$  agrees with the usual restriction of smooth functions.*

**Definition D.16** (Support of a Distribution). *Let  $\Omega$  be a nonempty open set in  $\mathbb{R}^n$ . Let  $u \in D'(\Omega)$ .*

- We say  $u$  is equal to zero on some open subset  $V$  of  $\Omega$  if  $u|_V = 0$
- Let  $\{V_i\}_{i \in I}$  be the collection of all subsets of  $\Omega$  such that  $u$  is equal to zero on  $V_i$ . Let  $V = \bigcup_{i \in I} V_i$ . The support of  $u$  is defined as follows

$$\text{supp}u := \Omega \setminus V$$

Note that  $\text{supp}u$  is closed in  $\Omega$  but it is not necessarily closed in  $\mathbb{R}^n$ .

**Theorem D.17** (Properties of the Support). [38, 39, 23] *Let  $\Omega$  and  $\Omega'$  be nonempty open sets in  $\mathbb{R}^n$ .*

- If  $f \in L^1_{loc}(\Omega)$ , then  $\text{supp}f = \text{supp}u_f$ .
- For all  $u \in D'(\Omega)$ ,  $u = 0$  on  $\Omega \setminus \text{supp}u$ .
- If  $u \in D'(\Omega)$  and  $\varphi \in D(\Omega)$  vanishes on an open neighborhood of  $\text{supp}u$ , then  $u(\varphi) = 0$ .
- For every closed subset  $A$  of  $\Omega$  and every  $u \in D'(\Omega)$ , we have  $\text{supp}u \subseteq A$  if and only if  $u(\varphi) = 0$  for every  $\varphi \in D(\Omega)$  with  $\text{supp}\varphi \subseteq \Omega \setminus A$ .
- For every  $u \in D'(\Omega)$  and  $\psi \in \mathcal{E}(\Omega)$ ,  $\text{supp}(\psi u) \subseteq \text{supp}(\psi) \cap \text{supp}(u)$ .
- Let  $u, v \in D'(\Omega)$ . If there exists a nonempty open subset  $U$  of  $\Omega$  such that  $\text{supp}u \subseteq U$  and  $\text{supp}v \subseteq U$  and

$$\langle u|_U, \varphi \rangle_{D'(U) \times D(U)} = \langle v|_U, \varphi \rangle_{D'(U) \times D(U)} \quad \forall \varphi \in C_c^\infty(U)$$

then  $u = v$  as elements of  $D'(\Omega)$ .

- Let  $u, v \in D'(\Omega)$ . Then  $\text{supp}(u + v) \subseteq \text{supp}u \cup \text{supp}v$ .
- Let  $\{u_i\}$  be a sequence in  $D'(\Omega)$ ,  $u \in D(\Omega)$ , and  $K \in \mathcal{K}(\Omega)$  such that  $u_i \rightarrow u$  in  $D'(\Omega)$  and  $\text{supp}u_i \subseteq K$  for all  $i$ . Then also  $\text{supp}u \subseteq K$ .
- Let  $\{u_i\}$  be a sequence in  $D'(\Omega)$ ,  $u \in D(\Omega)$ , and  $K \in \mathcal{K}(\Omega)$  such that  $u_i \rightarrow u$  in  $D'(\Omega)$  and  $\text{supp}u \subseteq K$ . If  $V$  is an open bounded set in  $\Omega$  that contains  $K$ , then there exists  $N$  such that  $\text{supp}u_i \subseteq \bar{V}$  for all  $i \geq N$ .
- For every  $u \in D'(\Omega)$  and  $\alpha \in \mathbb{N}_0^n$ ,  $\text{supp}(\partial^\alpha u) \subseteq \text{supp}(u)$ .
- If  $T : \Omega \rightarrow \Omega'$  is a diffeomorphism, then  $\text{supp}(T_*u) = T(\text{supp}u)$ . In particular, if  $u$  has compact support, then so has  $T_*u$ .

**Theorem D.18.** ([38], Pages 10 and 20) *Let  $\Omega$  be a nonempty open set in  $\mathbb{R}^n$ . Let  $\mathcal{E}'(\Omega)$  denote the topological dual of  $\mathcal{E}(\Omega)$  equipped with the strong topology. Then*

- The map that sends  $u \in \mathcal{E}'(\Omega)$  to  $u|_{D(\Omega)}$  is an injective continuous linear map from  $\mathcal{E}'(\Omega)$  into  $D'(\Omega)$ .
- The image of the above map consists precisely of those  $u \in D'(\Omega)$  for which  $\text{supp}(u)$  is compact.

Due to the above theorem we may identify  $\mathcal{E}'(\Omega)$  with distributions on  $\Omega$  with compact support.

**Definition D.19** (Extension by Zero of Distributions With Compact Support). *Let  $\Omega$  be a nonempty open set in  $\mathbb{R}^n$  and  $V$  be a nonempty open subset of  $\Omega$ . We define the linear map*

$\text{ext}_{V'}^0 : \mathcal{E}'(V) \rightarrow \mathcal{E}'(\Omega)$  as the adjoint of the continuous linear map  $\text{res}_{,V'} : \mathcal{E}(\Omega) \rightarrow \mathcal{E}(V)$ ; that is

$$\langle \text{ext}_{V'}^0 u, \varphi \rangle_{\mathcal{E}'(\Omega) \times \mathcal{E}(\Omega)} := \langle u, \varphi|_V \rangle_{\mathcal{E}'(V) \times \mathcal{E}(V)}$$

Suppose  $\Omega'$  and  $\Omega$  are two nonempty open sets in  $\mathbb{R}^n$  such that  $\Omega' \subseteq \Omega$  and  $K \in \mathcal{K}(\Omega')$ . One can easily show that

- For all  $u \in \mathcal{E}_K(\Omega')$ ,  $\text{res}_{\mathbb{R}^n, \Omega'} \circ \text{ext}_{, \mathbb{R}^n}^0 u = \text{ext}_{, \Omega'}^0 u$ .
- For all  $u \in \mathcal{E}_K(\Omega')$ ,  $\text{ext}_{, \mathbb{R}^n}^0 \circ \text{ext}_{, \Omega'}^0 u = \text{ext}_{, \mathbb{R}^n}^0 u$ .
- For all  $u \in \mathcal{E}_K(\Omega)$ ,  $\text{ext}_{, \Omega'}^0 \circ \text{res}_{, \Omega'} u = u$ .

We summarize the important topological properties of the spaces of test functions and distributions in the table below.

	$D(\Omega)$	$\mathcal{E}(\Omega)$	$D'(\Omega)$ Strong	$\mathcal{E}'(\Omega)$ Strong	$D'(\Omega)$ Weak	$\mathcal{E}'(\Omega)$ Weak
Sequential	No	Yes	No	No	No	No
First Countable	No	Yes	No	No	No	No
Metrizable	No	Yes	No	No	No	No
Second Countable	No	Yes	No	No	No	No
Sequentially Complete	Yes	Yes	Yes	Yes	Yes	Yes
Complete	Yes	Yes	Yes	Yes	No	No

## D.2. Distributions on Vector Bundles.

D.2.1. *Basic Definitions, Notations.* Let  $M^n$  be a smooth manifold ( $M$  is not necessarily compact). Let  $\pi : E \rightarrow M$  be a vector bundle of rank  $r$ .

- (1)  $\mathcal{E}(M, E)$  is defined as  $C^\infty(M, E)$  equipped with the locally convex topology induced by the following family of seminorms: let  $\{(U_\alpha, \varphi_\alpha, \rho_\alpha)\}_{\alpha \in I}$  be a total trivialization atlas. Then for every  $\alpha \in I$ ,  $1 \leq l \leq r$ , and  $f \in C^\infty(M, E)$ ,  $\tilde{f}_\alpha^l := \rho_\alpha^l \circ f \circ \varphi_\alpha^{-1}$  is an element of  $C^\infty(\varphi_\alpha(U_\alpha))$ . For every 4-tuple  $(l, \alpha, j, K)$  with  $1 \leq l \leq r$ ,  $\alpha \in I$ ,  $j \in \mathbb{N}$ ,  $K$  a compact subset of  $U_\alpha$  (i.e.  $K \in \mathcal{K}(U_\alpha)$ ) we define

$$\|\cdot\|_{l, \alpha, j, K} : C^\infty(M, E) \rightarrow \mathbb{R}, \quad f \mapsto \|\rho_\alpha^l \circ f \circ \varphi_\alpha^{-1}\|_{j, \varphi_\alpha(K)}$$

It is easy to check that  $\|\cdot\|_{l, \alpha, j, K}$  is a seminorm on  $C^\infty(M, E)$  and the locally convex topology induced by the above family of seminorms does not depend on the choice of the total trivialization atlas. Sometimes we may write  $\|\cdot\|_{l, \varphi_\alpha, j, K}$  instead of  $\|\cdot\|_{l, \alpha, j, K}$ .

- (2) For any compact subset  $K \subseteq M$  we define

$$\mathcal{E}_K(M, E) := \{f \in \mathcal{E}(M, E) : \text{supp } f \subseteq K\} \quad \text{equipped with the subspace topology}$$

- (3)  $D(M, E) := C_c^\infty(M, E) = \cup_{K \in \mathcal{K}(M)} \mathcal{E}_K(M, E)$  (union over all compact subsets of  $M$ ) equipped with the inductive limit topology with respect to the family  $\{\mathcal{E}_K(M, E)\}_{K \in \mathcal{K}(M)}$ . Clearly if  $M$  is compact, then  $D(M, E) = \mathcal{E}(M, E)$  (as topological vector spaces).

### Remark D.20.

- If for each  $\alpha \in I$ ,  $\{K_m^\alpha\}_{m \in \mathbb{N}}$  is an exhaustion by compact sets of  $U_\alpha$ , then the topology induced by the family of seminorms

$$\{\|\cdot\|_{l, \alpha, j, K_m^\alpha} : 1 \leq l \leq r, \alpha \in I, j \in \mathbb{N}, m \in \mathbb{N}\}$$

on  $C^\infty(M, E)$  is the same as the topology of  $\mathcal{E}(M, E)$ . This together with the fact that every manifold has a countable total trivialization atlas shows that the topology of  $\mathcal{E}(M, E)$  is induced by a countable family of seminorms. So  $\mathcal{E}(M, E)$  is metrizable.

- If  $\{K_j\}_{j \in \mathbb{N}}$  is an exhaustion by compact sets of  $M$ , then the inductive limit topology on  $C_c^\infty(M, E)$  with respect to the family  $\{\mathcal{E}_{K_j}(M, E)\}$  is the same as the topology on  $D(M, E)$ .

**Definition D.21.** The space of distributions on the vector bundle  $E$ , denoted  $D'(M, E)$ , is defined as the topological dual of  $D(M, E^\vee)$ . That is,

$$D'(M, E) = [D(M, E^\vee)]^*$$

As usual we equip the dual space with the strong topology. Recall that  $E^\vee$  denotes the bundle  $\text{Hom}(E, \mathcal{D}(M))$  where  $\mathcal{D}(M)$  is the density bundle of  $M$ .

**Remark D.22.** The reason that space of distributions on the vector bundle  $E$  is defined as the dual of  $D(M, E^\vee)$  rather than the dual of the seemingly natural choice  $D(M, E)$  is well explained in [22] and [38]. Of course, there are other non-equivalent ways to make sense of distributions on vector bundles (see [22] for a detailed discussion). Also see Lemma H.27 where it is proved that Riemannian density can be used to identify  $D'(M, E)$  with  $[D(M, E)]^*$ .

**Remark D.23.** Let  $U$  and  $V$  be nonempty open sets in  $M$  with  $V \subseteq U$ .

- As in the Euclidean case, the linear map  $\text{ext}_{V,U}^0 : \Gamma(V, E_V^\vee) \rightarrow \Gamma(U, E_U^\vee)$  defined by

$$\text{ext}_{V,U}^0 f(x) = \begin{cases} f(x) & x \in V \\ 0 & x \in U \setminus V \end{cases}$$

restricts to a continuous linear map from  $D(V, E_V^\vee)$  to  $D(U, E_U^\vee)$ .

- As in the Euclidean case, the restriction map  $\text{res}_{U,V} : D'(U, E_U) \rightarrow D'(V, E_V)$  is defined as the adjoint of  $\text{ext}_{V,U}^0$ :

$$\langle \text{res}_{U,V} u, \varphi \rangle_{D'(V, E_V) \times D(V, E_V^\vee)} = \langle u, \text{ext}_{V,U}^0 \varphi \rangle_{D'(U, E_U) \times D(U, E_U^\vee)}$$

- Support of a distribution  $u \in D'(M, E)$  is defined in the exact same way as for distributions in the Euclidean space. It can be shown that

(1) ([38], Page 105) If  $u \in D'(M, E)$  and  $\varphi \in D(M, E^\vee)$  vanishes on an open neighborhood of  $\text{supp} u$ , then  $u(\varphi) = 0$ .

(2) ([38], Page 104) For every closed subset  $A$  of  $M$  and every  $u \in D'(M, E)$ , we have  $\text{supp} u \subseteq A$  if and only if  $u(\varphi) = 0$  for every  $\varphi \in D(M, E^\vee)$  with  $\text{supp} \varphi \subseteq M \setminus A$ .

The strength of the theory of distributions in the Euclidean case is largely due to the fact that it is possible to identify a huge class of ordinary functions with distributions. A question that arises is that whether there is a natural way to identify regular sections of  $E$  (i.e. elements of  $\Gamma(M, E)$ ) with distributions. The following theorem provides a partial answer to this question. Recall that compactly supported continuous sections of the density bundle can be integrated over  $M$ .

**Theorem D.24.** Every  $f \in \mathcal{E}(M, E)$  defines the following continuous map:

$$u_f : D(M, E^\vee) \rightarrow \mathbb{R}, \quad \psi \mapsto \int_M [\psi, f] \tag{D.2}$$

where the pairing  $[\psi, f]$  defines a compactly supported continuous section of the density bundle:

$$\forall x \in M \quad [\psi, f](x) := [\psi(x)][f(x)] \quad (\psi(x) \in \text{Hom}(E_x, \mathcal{D}_x) \text{ evaluated at } f(x) \in E_x)$$

In general, we define  $\Gamma_{reg}(M, E)$  as the set

$$\{f \in \Gamma(M, E) : u_f \text{ defined by Equation D.2 is well defined and continuous}\}$$

(Compare this with the definition of  $\text{Func}_{reg}(\Omega)$  in Remark D.11.) Theorem D.24 tells us that  $\mathcal{E}(M, E)$  is contained in  $\Gamma_{reg}(M, E)$ . If  $u \in D'(M, E)$  is such that  $u = u_f$  for some  $f \in \Gamma_{reg}(M, E)$ , then we say that  $u$  is a **regular distribution**.

Now let  $(U, \varphi, \rho)$  be a total trivialization triple for  $E$  and let  $(U, \varphi, \rho_{\mathcal{D}})$  and  $(U, \varphi, \rho^{\vee})$  be the corresponding standard total trivialization triples for  $\mathcal{D}(M)$  and  $E^{\vee}$ , respectively. The local representation of the pairing  $[\psi, f]$  has a very simple expression in terms of the local representations of  $f$  and  $\psi$ :

$$\begin{aligned} f \in \Gamma_{reg}(M, E) &\implies (\tilde{f}^1, \dots, \tilde{f}^r) := (f^1 \circ \varphi^{-1}, \dots, f^r \circ \varphi^{-1}) := \rho \circ f \circ \varphi^{-1} \in [\text{Func}(\varphi(U), \mathbb{R})]^{\times r} \\ &(\tilde{f}^1, \dots, \tilde{f}^r) \text{ is the local representation of } f \\ \psi \in D(M, E^{\vee}) &\implies (\tilde{\psi}^1, \dots, \tilde{\psi}^r) := (\psi^1 \circ \varphi^{-1}, \dots, \psi^r \circ \varphi^{-1}) := \rho^{\vee} \circ \psi \circ \varphi^{-1} \in [D(\varphi(U))]^{\times r} \\ &(\tilde{\psi}^1, \dots, \tilde{\psi}^r) \text{ is the local representation of } \psi \end{aligned}$$

Our claim is that the local representation of  $[\psi, f]$ , that is  $\rho_{\mathcal{D}} \circ [\psi, f] \circ \varphi^{-1}$ , is equal to the Euclidean dot product of the local representations of  $f$  and  $\psi$ :

$$\rho_{\mathcal{D}} \circ [\psi, f] \circ \varphi^{-1} = \sum_i \tilde{f}^i \tilde{\psi}^i$$

The reason is as follows: Let  $y \in \varphi(U)$  and  $x = \varphi^{-1}(y)$

$$\begin{aligned} [\rho_{\mathcal{D}} \circ [\psi, f] \circ \varphi^{-1}](y) &= \rho_{\mathcal{D}}([\psi(x)][f(x)]) = \rho_{\mathcal{D}}([\psi(x)][(\rho|_{E_x})^{-1}(\tilde{f}^1(y), \dots, \tilde{f}^r(y))]) \\ &= [\rho_{\mathcal{D}} \circ \psi(x) \circ (\rho|_{E_x})^{-1}](\tilde{f}^1(y), \dots, \tilde{f}^r(y)) \\ &= [\rho^{\vee}(\psi(x))][(\tilde{f}^1(y), \dots, \tilde{f}^r(y))] \quad \text{the left bracket is applied to the right bracket} \\ &= \rho^{\vee}(\psi(x)) \cdot (\tilde{f}^1(y), \dots, \tilde{f}^r(y)) \quad \text{dot product! } \rho^{\vee}(\psi(x)) \text{ viewed as an element of } \mathbb{R}^r \\ &= (\tilde{\psi}^1(y), \dots, \tilde{\psi}^r(y)) \cdot (\tilde{f}^1(y), \dots, \tilde{f}^r(y)) \end{aligned}$$

**D.2.2. Local Representation of Distributions.** Let  $(U, \varphi, \rho)$  be a total trivialization triple for  $\pi : E \rightarrow M$ . We know that each  $f \in \Gamma(M, E)$  can locally be represented by  $r$  components  $\tilde{f}^1, \dots, \tilde{f}^r$  defined by

$$\forall 1 \leq l \leq r \quad \tilde{f}^l : \varphi(U) \rightarrow \mathbb{R}, \quad \tilde{f}^l = \rho^l \circ f \circ \varphi^{-1}$$

These components play a crucial role in our study of Sobolev spaces. Now the question is that whether we can similarly use the total trivialization triple  $(U, \varphi, \rho)$  to locally associate with each distribution  $u \in D'(M, E)$ ,  $r$  components  $\tilde{u}^1, \dots, \tilde{u}^r$  belonging to  $D'(\varphi(U))$ . That is, we want to see whether we can define a nice map

$$D'(U, E_U) = [D(U, E_U^{\vee})]^* \rightarrow \underbrace{D'(\varphi(U)) \times \dots \times D'(\varphi(U))}_{r \text{ times}}$$

(Note that according to Remark D.23, if  $u \in D'(M, E)$ , then  $u|_U \in D'(U, E_U)$ .) Such a map, in particular, will be important when we want to make sense of Sobolev spaces with negative exponents of sections of vector bundles. Also it would be desirable to ensure that if  $u$  is a regular distribution then the components of  $u$  as a distribution agree with the components obtained when  $u$  is viewed as an element of  $\Gamma(M, E)$ .



We begin with the following map at the level of compactly supported smooth functions:

$$\tilde{T}_{E^\vee, U, \varphi} : D(U, E_U^\vee) \rightarrow [D(\varphi(U))]^{\times r}, \quad \xi \rightarrow \rho^\vee \circ \xi \circ \varphi^{-1} = ((\rho^\vee)^1 \circ \xi \circ \varphi^{-1}, \dots, (\rho^\vee)^r \circ \xi \circ \varphi^{-1})$$

Note that  $\tilde{T}_{E^\vee, U, \varphi}$  has the property that for all  $\psi \in C^\infty(U)$  and  $\xi \in D(U, E_U^\vee)$

$$\tilde{T}_{E^\vee, U, \varphi}(\psi\xi) = (\psi \circ \varphi^{-1})\tilde{T}_{E^\vee, U, \varphi}(\xi).$$

**Theorem D.25.** *The map  $\tilde{T}_{E^\vee, U, \varphi} : D(U, E_U^\vee) \rightarrow [D(\varphi(U))]^{\times r}$  is a linear topological isomorphism. ( $[D(\varphi(U))]^{\times r}$  is equipped with the product topology.)*

*Proof.* Clearly  $\tilde{T}_{E^\vee, U, \varphi}$  is linear. Also the map  $\tilde{T}_{E^\vee, U, \varphi}$  is bijective. Indeed, the inverse of  $\tilde{T}_{E^\vee, U, \varphi}$  (which we denote by  $T_{E^\vee, U, \varphi}$ ) is given by

$$\begin{aligned} T_{E^\vee, U, \varphi} : [D(\varphi(U))]^{\times r} &\rightarrow D(U, E_U^\vee) \\ \forall x \in U \quad T_{E^\vee, U, \varphi}(\xi_1, \dots, \xi_r)(x) &= (\rho^\vee|_{E_x^\vee})^{-1} \circ (\xi_1, \dots, \xi_r) \circ \varphi(x) \end{aligned}$$

Now we show that  $\tilde{T}_{E^\vee, U, \varphi} : D(U, E_U^\vee) \rightarrow [D(\varphi(U))]^{\times r}$  is continuous. To this end, it is enough to prove that for each  $1 \leq l \leq r$  the map

$$\pi^l \circ \tilde{T}_{E^\vee, U, \varphi} : D(U, E_U^\vee) \rightarrow D(\varphi(U)), \quad \xi \mapsto (\rho^\vee)^l \circ \xi \circ \varphi^{-1}$$

is continuous. The topology on  $D(U, E_U^\vee)$  is the inductive limit topology with respect to  $\{\mathcal{E}_K(U, E_U^\vee)\}_{K \in \mathcal{K}(U)}$ , so it is enough to show that for each  $K \in \mathcal{K}(U)$ ,  $\pi^l \circ \tilde{T}_{E^\vee, U, \varphi} : \mathcal{E}_K(U, E_U^\vee) \rightarrow D(\varphi(U))$  is continuous. Note that  $\pi^l \circ \tilde{T}_{E^\vee, U, \varphi}[\mathcal{E}_K(U, E_U^\vee)] \subseteq \mathcal{E}_{\varphi(K)}(\varphi(U))$ . Considering that  $\mathcal{E}_{\varphi(K)}(\varphi(U)) \hookrightarrow D(\varphi(U))$ , it is enough to show that

$$\pi^l \circ \tilde{T}_{E^\vee, U, \varphi} : \mathcal{E}_K(U, E_U^\vee) \rightarrow \mathcal{E}_{\varphi(K)}(\varphi(U))$$

is continuous. For all  $\xi \in \mathcal{E}_K(U, E_U^\vee)$  and  $j \in \mathbb{N}$  we have

$$\|\pi^l \circ \tilde{T}_{E^\vee, U, \varphi}(\xi)\|_{j, \varphi(K)} = \|(\rho^\vee)^l \circ \xi \circ \varphi^{-1}\|_{j, \varphi(K)} = \|\xi\|_{l, \varphi, j, K}$$

which implies the continuity (note that even an inequality in place of the last equality would have been enough to prove the continuity). It remains to prove the continuity of  $T_{E^\vee, U, \varphi} : [D(\varphi(U))]^{\times r} \rightarrow D(U, E_U^\vee)$ . By Theorem D.6 it is enough to show that for all  $K \in \mathcal{K}(\varphi(U))$ ,  $T_{E^\vee, U, \varphi} : [\mathcal{E}_K(\varphi(U))]^{\times r} \rightarrow D(U, E_U^\vee)$  is continuous. It is clear that  $T_{E^\vee, U, \varphi}([\mathcal{E}_K(\varphi(U))]^{\times r}) \subseteq \mathcal{E}_{\varphi^{-1}(K)}(U, E_U^\vee)$ . Since  $\mathcal{E}_{\varphi^{-1}(K)}(U, E_U^\vee) \hookrightarrow D(U, E_U^\vee)$ , it is sufficient to show that  $T_{E^\vee, U, \varphi} : [\mathcal{E}_K(\varphi(U))]^{\times r} \rightarrow \mathcal{E}_{\varphi^{-1}(K)}(U, E_U^\vee)$  is continuous. To this end, by Theorem D.6, we just need to show that for all  $j \in \mathbb{N}$  and  $1 \leq l \leq r$  there exists  $j_1, \dots, j_r$  such that

$$\|T_{E^\vee, U, \varphi}(\xi_1, \dots, \xi_r)\|_{l, \varphi, j, \varphi^{-1}(K)} \leq C(\|\xi_1\|_{j_1, K} + \dots + \|\xi_r\|_{j_r, K})$$

But this obviously holds because

$$\|T_{E^\vee, U, \varphi}(\xi_1, \dots, \xi_r)\|_{l, \varphi, j, \varphi^{-1}(K)} = \|\xi_l\|_{j, K}$$

□

The adjoint of  $T_{E^\vee, U, \varphi}$  is

$$\begin{aligned} T_{E^\vee, U, \varphi}^* : [D(U, E_U^\vee)]^* &\rightarrow ([D(\varphi(U))]^{\times r})^* \\ \langle T_{E^\vee, U, \varphi}^* u, (\xi_1, \dots, \xi_r) \rangle &= \langle u, T_{E^\vee, U, \varphi}(\xi_1, \dots, \xi_r) \rangle \end{aligned}$$

Note that, since  $T_{E^\vee, U, \varphi}$  is a linear topological isomorphism,  $T_{E^\vee, U, \varphi}^*$  is also a linear topological isomorphism (and in particular it is bijective). For every  $u \in [D(U, E_U^\vee)]^*$ ,  $T_{E^\vee, U, \varphi}^* u$  is in  $([D(\varphi(U))]^{\times r})^*$ ; we can combine this with the bijective map

$$L : ([D(\varphi(U))]^{\times r})^* \rightarrow [D'(\varphi(U))]^{\times r}, \quad L(v) = (v \circ i_1, \dots, v \circ i_r)$$

(see Theorem B.46) to send  $u \in [D(U, E_U^\vee)]^*$  into an element of  $[D'(\varphi(U))]^{\times r}$ :

$$L(T_{E^\vee, U, \varphi}^* u) = ((T_{E^\vee, U, \varphi}^* u) \circ i_1, \dots, (T_{E^\vee, U, \varphi}^* u) \circ i_r)$$

where for all  $1 \leq l \leq r$ ,  $(T_{E^\vee, U, \varphi}^* u) \circ i_l \in D'(\varphi(U))$  is given by

$$\begin{aligned} ((T_{E^\vee, U, \varphi}^* u) \circ i_l)(\xi) &= (T_{E^\vee, U, \varphi}^* u)(i_l(\xi)) = (T_{E^\vee, U, \varphi}^* u)(0, \dots, 0, \underbrace{\xi}_{l^{\text{th}} \text{ position}}, 0, \dots, 0) \\ &= \langle u, T_{E^\vee, U, \varphi}(0, \dots, 0, \underbrace{\xi}_{l^{\text{th}} \text{ position}}, 0, \dots, 0) \rangle \end{aligned}$$

If we define  $g_{l, \xi, U, \varphi} \in D(U, E_U^\vee)$  by

$$\begin{aligned} g_{l, \xi, U, \varphi}(x) &= T_{E^\vee, U, \varphi}(0, \dots, 0, \underbrace{\xi}_{l^{\text{th}} \text{ position}}, 0, \dots, 0)(x) \\ &= (\rho^\vee|_{E_x^\vee})^{-1} \circ (0, \dots, 0, \underbrace{\xi}_{l^{\text{th}} \text{ position}}, 0, \dots, 0) \circ \varphi(x) \end{aligned}$$

then we may write

$$\langle (T_{E^\vee, U, \varphi}^* u) \circ i_l, \xi \rangle_{D'(\varphi(U)) \times D(\varphi(U))} = \langle u, g_{l, \xi, U, \varphi} \rangle_{[D(U, E_U^\vee)]^* \times D(U, E_U^\vee)}$$

**Summary:** We can associate with  $u \in D'(U, E_U) = (D(U, E_U^\vee))^*$  the following  $r$  distributions in  $D'(\varphi(U))$ :

$$\forall 1 \leq l \leq r \quad \tilde{u}^l = T_{E^\vee, U, \varphi}^* u \circ i_l$$

that is

$$\forall \xi \in D(\varphi(U)) \quad \langle \tilde{u}^l, \xi \rangle = \langle u, g_{l, \xi, U, \varphi} \rangle$$

where  $g_{l, \xi, U, \varphi} \in D(U, E_U^\vee)$  is defined by

$$(\rho^\vee|_{E_x^\vee})^{-1} \circ (0, \dots, 0, \underbrace{\xi}_{l^{\text{th}} \text{ position}}, 0, \dots, 0) \circ \varphi(x)$$

In particular,

$$\rho^\vee \circ g_{l, \xi, U, \varphi} \circ \varphi^{-1} = (0, \dots, 0, \underbrace{\xi}_{l^{\text{th}} \text{ position}}, 0, \dots, 0)$$

and so  $(\rho^\vee \circ g_{l, \xi, U, \varphi} \circ \varphi^{-1})^l = \xi$ .

Let's give a name to the composition of  $L$  with  $T_{E^\vee, U, \varphi}^*$  that we used above. We set  $H_{E^\vee, U, \varphi} := L \circ T_{E^\vee, U, \varphi}^*$ :

$$H_{E^\vee, U, \varphi} : [D(U, E_U^\vee)]^* \rightarrow (D'(\varphi(U)))^{\times r}, \quad u \mapsto L(T_{E^\vee, U, \varphi}^* u) = (\tilde{u}^1, \dots, \tilde{u}^r)$$

**Remark D.26.** Here we make three observations about the mapping  $H_{E^\vee, U, \varphi}$ .

(1) For every  $u \in [D(U, E_U^\vee)]^*$

$$\text{supp}[H_{E^\vee, U, \varphi}]^l = \text{supp}\tilde{u}^l \subseteq \varphi(\text{supp}(u))$$

Indeed, let  $A = \varphi(\text{supp}u)$ . By Theorem D.17, it is enough to show that if  $\eta \in D(\varphi(U))$  is such that  $\text{supp}\eta \subseteq \varphi(U) \setminus A$ , then  $\tilde{u}^l(\eta) = 0$ . Note that

$$\langle \tilde{u}^l, \eta \rangle = \langle u, g_{l, \eta, U, \varphi} \rangle$$

So by Remark D.23 we just need to show that  $g_{l, \eta, U, \varphi} = 0$  on an open neighborhood of  $\text{supp}u$ . Let  $K = \text{supp}\eta$ . Clearly  $U \setminus \varphi^{-1}(K)$  is an open neighborhood of  $\text{supp}u$ . We will show that  $g_{l, \eta, U, \varphi}$  vanishes on this open neighborhood. Note that

$$g_{l, \eta, U, \varphi}(x) = (\rho^\vee|_{E_x^\vee})^{-1}(0, \dots, 0, \underbrace{\eta \circ \varphi(x)}_{l^{\text{th}} \text{ position}}, 0, \dots, 0)$$

Since  $\rho^\vee|_{E_x^\vee}$  is an isomorphism and  $\eta = 0$  on  $\varphi(U) \setminus K$ , we conclude that  $g_{l, \eta, U, \varphi} = 0$  on  $\varphi^{-1}(\varphi(U) \setminus K) = U \setminus \varphi^{-1}(K)$ .

(2) Clearly  $H_{E^\vee, U, \varphi} : D'(U, E_U) \rightarrow [D'(\varphi(U))]^{\times r}$  preserves addition. Moreover if  $f \in C^\infty(U)$  and  $u \in D'(U, E_U)$ , then  $H_{E^\vee, U, \varphi}(fu) = (f \circ \varphi^{-1})H_{E^\vee, U, \varphi}(u)$ . Recall that  $H = L \circ T_{E^\vee, U, \varphi}^*$ .

$$\begin{aligned} \langle T_{E^\vee, U, \varphi}^*(fu), (\xi_1, \dots, \xi_r) \rangle &= \langle fu, T_{E^\vee, U, \varphi}(\xi_1, \dots, \xi_r) \rangle \\ &= \langle u, fT_{E^\vee, U, \varphi}(\xi_1, \dots, \xi_r) \rangle \\ &= \langle u, T_{E^\vee, U, \varphi}[(f \circ \varphi^{-1})(\xi_1, \dots, \xi_r)] \rangle \\ &= \langle T_{E^\vee, U, \varphi}^*u, (f \circ \varphi^{-1})(\xi_1, \dots, \xi_r) \rangle \\ &= \langle (f \circ \varphi^{-1})T_{E^\vee, U, \varphi}^*u, (\xi_1, \dots, \xi_r) \rangle \end{aligned}$$

(the third equality follows directly from the definition of  $T_{E^\vee, U, \varphi}$ .) Therefore

$$T_{E^\vee, U, \varphi}^*(fu) = (f \circ \varphi^{-1})T_{E^\vee, U, \varphi}^*u$$

The fact that  $L((f \circ \varphi^{-1})T_{E^\vee, U, \varphi}^*u) = (f \circ \varphi^{-1})L(T_{E^\vee, U, \varphi}^*u)$  is an immediate consequence of the definition of  $L$ .

(3) Since  $T_{E^\vee, U, \varphi}$  and  $L$  are both linear topological isomorphisms,  $H_{E^\vee, U, \varphi}^{-1} = (L \circ T_{E^\vee, U, \varphi}^*)^{-1} : (D'(\varphi(U)))^{\times r} \rightarrow D^*(U, E_U^\vee)$  is also a linear topological isomorphism. It is useful for our later considerations to find an explicit formula for this map. Note that

$$\begin{aligned} H_{E^\vee, U, \varphi}^{-1} &= (L \circ T_{E^\vee, U, \varphi}^*)^{-1} = (T_{E^\vee, U, \varphi}^*)^{-1} \circ L^{-1} = (T_{E^\vee, U, \varphi}^{-1})^* \circ L^{-1} \\ &= (\tilde{T}_{E^\vee, U, \varphi}^*)^* \circ L^{-1} = (\tilde{T}_{E^\vee, U, \varphi}^*)^* \circ \tilde{L} \end{aligned}$$

Recall that

$$\begin{aligned} \tilde{L} : [D^*(\varphi(U))]^{\times r} &\rightarrow [(D(\varphi(U)))^{\times r}]^*, \quad (v^1, \dots, v^r) \mapsto v^1 \circ \pi_1 + \dots + v^r \circ \pi_r \\ \tilde{T}_{E^\vee, U, \varphi}^* : [(D(\varphi(U)))^{\times r}]^* &\rightarrow D^*(U, E_U^\vee) \end{aligned}$$

Therefore for all  $\xi \in D(U, E_U^\vee)$

$$\begin{aligned} H_{E_U^\vee, U, \varphi}^{-1}(v^1, \dots, v^r)(\xi) &= \langle \tilde{T}_{E_U^\vee, U, \varphi}^*(v^1 \circ \pi_1 + \dots + v^r \circ \pi_r), \xi \rangle \\ &= \langle (v^1 \circ \pi_1 + \dots + v^r \circ \pi_r), \tilde{T}\xi \rangle \\ &= \langle (v^1 \circ \pi_1 + \dots + v^r \circ \pi_r), ((\rho^\vee)^1 \circ \xi \circ \varphi^{-1}, \dots, (\rho^\vee)^r \circ \xi \circ \varphi^{-1}) \rangle \\ &= \sum_i v^i [(\rho^\vee)^i \circ \xi \circ \varphi^{-1}] \end{aligned}$$

**Remark D.27.** Suppose  $u \in D'(M, E)$  is a regular distribution, that is  $u = u_f$  where  $f \in \Gamma_{reg}(M, E)$ . We want to see whether the local components of such a distribution agree with its components as an element of  $\Gamma(M, E)$ . With respect to the total trivialization triple  $(U, \varphi, \rho)$  we have

- (1)  $f \mapsto (\tilde{f}^1, \dots, \tilde{f}^r), \tilde{f}^l = \rho^l \circ f \circ \varphi^{-1}$
- (2)  $u_f \mapsto (\tilde{u}_f^1, \dots, \tilde{u}_f^l)$

The question is whether  $u_{\tilde{f}^l} = \tilde{u}_f^l$ ? Here we will show that the answer is positive. Indeed, for all  $\xi \in D(\varphi(U))$  we have

$$\begin{aligned} \langle \tilde{u}_f^l, \xi \rangle &= \langle u_f, g_{l, \xi, U, \varphi} \rangle = \int_M [g_{l, \xi, U, \varphi}, f] = \int_{\varphi(U)} \sum_i (\tilde{g}_{l, \xi, U, \varphi})^i \tilde{f}^i dV = \int_{\varphi(U)} (\tilde{g}_{l, \xi, U, \varphi})^l \tilde{f}^l dV \\ &= \int_{\varphi(U)} \tilde{f}^l \xi dV = \langle u_{\tilde{f}^l}, \xi \rangle \end{aligned}$$

Note that the above calculation in fact shows that the restriction of  $H$  to  $D(U, E_U)$  is  $\tilde{T}_{E, U, \varphi}$ .

## APPENDIX E. PROPERTIES OF SOBOLEV SPACES

In this section we present a brief overview of the basic definitions and properties related to Sobolev spaces on Euclidean spaces.

### E.1. Basic Definitions.

**Definition E.1.** Let  $s \geq 0$  and  $p \in [1, \infty]$ . The Sobolev-Slobodeckij space  $W^{s,p}(\mathbb{R}^n)$  is defined as follows:

- If  $s = k \in \mathbb{N}_0, p \in [1, \infty)$ ,

$$W^{k,p}(\mathbb{R}^n) = \{u \in L^p(\mathbb{R}^n) : \|u\|_{W^{k,p}(\mathbb{R}^n)} := \sum_{|\nu| \leq k} \|\partial^\nu u\|_p < \infty\}$$

- If  $s = \theta \in (0, 1), p \in [1, \infty)$ ,

$$W^{\theta,p}(\mathbb{R}^n) = \{u \in L^p(\mathbb{R}^n) : |u|_{W^{\theta,p}(\mathbb{R}^n)} := \left( \int \int_{\mathbb{R}^n \times \mathbb{R}^n} \frac{|u(x) - u(y)|^p}{|x - y|^{n+\theta p}} dx dy \right)^{\frac{1}{p}} < \infty\}$$

- If  $s = \theta \in (0, 1), p = \infty$ ,

$$W^{\theta,\infty}(\mathbb{R}^n) = \{u \in L^\infty(\mathbb{R}^n) : |u|_{W^{\theta,\infty}(\mathbb{R}^n)} := \operatorname{ess\,sup}_{x,y \in \mathbb{R}^n, x \neq y} \frac{|u(x) - u(y)|}{|x - y|^\theta} < \infty\}$$

- If  $s = k + \theta, k \in \mathbb{N}_0, \theta \in (0, 1), p \in [1, \infty]$ ,

$$W^{s,p}(\mathbb{R}^n) = \{u \in W^{k,p}(\mathbb{R}^n) : \|u\|_{W^{s,p}(\mathbb{R}^n)} := \|u\|_{W^{k,p}(\mathbb{R}^n)} + \sum_{|\nu|=k} \|\partial^\nu u\|_{W^{\theta,p}(\mathbb{R}^n)} < \infty\}$$

**Remark E.2.** Clearly for all  $s \geq 0$ ,  $W^{s,p}(\mathbb{R}^n) \subseteq L^p(\mathbb{R}^n)$ . Recall that  $L^p(\mathbb{R}^n) \subseteq L^1_{loc}(\mathbb{R}^n) \subseteq D'(\mathbb{R}^n)$ . So we may consider elements of  $W^{s,p}(\mathbb{R}^n)$  as distributions in  $D'(\mathbb{R}^n)$ . Indeed, for  $s \geq 0$ ,  $p \in (1, \infty)$ , and  $u \in D'(\mathbb{R}^n)$  we define

$$\begin{cases} \|u\|_{W^{s,p}(\mathbb{R}^n)} := \|f\|_{W^{s,p}(\mathbb{R}^n)} & \text{if } u = u_f \text{ for some } f \in L^p(\mathbb{R}^n) \\ \|u\|_{W^{s,p}(\mathbb{R}^n)} := \infty & \text{otherwise} \end{cases}$$

As a consequence we may write

$$W^{s,p}(\mathbb{R}^n) = \{u \in D'(\mathbb{R}^n) : \|u\|_{W^{s,p}(\mathbb{R}^n)} < \infty\}$$

**Remark E.3.** Let us make some observations that will be helpful in the proof of a number of important theorems. Let  $A$  be a nonempty measurable set in  $\mathbb{R}^n$ .

(1) We may write:

$$\begin{aligned} & \int \int_{\mathbb{R}^n \times \mathbb{R}^n} \frac{|\partial^\nu u(x) - \partial^\nu u(y)|^p}{|x - y|^{n+\theta p}} dx dy \\ &= \int \int_{A \times A} \cdots dx dy + \int_A \int_{\mathbb{R}^n \setminus A} \cdots dx dy + \int_{\mathbb{R}^n \setminus A} \int_A \cdots dx dy + \int_{\mathbb{R}^n \setminus A} \int_{\mathbb{R}^n \setminus A} \cdots dx dy \end{aligned}$$

In particular, if  $\text{supp } u \subseteq A$ , then the last integral vanishes and the sum of the two middle integrals will be equal to  $2 \int_A \int_{\mathbb{R}^n \setminus A} \frac{|\partial^\nu u(x)|^p}{|x - y|^{n+\theta p}} dy dx$ . Therefore in this case

$$\begin{aligned} & \int \int_{\mathbb{R}^n \times \mathbb{R}^n} \frac{|\partial^\nu u(x) - \partial^\nu u(y)|^p}{|x - y|^{n+\theta p}} dx dy = \\ & \int \int_{A \times A} \frac{|\partial^\nu u(x) - \partial^\nu u(y)|^p}{|x - y|^{n+\theta p}} dx dy + 2 \int_A \int_{\mathbb{R}^n \setminus A} \frac{|\partial^\nu u(x)|^p}{|x - y|^{n+\theta p}} dy dx \end{aligned}$$

(2) If  $A$  is open,  $K \subseteq A$  is compact and  $\alpha > n$ , then there exists a number  $C$  such that for all  $x \in K$  we have

$$\int_{\mathbb{R}^n \setminus A} \frac{1}{|x - y|^\alpha} dy \leq C$$

( $C$  depends on  $A$ ,  $n$ , and  $\alpha$  but is independent of  $x$ .) The reason is as follows: Let  $R = \frac{1}{2} \text{dist}(K, A^c) > 0$ . Clearly for all  $x \in K$  the ball  $B_R(x)$  is inside  $A$ . Therefore for all  $x \in K$ ,  $\mathbb{R}^n \setminus A \subseteq \mathbb{R}^n \setminus B_R(x)$  which implies that for all  $x \in K$

$$\int_{\mathbb{R}^n \setminus A} \frac{1}{|x - y|^\alpha} dy \leq \int_{\mathbb{R}^n \setminus B_R(x)} \frac{1}{|x - y|^\alpha} dy \stackrel{z=y-x}{=} \int_{\mathbb{R}^n \setminus B_R(0)} \frac{1}{|z|^\alpha} dz = \sigma(S^{n-1}) \int_R^\infty \frac{1}{r^\alpha} r^{n-1} dr$$

which converges because  $\alpha > n$ . We can let  $C = \sigma(S^{n-1}) \int_R^\infty \frac{1}{r^\alpha} r^{n-1} dr$ .

(3) If  $A$  is bounded and  $\alpha < n$ , then there exists a number  $C$  such that for all  $x \in A$

$$\int_A \frac{1}{|x - y|^\alpha} dy \leq C$$

( $C$  depends on  $A$ ,  $n$ , and  $\alpha$  but is independent of  $x$ .) The reason is as follows: Since  $A$  is bounded there exists  $R > 0$  such that for all  $x, y \in A$  we have  $|x - y| < R$ . So for all  $x \in A$

$$\int_A \frac{1}{|x - y|^\alpha} dy \leq \sigma(S^{n-1}) \int_0^R \frac{1}{r^\alpha} r^{n-1} dr$$

which converges because  $\alpha < n$ .

**Theorem E.4.** Let  $s \geq 0$  and  $p \in (1, \infty)$ .  $C_c^\infty(\mathbb{R}^n)$  is dense in  $W^{s,p}(\mathbb{R}^n)$ . In fact, the identity map  $i_{D,W} : D(\mathbb{R}^n) \rightarrow W^{s,p}(\mathbb{R}^n)$  is a linear continuous map with dense image.

*Proof.* The fact that  $C_c^\infty(\mathbb{R}^n)$  is dense in  $W^{s,p}(\mathbb{R}^n)$  follows from Theorem 7.38 and Lemma 7.44 in [1] combined with Remark E.13. Linearity of  $i_{D,W}$  is obvious. It remains to prove that this map is continuous. By Theorem D.4 it is enough to show that

$$\forall K \in \mathcal{K}(\mathbb{R}^n), \forall \varphi \in \mathcal{E}_K(\mathbb{R}^n) \quad \exists j \in \mathbb{N} \quad \text{s.t.} \quad \|\varphi\|_{W^{s,p}(\mathbb{R}^n)} \preceq \|\varphi\|_{j,K}$$

Let  $s = m + \theta$  where  $m \in \mathbb{N}_0$  and  $\theta \in [0, 1)$ . If  $\theta \neq 0$ , by definition  $\|\varphi\|_{W^{s,p}(\mathbb{R}^n)} = \|\varphi\|_{W^{m,p}(\mathbb{R}^n)} + \sum_{|\nu|=m} \|\partial^\nu \varphi\|_{W^{\theta,p}(\mathbb{R}^n)}$ . It is enough to show that each summand can be bounded by a constant multiple of  $\|\varphi\|_{j,K}$  for some  $j$ .

- **Step 1:** If  $\theta = 0$ ,

$$\begin{aligned} \|\varphi\|_{W^{m,p}(\mathbb{R}^n)} &= \sum_{|\nu| \leq m} \|\partial^\nu \varphi\|_{L^p(\mathbb{R}^n)} = \sum_{|\nu| \leq m} \|\partial^\nu \varphi\|_{L^p(K)} \\ &= \sum_{|\nu| \leq m} (\|\varphi\|_{m,K} |K|^{\frac{1}{p}}) \preceq \|\varphi\|_{m,K} \end{aligned}$$

where the implicit constant depends on  $m$  and  $K$  but is independent of  $\varphi$ .

- **Step 2:** Let  $A$  be an open ball that contains  $K$  (in particular,  $A$  is bounded). As it was pointed out in Remark E.3 we may write

$$\begin{aligned} &\int \int_{\mathbb{R}^n \times \mathbb{R}^n} \frac{|\partial^\nu \varphi(x) - \partial^\nu \varphi(y)|^p}{|x - y|^{n+\theta p}} dx dy = \\ &\int \int_{A \times A} \frac{|\partial^\nu \varphi(x) - \partial^\nu \varphi(y)|^p}{|x - y|^{n+\theta p}} dx dy + 2 \int_A \int_{\mathbb{R}^n \setminus A} \frac{|\partial^\nu \varphi(x)|^p}{|x - y|^{n+\theta p}} dy dx \end{aligned}$$

First note that  $\mathbb{R}^n$  is a convex open set; so by Theorem B.10 every function  $f \in \mathcal{E}_K(\mathbb{R}^n)$  is Lipschitz; Indeed, for all  $x, y \in \mathbb{R}^n$  we have  $|f(x) - f(y)| \preceq \|f\|_{1,K} \|x - y\|$ . Hence

$$\begin{aligned} \int \int_{A \times A} \frac{|\partial^\nu \varphi(x) - \partial^\nu \varphi(y)|^p}{|x - y|^{n+\theta p}} dx dy &\leq \int_A \|\partial^\nu \varphi\|_{1,K}^p \int_A \frac{|x - y|^p}{|x - y|^{n+\theta p}} dy dx \\ &= \int_A \|\partial^\nu \varphi\|_{1,K}^p \int_A \frac{1}{|x - y|^{n+(\theta-1)p}} dy dx \end{aligned}$$

By part 3 of Remark E.3  $\int_A \frac{1}{|x - y|^{n+(\theta-1)p}} dy$  is bounded by a constant independent of  $x$ ; also clearly  $\|\partial^\nu \varphi\|_{1,K} \leq \|\varphi\|_{m+1,K}$ . Considering that  $|A|$  is finite we get

$$\int \int_{A \times A} \frac{|\partial^\nu \varphi(x) - \partial^\nu \varphi(y)|^p}{|x - y|^{n+\theta p}} dx dy \preceq \|\varphi\|_{m+1,K}^p$$

Finally for the remaining integral we have

$$\int_A \int_{\mathbb{R}^n \setminus A} \frac{|\partial^\nu \varphi(x)|^p}{|x - y|^{n+\theta p}} dy dx = \int_K \int_{\mathbb{R}^n \setminus A} \frac{|\partial^\nu \varphi(x)|^p}{|x - y|^{n+\theta p}} dy dx$$

because the inner integral is zero for  $x \notin K$ . Now we can write

$$\int_K \int_{\mathbb{R}^n \setminus A} \frac{|\partial^\nu \varphi(x)|^p}{|x - y|^{n+\theta p}} dx dy \preceq \int_K \|\varphi\|_{m,K}^p \int_{\mathbb{R}^n \setminus A} \frac{1}{|x - y|^{n+\theta p}} dy dx$$

By part 2 of Remark E.3 for all  $x \in K$ , the inner integral is bounded by a constant. Since  $|K|$  is finite we conclude that

$$\int_A \int_{\mathbb{R}^n \setminus A} \frac{|\partial^\nu \varphi(x)|^p}{|x - y|^{n+\theta p}} dy dx \preceq \|\varphi\|_{m,K}^p$$

Hence

$$\|u\|_{W^{s,p}(\mathbb{R}^n)} \leq \|\varphi\|_{m+1,K}$$

□

**Definition E.5.** Let  $s < 0$  and  $p \in (1, \infty)$ . We define

$$W^{s,p}(\mathbb{R}^n) = (W^{-s,p'}(\mathbb{R}^n))^* \quad \left(\frac{1}{p} + \frac{1}{p'} = 1\right).$$

**Remark E.6.** Note that since the identity map from  $D(\mathbb{R}^n)$  to  $W^{s,p}(\mathbb{R}^n)$  is continuous with dense image, the dual space  $W^{-s,p'}(\mathbb{R}^n)$  can be viewed as a subspace of  $D'(\mathbb{R}^n)$ . Indeed, by Theorem B.47 the adjoint of the identity map,  $i_{D,W}^* : W^{-s,p'}(\mathbb{R}^n) \rightarrow D'(\mathbb{R}^n)$  is an injective linear continuous map and we can use this map to identify  $W^{-s,p'}(\mathbb{R}^n)$  with a subspace of  $D'(\mathbb{R}^n)$ . It is a direct consequence of the definition of adjoint that for all  $u \in W^{-s,p'}(\mathbb{R}^n)$ ,  $i_{D,W}^* u = u|_{D(\mathbb{R}^n)}$ . So by identifying  $u : W^{s,p}(\mathbb{R}^n) \rightarrow \mathbb{R}$  with  $u|_{D(\mathbb{R}^n)} : D(\mathbb{R}^n) \rightarrow \mathbb{R}$ , we can view  $W^{-s,p'}(\mathbb{R}^n)$  as a subspace of  $D'(\mathbb{R}^n)$ .

**Remark E.7.**

- It is a direct consequence of the contents of pages 88 and 178 of [44] that for  $m \in \mathbb{Z}$  and  $1 < p < \infty$

$$W^{m,p}(\mathbb{R}^n) = H_p^m(\mathbb{R}^n) = F_{p,2}^m(\mathbb{R}^n)$$

- It is a direct consequence of the contents of pages 38, 51, 90 and 178 of [44] that for  $s \notin \mathbb{Z}$  and  $1 < p < \infty$

$$W^{s,p}(\mathbb{R}^n) = B_{p,p}^s(\mathbb{R}^n)$$

**Theorem E.8.** For all  $s \in \mathbb{R}$  and  $1 < p < \infty$ ,  $W^{s,p}(\mathbb{R}^n)$  is reflexive.

*Proof.* See the proof of Theorem E.30. Also see [43], Section 2.6, Page 198. □

Note that by definition for all  $s > 0$  we have  $[W^{s,p}(\mathbb{R}^n)]^* = W^{-s,p'}(\mathbb{R}^n)$ . Now since  $W^{s,p}(\mathbb{R}^n)$  is reflexive,  $[W^{-s,p'}(\mathbb{R}^n)]^*$  is isometrically isomorphic to  $W^{s,p}(\mathbb{R}^n)$  and so they can be identified with one another. Thus for all  $s \in \mathbb{R}$  and  $1 < p < \infty$  we may write

$$[W^{s,p}(\mathbb{R}^n)]^* = W^{-s,p'}(\mathbb{R}^n)$$

Let  $s \geq 0$  and  $p \in (1, \infty)$ . Every function  $\varphi \in C_c^\infty(\mathbb{R}^n)$  defines a linear functional  $L_\varphi : W^{s,p}(\mathbb{R}^n) \rightarrow \mathbb{R}$  defined by

$$L_\varphi(u) = \int_{\mathbb{R}^n} u\varphi dx$$

$L_\varphi$  is continuous because by Holder's inequality

$$|L_\varphi(u)| = \left| \int_{\mathbb{R}^n} u\varphi dx \right| \leq \|u\|_{L^p(\mathbb{R}^n)} \|\varphi\|_{L^{p'}(\mathbb{R}^n)} \leq \|\varphi\|_{L^{p'}(\mathbb{R}^n)} \|u\|_{W^{s,p}(\mathbb{R}^n)}$$

Also the map  $L : C_c^\infty(\mathbb{R}^n) \rightarrow W^{s,p}(\mathbb{R}^n)$  which maps  $\varphi$  into  $L_\varphi$  is injective because

$$L_\varphi = L_\psi \rightarrow \forall u \in W^{s,p}(\mathbb{R}^n) \quad \int_{\mathbb{R}^n} u(\varphi - \psi) dx = 0 \rightarrow \int_{\mathbb{R}^n} |\varphi - \psi|^2 dx = 0 \rightarrow \varphi = \psi$$

Thus we may identify  $\varphi$  with  $L_\varphi$  and consider  $C_c^\infty(\mathbb{R}^n)$  as a subspace of  $W^{-s,p'}(\mathbb{R}^n)$ .

**Theorem E.9.** For all  $s > 0$  and  $p \in (1, \infty)$ ,  $C_c^\infty(\mathbb{R}^n)$  is dense in  $W^{-s,p'}(\mathbb{R}^n)$ .

*Proof.* The proof given in Page 65 of [2] for integer order Sobolev spaces, which is based on reflexivity of Sobolev spaces, works equally well for fractional order Sobolev spaces too. □

**Remark E.10.** As a consequence of the above theorems, for all  $s \in \mathbb{R}$  and  $p \in (1, \infty)$ ,  $W^{s,p}(\mathbb{R}^n)$  can be considered as a subspace of  $D'(\mathbb{R}^n)$ . See Theorem B.47 and the discussion thereafter for further insights. Also see Remark E.46.

Next we list several definitions pertinent to Sobolev spaces on open subsets of  $\mathbb{R}^n$ .

**Definition E.11.** Let  $\Omega$  be a nonempty open set in  $\mathbb{R}^n$ . Let  $s \in \mathbb{R}$  and  $p \in (1, \infty)$ .

(1) • If  $s = k \in \mathbb{N}_0$ ,

$$W^{k,p}(\Omega) = \{u \in L^p(\Omega) : \|u\|_{W^{k,p}(\Omega)} := \sum_{|\nu| \leq k} \|\partial^\nu u\|_{L^p(\Omega)} < \infty\}$$

• If  $s = \theta \in (0, 1)$ ,

$$W^{\theta,p}(\Omega) = \{u \in L^p(\Omega) : |u|_{W^{\theta,p}(\Omega)} := \left( \int \int_{\Omega \times \Omega} \frac{|u(x) - u(y)|^p}{|x - y|^{n+\theta p}} dx dy \right)^{\frac{1}{p}} < \infty\}$$

• If  $s = k + \theta$ ,  $k \in \mathbb{N}_0$ ,  $\theta \in (0, 1)$ ,

$$W^{s,p}(\Omega) = \{u \in W^{k,p}(\Omega) : \|u\|_{W^{s,p}(\Omega)} := \|u\|_{W^{k,p}(\Omega)} + \sum_{|\nu|=k} \|\partial^\nu u\|_{W^{\theta,p}(\Omega)} < \infty\}$$

• If  $s < 0$ ,

$$W^{s,p}(\Omega) = (W_0^{-s,p'}(\Omega))^* \quad \left( \frac{1}{p} + \frac{1}{p'} = 1 \right).$$

where for all  $e \geq 0$  and  $1 < q < \infty$ ,  $W_0^{e,q}(\Omega)$  is defined as the closure of  $C_c^\infty(\Omega)$  in  $W^{e,q}(\Omega)$ .

(2)  $W^{s,p}(\bar{\Omega})$  is defined as the restriction of  $W^{s,p}(\mathbb{R}^n)$  to  $\Omega$ . That is,  $W^{s,p}(\bar{\Omega})$  is the collection of all  $u \in D'(\Omega)$  such that there is a  $v \in W^{s,p}(\mathbb{R}^n)$  with  $v|_{\Omega} = u$ . Here  $v|_{\Omega}$  should be interpreted as the restriction of a distribution in  $D'(\mathbb{R}^n)$  to a distribution in  $D'(\Omega)$ .  $W^{s,p}(\bar{\Omega})$  is equipped with the following norm:

$$\|u\|_{W^{s,p}(\bar{\Omega})} = \inf_{v \in W^{s,p}(\mathbb{R}^n), v|_{\Omega} = u} \|v\|_{W^{s,p}(\mathbb{R}^n)}.$$

(3)

$$\tilde{W}^{s,p}(\bar{\Omega}) = \{u \in W^{s,p}(\mathbb{R}^n) : \text{supp } u \subseteq \bar{\Omega}\}$$

$\tilde{W}^{s,p}(\bar{\Omega})$  is equipped with the norm  $\|u\|_{\tilde{W}^{s,p}(\bar{\Omega})} = \|u\|_{W^{s,p}(\mathbb{R}^n)}$ .

(4)

$$\tilde{W}^{s,p}(\Omega) = \{u = v|_{\Omega}, v \in \tilde{W}^{s,p}(\bar{\Omega})\} \quad (\text{E.1})$$

Again  $v|_{\Omega}$  should be interpreted as the restriction of an element in  $D'(\mathbb{R}^n)$  to  $D'(\Omega)$ . So  $\tilde{W}^{s,p}(\Omega)$  is a subspace of  $D'(\Omega)$ . This space is equipped with the norm  $\|u\|_{\tilde{W}^{s,p}(\Omega)} = \inf \|v\|_{W^{s,p}(\mathbb{R}^n)}$  where the infimum is taken over all  $v$  that satisfy (E.1). Note that two elements  $v_1$  and  $v_2$  of  $\tilde{W}^{s,p}(\bar{\Omega})$  restrict to the same element in  $D'(\Omega)$  if and only if  $\text{supp}(v_1 - v_2) \subseteq \partial\Omega$ . Therefore

$$\tilde{W}^{s,p}(\Omega) = \frac{\tilde{W}^{s,p}(\bar{\Omega})}{\{v \in W^{s,p}(\mathbb{R}^n) : \text{supp } v \subseteq \partial\Omega\}}$$

(5) For  $s \geq 0$  we define

$$W_{00}^{s,p}(\Omega) = \{u \in W^{s,p}(\Omega) : \text{ext}_{\mathbb{R}^n}^0 u \in W^{s,p}(\mathbb{R}^n)\}$$

We equip this space with the norm

$$\|u\|_{W_{00}^{s,p}(\Omega)} := \|\text{ext}_{\mathbb{R}^n}^0 u\|_{W^{s,p}(\mathbb{R}^n)}$$



Note that previously we defined the operator  $\text{ext}_{\mathbb{R}^n}^0$  only for distributions with compact support and functions; this is why the values of  $s$  are restricted to be nonnegative in this definition.

(6) For all  $K \in \mathcal{K}(\Omega)$  we define

$$W_K^{s,p}(\Omega) = \{u \in W^{s,p}(\Omega) : \text{supp } u \subseteq K\}$$

with  $\|u\|_{W_K^{s,p}(\Omega)} := \|u\|_{W^{s,p}(\Omega)}$ .

(7)

$$W_{\text{comp}}^{s,p}(\Omega) = \bigcup_{K \in \mathcal{K}(\Omega)} W_K^{s,p}(\Omega)$$

This space is normally equipped with the inductive limit topology with respect to the family  $\{W_K^{s,p}(\Omega)\}_{K \in \mathcal{K}(\Omega)}$ . **However, in these notes we always consider  $W_{\text{comp}}^{s,p}(\Omega)$  as a normed space equipped with the norm induced from  $W^{s,p}(\Omega)$ .**

**Remark E.12.** Each of these definitions has its advantages and disadvantages. For example, the way we defined the spaces  $W^{s,p}(\Omega)$  is well suited for using duality arguments while proving the usual embedding theorems for these spaces on an arbitrary open set  $\Omega$  is not trivial; on the other hand, duality arguments do not work as well for spaces  $W^{s,p}(\bar{\Omega})$  but the embedding results for these spaces on an arbitrary open set  $\Omega$  automatically follow from the corresponding results on  $\mathbb{R}^n$ . Various authors adopt different definitions for Sobolev spaces on domains based on the applications that they are interested in. Unfortunately the notations used in the literature for the various spaces introduced above are not uniform. First note that it is a direct consequence of Remark E.7 and the definitions of  $B_{p,q}^s(\Omega)$ ,  $H_p^s(\Omega)$  and  $F_{p,q}^s(\Omega)$  in [43] Page 310 and [46] that

$$W^{s,p}(\bar{\Omega}) = \begin{cases} F_{p,2}^s(\Omega) = H_p^s(\Omega) & \text{if } s \in \mathbb{Z} \\ B_{p,p}^s(\Omega) & \text{if } s \notin \mathbb{Z} \end{cases}$$

With this in mind, we have the following table which displays the connection between the notations used in this work with the notations in a number of well known references.

Holst	Triebel [43]	Triebel [46]	Grisvard [20]	Bhattacharyya [9]
$W^{s,p}(\Omega)$			$W_p^s(\Omega)$	$W^{s,p}(\Omega)$
$W^{s,p}(\bar{\Omega})$	$W_p^s(\Omega)$	$W_p^s(\Omega)$	$W_p^s(\bar{\Omega})$	$W^{s,p}(\bar{\Omega})$
$\tilde{W}^{s,p}(\bar{\Omega})$	$\tilde{W}_p^s(\Omega)$	$\tilde{W}_p^s(\bar{\Omega})$		
$\tilde{W}^{s,p}(\Omega)$		$\tilde{W}_p^s(\Omega)$		
$W_{00}^{s,p}(\Omega)$			$\tilde{W}_p^s(\Omega)$	$W_{00}^{s,p}(\Omega)$

**Remark E.13.**

- *Note that*

$$\begin{aligned}
\|u\|_{W^{k,p}(\cdot)} + \sum_{|\nu|=k} |\partial^\nu u|_{W^{\theta,p}(\cdot)} &\leq \|u\|_{W^{k,p}(\cdot)} + \sum_{|\nu|=k} \|\partial^\nu u\|_{W^{\theta,p}(\cdot)} \\
&= \|u\|_{W^{k,p}(\cdot)} + \sum_{|\nu|=k} \left( \|u\|_{L^p(\cdot)} + \sum_{|\nu|=k} |\partial^\nu u|_{W^{\theta,p}(\cdot)} \right) \\
&\leq \|u\|_{W^{k,p}(\cdot)} + \sum_{|\nu|=k} |\partial^\nu u|_{W^{\theta,p}(\cdot)} \quad (\text{since } \|u\|_{L^p(\cdot)} \leq \|u\|_{W^{k,p}(\cdot)})
\end{aligned}$$

Therefore the following is an equivalent norm on  $W^{s,p}(\Omega)$

$$\|u\|_{W^{s,p}(\cdot)} := \|u\|_{W^{k,p}(\cdot)} + \sum_{|\alpha|=k} \|\partial^\alpha u\|_{W^{\theta,p}(\cdot)}$$

- For  $p \in (1, \infty)$  and  $a, b > 0$  we have  $(a^p + b^p)^{\frac{1}{p}} \simeq a + b$ ; indeed,

$$a^p + b^p \leq (a + b)^p \leq (2 \max\{a, b\})^p \leq 2^p (a^p + b^p)$$

Therefore for any nonempty open set  $\Omega$  in  $\mathbb{R}^n$ ,  $s > 0$ , the following expressions are both equivalent to the original norm on  $W^{s,p}(\Omega)$

$$\begin{aligned}
\|u\|_{W^{s,p}(\cdot)} &:= \left[ \|u\|_{W^{k,p}(\cdot)}^p + \sum_{|\nu|=k} |\partial^\nu u|_{W^{\theta,p}(\cdot)}^p \right]^{\frac{1}{p}} \\
\|u\|_{W^{s,p}(\cdot)} &:= \left[ \|u\|_{W^{k,p}(\cdot)}^p + \sum_{|\nu|=k} \|\partial^\nu u\|_{W^{\theta,p}(\cdot)}^p \right]^{\frac{1}{p}}
\end{aligned}$$

where  $s = k + \theta$ ,  $k \in \mathbb{N}_0$ ,  $\theta \in (0, 1)$ .

**E.2. Properties of Sobolev Spaces on the Whole Space  $\mathbb{R}^n$ .**

**Theorem E.14** (Embedding Theorem I, [43], Section 2.8.1). *Suppose  $1 < p \leq q < \infty$  and  $-\infty < t \leq s < \infty$  satisfy  $s - \frac{n}{p} \geq t - \frac{n}{q}$ . Then  $W^{s,p}(\mathbb{R}^n) \hookrightarrow W^{t,q}(\mathbb{R}^n)$ . In particular,  $W^{s,p}(\mathbb{R}^n) \hookrightarrow W^{t,p}(\mathbb{R}^n)$ .*

**Theorem E.15** (Multiplication by smooth functions, [45], Page 203). *Let  $s \in \mathbb{R}$ ,  $1 < p < \infty$ , and  $\varphi \in BC^\infty(\mathbb{R}^n)$ . Then the linear map*

$$m_\varphi : W^{s,p}(\mathbb{R}^n) \rightarrow W^{s,p}(\mathbb{R}^n), \quad u \mapsto \varphi u$$

*is well defined and bounded.*

A detailed study of the following multiplication theorems can be found in [7].

**Theorem E.16.** *Let  $s_i, s$  and  $1 \leq p, p_i < \infty$  ( $i = 1, 2$ ) be real numbers satisfying*

- (i)  $s_i \geq s \geq 0$
- (ii)  $s \in \mathbb{N}_0$ ,
- (iii)  $s_i - s \geq n \left( \frac{1}{p_i} - \frac{1}{p} \right)$ ,
- (iv)  $s_1 + s_2 - s > n \left( \frac{1}{p_1} + \frac{1}{p_2} - \frac{1}{p} \right) \geq 0$ .

*where the strictness of the inequalities in items (iii) and (iv) can be interchanged.*

*If  $u \in W^{s_1,p_1}(\mathbb{R}^n)$  and  $v \in W^{s_2,p_2}(\mathbb{R}^n)$ , then  $uv \in W^{s,p}(\mathbb{R}^n)$  and moreover the pointwise multiplication of functions is a continuous bilinear map*

$$W^{s_1,p_1}(\mathbb{R}^n) \times W^{s_2,p_2}(\mathbb{R}^n) \rightarrow W^{s,p}(\mathbb{R}^n).$$

**Theorem E.17** (Multiplication theorem for Sobolev spaces on the whole space, non-negative exponents). *Assume  $s_i, s$  and  $1 \leq p_i \leq p < \infty$  ( $i = 1, 2$ ) are real numbers satisfying*

- (i)  $s_i \geq s$
- (ii)  $s \geq 0$ ,
- (iii)  $s_i - s \geq n\left(\frac{1}{p_i} - \frac{1}{p}\right)$ ,
- (iv)  $s_1 + s_2 - s > n\left(\frac{1}{p_1} + \frac{1}{p_2} - \frac{1}{p}\right)$ .

*If  $u \in W^{s_1, p_1}(\mathbb{R}^n)$  and  $v \in W^{s_2, p_2}(\mathbb{R}^n)$ , then  $uv \in W^{s, p}(\mathbb{R}^n)$  and moreover the pointwise multiplication of functions is a continuous bilinear map*

$$W^{s_1, p_1}(\mathbb{R}^n) \times W^{s_2, p_2}(\mathbb{R}^n) \rightarrow W^{s, p}(\mathbb{R}^n).$$

**Theorem E.18** (Multiplication theorem for Sobolev spaces on the whole space, negative exponents I). *Assume  $s_i, s$  and  $1 < p_i \leq p < \infty$  ( $i = 1, 2$ ) are real numbers satisfying*

- (i)  $s_i \geq s$ ,
- (ii)  $\min\{s_1, s_2\} < 0$ ,
- (iii)  $s_i - s \geq n\left(\frac{1}{p_i} - \frac{1}{p}\right)$ ,
- (iv)  $s_1 + s_2 - s > n\left(\frac{1}{p_1} + \frac{1}{p_2} - \frac{1}{p}\right)$ .
- (v)  $s_1 + s_2 \geq n\left(\frac{1}{p_1} + \frac{1}{p_2} - 1\right) \geq 0$ .

*Then the pointwise multiplication of smooth functions extends uniquely to a continuous bilinear map*

$$W^{s_1, p_1}(\mathbb{R}^n) \times W^{s_2, p_2}(\mathbb{R}^n) \rightarrow W^{s, p}(\mathbb{R}^n).$$

**Theorem E.19** (Multiplication theorem for Sobolev spaces on the whole space, negative exponents II). *Assume  $s_i, s$  and  $1 < p, p_i < \infty$  ( $i = 1, 2$ ) are real numbers satisfying*

- (i)  $s_i \geq s$ ,
- (ii)  $\min\{s_1, s_2\} \geq 0$  and  $s < 0$ ,
- (iii)  $s_i - s \geq n\left(\frac{1}{p_i} - \frac{1}{p}\right)$ ,
- (iv)  $s_1 + s_2 - s > n\left(\frac{1}{p_1} + \frac{1}{p_2} - \frac{1}{p}\right) \geq 0$ .
- (v)  $s_1 + s_2 > n\left(\frac{1}{p_1} + \frac{1}{p_2} - 1\right)$ . *(the inequality is strict)*

*Then the pointwise multiplication of smooth functions extends uniquely to a continuous bilinear map*

$$W^{s_1, p_1}(\mathbb{R}^n) \times W^{s_2, p_2}(\mathbb{R}^n) \rightarrow W^{s, p}(\mathbb{R}^n).$$

**E.3. Properties of Sobolev Spaces on Smooth Bounded Domains.** In this section we assume that  $\Omega$  is an open bounded set in  $\mathbb{R}^n$  with smooth boundary unless a weaker assumption is stated. First we list some facts that can be useful in understanding the relationship between various definitions of Sobolev spaces on domains.

- ([9], Page 584)[Theorem 8.10.13 and its proof] Suppose  $s > 0$  and  $1 < p < \infty$ . Then  $W^{s, p}(\Omega) = W^{s, p}(\bar{\Omega})$  in the sense of equivalent normed spaces.
- For  $s > 0$  and  $1 < p < \infty$ ,  $W_{00}^{s, p}(\Omega)$  is isomorphic to  $\tilde{W}^{s, p}(\bar{\Omega})$ . Moreover  $[\tilde{W}^{s, p}(\bar{\Omega})]^* = W^{-s, p'}(\bar{\Omega})$ .

- Let  $s \geq 0$  and  $1 < p < \infty$ . Then for  $s \neq \frac{1}{p}, 1 + \frac{1}{p}, 2 + \frac{1}{p}, \dots$  (that is, when the fractional part of  $s$  is not equal to  $\frac{1}{p}$ ) we have

$$(1) W_{00}^{s,p}(\Omega) = W_0^{s,p}(\Omega) \text{ and so}$$

$$(W_0^{s,p}(\bar{\Omega}))^* = W^{-s,p'}(\bar{\Omega}) \quad (\text{in the sense of equivalent normed spaces})$$

where  $W_0^{s,p}(\bar{\Omega})$  is the closure of  $C_c^\infty(\Omega)$  in  $W^{s,p}(\bar{\Omega})$ . This claim is a direct consequence of Theorem 1 Page 317 and Theorem 4.8.2 Page 332 of [43].

(2)

$$\text{ext}_{\mathbb{R}^n}^0 : (C_c^\infty(\Omega), \|\cdot\|_{s,p}) \rightarrow W^{s,p}(\mathbb{R}^n)$$

is a well defined bounded linear operator.

(3)

$$\text{res}_{\mathbb{R}^n} : W^{-s,p'}(\mathbb{R}^n) \rightarrow W^{-s,p'}(\Omega) \quad u \mapsto u|_{\Omega}$$

is a well defined bounded linear operator.

$$(4) W^{-s,p'}(\Omega) = W^{-s,p'}(\bar{\Omega}).$$

- As a consequence of the above items  $W^{s,p}(\Omega) = W^{s,p}(\bar{\Omega})$  in the sense of equivalent normed spaces for  $1 < p < \infty$ ,  $s \in \mathbb{R}$  with  $s \neq \frac{1}{p} - 1, \frac{1}{p} - 2, \frac{1}{p} - 3, \dots$ . (Note that if we want the definitions agree for  $s < 0$ , it is enough to assume that  $-s \neq \frac{1}{p'}, 1 + \frac{1}{p'}, 2 + \frac{1}{p'}, \dots$ )

- ([46], Pages 481 and 494) For  $s > \frac{1}{p} - 1$ ,  $\tilde{W}^{s,p}(\bar{\Omega}) = \tilde{W}^{s,p}(\Omega)$ . That is for  $s > \frac{1}{p} - 1$

$$\{v \in W^{s,p}(\mathbb{R}^n) : \text{supp } v \subseteq \partial\Omega\} = \{0\}$$

Next we recall some facts about extension operator and embedding properties of Sobolev spaces. The existence of extension operator can be helpful in transferring known results for Sobolev spaces defined on  $\mathbb{R}^n$  to Sobolev spaces defined on bounded domains.

**Theorem E.20** (Extension Property I). ([9], Page 584) *Let  $\Omega \subset \mathbb{R}^n$  be a bounded open set with Lipschitz continuous boundary. Then for all  $s > 0$  and for  $1 \leq p < \infty$ , there exists a continuous linear extension operator  $P : W^{s,p}(\Omega) \hookrightarrow W^{s,p}(\mathbb{R}^n)$  such that  $(Pu)|_{\Omega} = u$  and  $\|Pu\|_{W^{s,p}(\mathbb{R}^n)} \leq C \|u\|_{W^{s,p}(\Omega)}$  for some constant  $C$  that may depend on  $s$ ,  $p$ , and  $\Omega$  but is independent of  $u$ .*

The next theorem states that the claim of Theorem E.20 holds for all values of  $s$  (positive and negative) if we replace  $W^{s,p}(\Omega)$  with  $W^{s,p}(\bar{\Omega})$ .

**Theorem E.21** (Extension Property II). ([46], Page 487, [44], Page 201) *Let  $\Omega \subset \mathbb{R}^n$  be a bounded open set with Lipschitz continuous boundary,  $p \in (1, \infty)$  and  $s \in \mathbb{R}$ . Let  $R : W^{s,p}(\mathbb{R}^n) \rightarrow W^{s,p}(\bar{\Omega})$  be the restriction operator ( $R(u) = u|_{\bar{\Omega}}$ ). Then there exists a continuous linear operator  $S : W^{s,p}(\bar{\Omega}) \rightarrow W^{s,p}(\mathbb{R}^n)$  such that  $R \circ S = Id$ .*

**Corollary E.22.** *As it was pointed out earlier for  $s \neq \frac{1}{p} - 1, \frac{1}{p} - 2, \dots$   $W^{s,p}(\Omega) = W^{s,p}(\bar{\Omega})$ . Therefore it follows from the above theorems that if  $s \neq \frac{1}{p} - 1, \frac{1}{p} - 2, \dots$ , then there exists a continuous linear extension operator  $P : W^{s,p}(\Omega) \hookrightarrow W^{s,p}(\mathbb{R}^n)$  such that  $(Pu)|_{\Omega} = u$  and  $\|Pu\|_{W^{s,p}(\mathbb{R}^n)} \leq C \|u\|_{W^{s,p}(\Omega)}$  for some constant  $C$  that may depend on  $s$ ,  $p$ , and  $\Omega$  but is independent of  $u$ .*

**Corollary E.23.** *One can easily show that the results of Sobolev multiplication theorems in the previous section (Theorems E.16, E.17, E.18, and E.19) hold also for Sobolev spaces on any domain as long as extension operators for the corresponding*

*Sobolev spaces exist. Indeed, if  $P_1 : W^{s_1, p_1}(\Omega) \rightarrow W^{s_1, p_1}(\mathbb{R}^n)$  and  $P_2 : W^{s_2, p_2}(\Omega) \rightarrow W^{s_2, p_2}(\mathbb{R}^n)$  are extension operators, then  $(P_1 u)(P_2 v) = uv$  and therefore*

$$\begin{aligned} \|uv\|_{W^{s,p}(\cdot)} &\leq \| (P_1 u)(P_2 v) \|_{W^{s,p}(\mathbb{R}^n)} \leq \| P_1 u \|_{W^{s_1, p_1}(\mathbb{R}^n)} \| P_2 v \|_{W^{s_2, p_2}(\mathbb{R}^n)} \\ &\leq \| u \|_{W^{s_1, p_1}(\cdot)} \| v \|_{W^{s_2, p_2}(\cdot)} . \end{aligned}$$

**Theorem E.24** (Embedding Theorem II). [20] *Let  $\Omega$  be a nonempty bounded open subset of  $\mathbb{R}^n$  with Lipschitz continuous boundary or  $\Omega = \mathbb{R}^n$ . If  $sp > n$ , then  $W^{s,p}(\Omega) \hookrightarrow L^\infty(\Omega) \cap C^0(\Omega)$  and  $W^{s,p}(\Omega)$  is a Banach algebra.*

**Theorem E.25** (Embedding Theorem III). [7] *Let  $\Omega$  be a nonempty bounded open subset of  $\mathbb{R}^n$  with Lipschitz continuous boundary. Suppose  $1 \leq p, q < \infty$  ( $p$  does NOT need to be less than or equal to  $q$ ) and  $0 \leq t \leq s$  satisfy  $s - \frac{n}{p} \geq t - \frac{n}{q}$ . Then  $W^{s,p}(\Omega) \hookrightarrow W^{t,q}(\Omega)$ . In particular,  $W^{s,p}(\Omega) \hookrightarrow W^{t,p}(\Omega)$ .*

The following theorem (and its corollary) will play an important role in our study of Sobolev spaces on manifolds.

**Theorem E.26** (Multiplication by smooth functions). *Let  $\Omega$  be a nonempty bounded open set in  $\mathbb{R}^n$  with Lipschitz continuous boundary.*

- (1) *Let  $k \in \mathbb{N}_0$  and  $1 < p < \infty$ . If  $\varphi \in BC^k(\Omega)$ , then the linear map  $W^{k,p}(\Omega) \rightarrow W^{k,p}(\Omega)$  defined by  $u \mapsto \varphi u$  is well defined and bounded.*
- (2) *Let  $s \in \mathbb{R}$  and  $1 < p < \infty$ . If  $\varphi \in BC^{\lfloor s \rfloor, 1}(\Omega)$  (all partial derivatives of  $\varphi$  up to and including order  $\lfloor s \rfloor$  exist and are bounded and Lipschitz continuous), then the linear map  $W^{s,p}(\Omega) \rightarrow W^{s,p}(\Omega)$  defined by  $u \mapsto \varphi u$  is well defined and bounded.*

*Proof.*

- **Step 1:**  $s = k \in \mathbb{N}_0$ . The claim is proved in ([15], Page 995).
- **Step 2:**  $0 < s < 1$ . The proof in Page 194 of [14], with obvious modifications, shows the validity of the claim for the case where  $s \in (0, 1)$ .
- **Step 3:**  $1 < s \notin \mathbb{N}$ . In this case we can proceed as follows: Let  $k = \lfloor s \rfloor$ ,  $\theta = s - k$ .

$$\begin{aligned} \|\varphi u\|_{s,p} &= \|\varphi u\|_{k,p} + \sum_{|\nu|=k} \|\partial^\nu(\varphi u)\|_{\theta,p} \\ &\leq \|\varphi u\|_{k,p} + \sum_{|\nu|=k} \sum_{\beta \leq \nu} \|\partial^{\nu-\beta} \varphi \partial^\beta u\|_{\theta,p} \\ &\leq \|u\|_{k,p} + \sum_{|\nu|=k} \sum_{\beta \leq \nu} \|\partial^\beta u\|_{\theta,p} \quad (\text{by Step1 and Step2; the implicit constant may depend on } \varphi) \\ &= \|u\|_{s,p} + \sum_{|\nu|=k} \sum_{\beta < \nu} \|\partial^\beta u\|_{\theta,p} \\ &\leq \|u\|_{s,p} + \sum_{|\nu|=k} \sum_{\beta < \nu} \|u\|_{\theta+|\beta|,p} \quad (\partial^\beta : W^{\theta+|\beta|,p}(\Omega) \rightarrow W^{\theta,p}(\Omega) \text{ is continuous}) \\ &\leq \|u\|_{s,p} + \sum_{|\nu|=k} \sum_{\beta < \nu} \|u\|_{s,p} \quad (\theta + |\beta| < s \Rightarrow W^{s,p}(\Omega) \hookrightarrow W^{\theta+|\beta|,p}(\Omega)) \\ &\leq \|u\|_{s,p}. \end{aligned}$$

Note that the embedding  $W^{s,p}(\Omega) \hookrightarrow W^{\theta+|\beta|,p}(\Omega)$  is valid due to the extra assumption that  $\Omega$  is bounded with Lipschitz continuous boundary. (See Theorem E.37 and Remark E.38).

- **Step 4:**  $s < 0$ . For this case we use a duality argument:

$$\begin{aligned} \|\varphi u\|_{s,p} &\stackrel{\text{Remark E.46}}{=} \sup_{v \in C_c^\infty \setminus \{0\}} \frac{|\langle \varphi u, v \rangle|}{\|v\|_{-s,p'}} = \sup_{v \in C_c^\infty \setminus \{0\}} \frac{|\langle u, \varphi v \rangle|}{\|v\|_{-s,p'}} \\ &\leq \sup_{v \in C_c^\infty \setminus \{0\}} \frac{\|u\|_{s,p} \|\varphi v\|_{-s,p'}}{\|v\|_{-s,p'}} \preceq \sup_{v \in C_c^\infty \setminus \{0\}} \frac{\|u\|_{s,p} \|v\|_{-s,p'}}{\|v\|_{-s,p'}} = \|u\|_{s,p}. \end{aligned}$$

□

**Corollary E.27.** *Let  $\Omega$  be a nonempty bounded open set in  $\mathbb{R}^n$  with Lipschitz continuous boundary. Let  $K \in \mathcal{K}(\Omega)$ . Suppose  $s \in \mathbb{R}$  and  $p \in (1, \infty)$ . If  $\varphi \in C^\infty(\Omega)$ , then the linear map  $W_K^{s,p}(\Omega) \rightarrow W_K^{s,p}(\Omega)$  defined by  $u \mapsto \varphi u$  is well defined and bounded.*

*Proof.* Let  $U$  be an open set such that  $K \subset U \subseteq \bar{U} \subseteq \Omega$ . Let  $\psi \in C_c^\infty(\Omega)$  be such that  $\psi = 1$  on  $K$  and  $\psi = 0$  outside  $U$ . Clearly  $\psi \varphi \in C_c^\infty(\Omega)$  and thus  $\psi \varphi \in BC^{\infty,1}(\Omega)$  (see the paragraph above Theorem B.11). So it follows from Theorem E.26 that  $\|\psi \varphi u\|_{s,p} \preceq \|u\|_{s,p}$  where the implicit constant in particular may depend on  $\varphi$  and  $\psi$ . Now the claim follows from the obvious observation that for all  $u \in W_K^{s,p}(\Omega)$ , we have  $\psi \varphi u = \varphi u$ . □

**Theorem E.28.** *Let  $\Omega = \mathbb{R}^n$  or  $\Omega$  be a nonempty bounded open set in  $\mathbb{R}^n$  with Lipschitz continuous boundary. Let  $K \subseteq \Omega$  be compact,  $s \in \mathbb{R}$  and  $p \in (1, \infty)$ . Then*

- (1)  $W_K^{s,p}(\Omega) \subseteq W_0^{s,p}(\Omega)$ . That is, every element of  $W_K^{s,p}(\Omega)$  is a limit of a sequence in  $C_c^\infty(\Omega)$ ;
- (2) if  $K \subseteq V \subseteq K' \subseteq \Omega$  where  $K'$  is compact and  $V$  is open, then for every  $u \in W_{K'}^{s,p}(\Omega)$ , there exists a sequence in  $C_{K'}^\infty(\Omega)$  that converges to  $u$  in  $W^{s,p}(\Omega)$ .

*Proof.* (1) Let  $u \in W_K^{s,p}(\Omega)$ . By Theorem E.31 and Theorem E.32, there exists a sequence  $\{\varphi_i\}$  in  $C^\infty(\Omega)$  such that  $\varphi_i \rightarrow u$  in  $W^{s,p}(\Omega)$ . Let  $\psi \in C_c^\infty(\Omega)$  be such that  $\psi = 1$  on  $K$ . Since  $C_c^\infty(\Omega) \subseteq BC^{\infty,1}(\Omega)$ , it follows from Theorem E.15 and Theorem E.26 that  $\psi \varphi_i \rightarrow \psi u$  in  $W^{s,p}(\Omega)$ . This proves the claim because  $\psi \varphi_i \in C_c^\infty(\Omega)$  and  $\psi u = u$ .

- (2) In the above argument, choose  $\psi \in C_c^\infty(\Omega)$  such that  $\psi = 1$  on  $K$  and  $\psi = 0$  outside  $V$ .

□

**Theorem E.29** (([46], Page 496), ([43], Pages 317, 330, and 332)). *Let  $\Omega$  be a bounded Lipschitz domain in  $\mathbb{R}^n$ . Suppose  $1 < p < \infty$ ,  $0 \leq s < \frac{1}{p}$ . Then  $C_c^\infty(\Omega)$  is dense in  $W^{s,p}(\Omega)$  (thus  $W^{s,p}(\Omega) = W_0^{s,p}(\Omega)$ ).*

**E.4. Properties Of Sobolev Spaces on General Domains.** In this section  $\Omega$  and  $\Omega'$  are arbitrary nonempty open sets in  $\mathbb{R}^n$ . We begin with some facts about the relationship between various Sobolev spaces defined on bounded domains.

- Suppose  $s \geq 0$  and  $\Omega' \subseteq \Omega$ . Then for all  $u \in W^{s,p}(\Omega)$ , we have  $\text{res}_{\Omega'} u \in W^{s,p}(\Omega')$ . Moreover  $\|\text{res}_{\Omega'} u\|_{W^{s,p}(\Omega')} \leq \|u\|_{W^{s,p}(\Omega)}$ . Indeed, if we let  $s = k + \theta$

$$\begin{aligned} \|u\|_{W^{s,p}(\Omega')} &= \|u\|_{W^{k,p}(\Omega')} + \sum_{|\nu|=k} \left( \int \int_{\Omega' \times \Omega'} \frac{|\partial^\nu u(x) - \partial^\nu u(y)|^p}{|x-y|^{n+\theta p}} dx dy \right)^{\frac{1}{p}} \\ &= \sum_{|\alpha| \leq k} \|\partial^\alpha u\|_{L^p(\Omega')} + \sum_{|\nu|=k} \left( \int \int_{\Omega' \times \Omega'} \frac{|\partial^\nu u(x) - \partial^\nu u(y)|^p}{|x-y|^{n+\theta p}} dx dy \right)^{\frac{1}{p}} \\ &\leq \sum_{|\alpha| \leq k} \|\partial^\alpha u\|_{L^p(\Omega)} + \sum_{|\nu|=k} \left( \int \int_{\Omega \times \Omega} \frac{|\partial^\nu u(x) - \partial^\nu u(y)|^p}{|x-y|^{n+\theta p}} dx dy \right)^{\frac{1}{p}} = \|u\|_{W^{s,p}(\Omega)} \end{aligned}$$

So  $\text{res}_{\Omega'} : W^{s,p}(\Omega) \rightarrow W^{s,p}(\Omega')$  is a continuous linear map. Also as a consequence for every real number  $s \geq 0$

$$W^{s,p}(\bar{\Omega}) \hookrightarrow W^{s,p}(\Omega)$$

Indeed, if  $u \in W^{s,p}(\bar{\Omega})$ , then there exists  $v \in W^{s,p}(\mathbb{R}^n)$  such that  $\text{res}_{\mathbb{R}^n} v = u$  and thus  $u \in W^{s,p}(\Omega)$ . Moreover for every such  $v$ ,  $\|u\|_{W^{s,p}(\Omega)} = \|\text{res}_{\mathbb{R}^n} v\|_{W^{s,p}(\Omega)} \leq \|v\|_{W^{s,p}(\mathbb{R}^n)}$ . This implies that

$$\|u\|_{W^{s,p}(\Omega)} \leq \inf_{v \in W^{s,p}(\mathbb{R}^n), v|_{\Omega} = u} \|v\|_{W^{s,p}(\mathbb{R}^n)} = \|u\|_{W^{s,p}(\Omega)}$$

- Clearly for all  $s \geq 0$

$$W_{00}^{s,p}(\Omega) \hookrightarrow W^{s,p}(\bar{\Omega})$$

- ([20], Page 18) For every integer  $m > 0$

$$W_0^{m,p}(\Omega) \subseteq W_{00}^{m,p}(\Omega) \subseteq W^{m,p}(\bar{\Omega}) \subseteq W^{m,p}(\Omega)$$

- Suppose  $s \geq 0$ . Clearly the restriction map  $\text{res}_{\mathbb{R}^n} : W^{s,p}(\mathbb{R}^n) \rightarrow W^{s,p}(\bar{\Omega})$  is a continuous linear map. This combined with the fact that  $C_c^\infty(\mathbb{R}^n)$  is dense in  $W^{s,p}(\mathbb{R}^n)$  implies that  $C_c^\infty(\bar{\Omega}) := \text{res}_{\mathbb{R}^n}(C_c^\infty(\mathbb{R}^n))$  is dense in  $W^{s,p}(\bar{\Omega})$  for all  $s \geq 0$ .
- $\tilde{W}^{s,p}(\bar{\Omega})$  is a closed subspace of  $W^{s,p}(\mathbb{R}^n)$ . Closed subspaces of reflexive spaces are reflexive, hence  $\tilde{W}^{s,p}(\bar{\Omega})$  is a reflexive space.

**Theorem E.30.** *Let  $\Omega$  be a nonempty open set in  $\mathbb{R}^n$  and  $1 < p < \infty$ .*

- (1) For all  $s \geq 0$ ,  $W^{s,p}(\Omega)$  is reflexive.
- (2) For all  $s \geq 0$ ,  $W_0^{s,p}(\Omega)$  is reflexive.
- (3) For all  $s < 0$ ,  $W^{s,p}(\Omega)$  is reflexive.

*Proof.*

- (1) The proof for  $s \in \mathbb{N}_0$  can be found in [2]. Let  $s = k + \theta$  where  $k \in \mathbb{N}_0$  and  $0 < \theta < 1$ .

$$r = \#\{\nu \in \mathbb{N}_0^n : |\nu| = k\}$$

Define  $P : W^{s,p}(\Omega) \rightarrow W^{k,p}(\Omega) \times [L^p(\Omega \times \Omega)]^{\times r}$  by

$$P(u) = \left( u, \left( \frac{|\partial^\nu u(x) - \partial^\nu u(y)|}{|x-y|^{\frac{n}{p} + \theta}} \right)_{|\nu|=k} \right)$$

The space  $W^{k,p}(\Omega) \times [L^p(\Omega \times \Omega)]^{\times r}$  equipped with the norm

$$\|(f, v_1, \dots, v_r)\| := \|f\|_{W^{k,p}(\Omega)} + \|v_1\|_{L^p(\Omega \times \Omega)} + \dots + \|v_r\|_{L^p(\Omega \times \Omega)}$$

is a product of reflexive spaces and so it is reflexive (see Theorem B.16). Clearly the operator  $P$  is an isometry from  $W^{s,p}(\Omega)$  to  $W^{k,p}(\Omega) \times [L^p(\Omega \times \Omega)]^{\times r}$ . Since  $W^{s,p}(\Omega)$  is a Banach space,  $P(W^{s,p}(\Omega))$  is a closed subspace of the reflexive space  $W^{k,p}(\Omega) \times [L^p(\Omega \times \Omega)]^{\times r}$  and thus it is reflexive. Hence  $W^{s,p}(\Omega)$  itself is reflexive.

- (2)  $W_0^{s,p}(\Omega)$  is the closure of  $C_c^\infty(\Omega)$  in  $W^{s,p}(\Omega)$ . Closed subspaces of reflexive spaces are reflexive. Therefore  $W_0^{s,p}(\Omega)$  is reflexive.
- (3) A normed space  $X$  is reflexive if and only if  $X^*$  is reflexive (see Theorem B.16). Since for  $s < 0$  we have  $W^{s,p}(\Omega) = [W_0^{-s,p'}(\Omega)]^*$ , the reflexivity of  $W^{s,p}(\Omega)$  follows from the reflexivity of  $W_0^{-s,p'}(\Omega)$ .

□

**Theorem E.31.** For all  $s < 0$  and  $1 < p < \infty$ ,  $C_c^\infty(\Omega)$  is dense in  $W^{s,p}(\Omega)$ .

*Proof.* The proof in page 65 of [2] for integer order Sobolev spaces, which is based on the reflexivity of  $W_0^{m,p}(\Omega)$ , works in the exact same way for fractional order Sobolev spaces. □

**Theorem E.32 (Meyers-Serrin).** For all  $s \geq 0$  and  $p \in (1, \infty)$ ,  $C^\infty(\Omega) \cap W^{s,p}(\Omega)$  is dense in  $W^{s,p}(\Omega)$ .

Next we consider *extension by zero* and its properties.

**Lemma E.33.** ([9], Page 201) Let  $\Omega$  be a nonempty open set in  $\mathbb{R}^n$  and  $u \in W_0^{m,p}(\Omega)$  where  $m \in \mathbb{N}_0$  and  $1 < p < \infty$ . Then

- (1)  $\forall |\alpha| \leq m$ ,  $\partial^\alpha \tilde{u} = \widetilde{(\partial^\alpha u)}$  as elements of  $D'(\mathbb{R}^n)$ .  
(2)  $\tilde{u} \in W^{m,p}(\mathbb{R}^n)$  with  $\|\tilde{u}\|_{W^{m,p}(\mathbb{R}^n)} = \|u\|_{W^{m,p}(\Omega)}$

Here,  $\tilde{u} := \text{ext}_{\mathbb{R}^n}^0 u$  and  $\widetilde{(\partial^\alpha u)} := \text{ext}_{\mathbb{R}^n}^0 (\partial^\alpha u)$ .

**Lemma E.34** ([35], Page 546). Let  $\Omega$  be a nonempty open set in  $\mathbb{R}^n$ ,  $K \in \mathcal{K}(\Omega)$ ,  $u \in W_K^{s,p}(\Omega)$  where  $s \in (0, 1)$  and  $1 < p < \infty$ . Then  $\tilde{u} \in W^{s,p}(\mathbb{R}^n)$  and

$$\|\tilde{u}\|_{W^{s,p}(\mathbb{R}^n)} \preceq \|u\|_{W^{s,p}(\Omega)}$$

where the implicit constant depends on  $n, p, s, K$  and  $\Omega$ .

**Theorem E.35 (Extension by Zero).** Let  $s \geq 0$  and  $p \in (1, \infty)$ . Let  $\Omega$  be a nonempty open set in  $\mathbb{R}^n$  and let  $K \in \mathcal{K}(\Omega)$ . Suppose  $u \in W_K^{s,p}(\Omega)$ . Then

- (1)  $\text{ext}_{\mathbb{R}^n}^0 u \in W^{s,p}(\mathbb{R}^n)$ . Indeed,  $\|\text{ext}_{\mathbb{R}^n}^0 u\|_{W^{s,p}(\mathbb{R}^n)} \preceq \|u\|_{W^{s,p}(\Omega)}$  where the implicit constant may depend on  $s, p, n, K, \Omega$  but it is independent of  $u \in W_K^{s,p}(\Omega)$ .  
(2) Moreover,

$$\|\text{ext}_{\mathbb{R}^n}^0 u\|_{W^{s,p}(\mathbb{R}^n)} \geq \|u\|_{W^{s,p}(\Omega)}$$

In short  $\|\text{ext}_{\mathbb{R}^n}^0 u\|_{W^{s,p}(\mathbb{R}^n)} \simeq \|u\|_{W^{s,p}(\Omega)}$ .



*Proof.* Let  $\tilde{u} = \text{ext}^0_{\mathbb{R}^n} u$ . If  $s \in \mathbb{N}_0$  then both items follow from Lemma E.33. So let  $s = m + \theta$  where  $m \in \mathbb{N}_0$  and  $\theta \in (0, 1)$ . We have

$$\begin{aligned} \|\tilde{u}\|_{W^{s,p}(\mathbb{R}^n)} &= \|\tilde{u}\|_{W^{m,p}(\mathbb{R}^n)} + \sum_{|\nu|=m} |\partial^\nu \tilde{u}|_{W^{\theta,p}(\mathbb{R}^n)} \\ &= \|u\|_{W^{m,p}(\cdot)} + \sum_{|\nu|=m} |\widetilde{\partial^\nu u}|_{W^{\theta,p}(\mathbb{R}^n)} \\ &\stackrel{\text{Lemma E.34}}{\preceq} \|u\|_{W^{m,p}(\cdot)} + \sum_{|\nu|=m} \|\partial^\nu u\|_{W^{\theta,p}(\cdot)} \\ &\preceq \|u\|_{W^{s,p}(\cdot)} \end{aligned}$$

The fact that  $\|\tilde{u}\|_{W^{s,p}(\mathbb{R}^n)} \geq \|u\|_{W^{s,p}(\cdot)}$  is a direct consequence of the decomposition stated in item 1. of Remark E.3.  $\square$

**Corollary E.36.** *Let  $s \geq 0$  and  $p \in (1, \infty)$ . Let  $\Omega$  and  $\Omega'$  be nonempty open sets in  $\mathbb{R}^n$  with  $\Omega' \subseteq \Omega$  and let  $K \in \mathcal{K}(\Omega')$ . Suppose  $u \in W^{s,p}_K(\Omega')$ . Then*

- (1)  $\text{ext}^0_{\cdot} u \in W^{s,p}(\Omega)$
- (2)  $\|\text{ext}^0_{\cdot} u\|_{W^{s,p}(\cdot)} \simeq \|u\|_{W^{s,p}(\cdot)}$

*Proof.*

$$u \in W^{s,p}_K(\Omega') \implies \text{ext}^0_{\mathbb{R}^n} u \in W^{s,p}(\mathbb{R}^n) \implies \text{ext}^0_{\mathbb{R}^n} u|_{\cdot} \in W^{s,p}(\bar{\Omega})$$

As it was shown for any arbitrary domain  $\Omega$ ,  $W^{s,p}(\bar{\Omega}) \hookrightarrow W^{s,p}(\Omega)$ . Also it is easy to see that  $\text{ext}^0_{\mathbb{R}^n} u|_{\cdot} = \text{ext}^0_{\cdot} u$ . Therefore  $\text{ext}^0_{\cdot} u \in W^{s,p}(\Omega)$ . Moreover

$$\|\text{ext}^0_{\cdot} u\|_{W^{s,p}(\cdot)} \simeq \|\text{ext}^0_{\mathbb{R}^n} u\|_{W^{s,p}(\mathbb{R}^n)} = \|\text{ext}^0_{\mathbb{R}^n} u|_{\cdot}\|_{W^{s,p}(\mathbb{R}^n)} \simeq \|u\|_{W^{s,p}(\cdot)} \quad \square$$

Extension by zero for Sobolev spaces with negative exponents will be discussed in Theorem E.43.

**Theorem E.37** (Embedding Theorem IV). *Let  $\Omega \subseteq \mathbb{R}^n$  be an arbitrary nonempty open set.*

- (1) *Suppose  $1 \leq p \leq q < \infty$  and  $0 \leq t \leq s$  satisfy  $s - \frac{n}{p} \geq t - \frac{n}{q}$ . Then  $W^{s,p}(\bar{\Omega}) \hookrightarrow W^{t,q}(\bar{\Omega})$ .*
- (2) *Suppose  $1 \leq p \leq q < \infty$  and  $0 \leq t \leq s$  satisfy  $s - \frac{n}{p} \geq t - \frac{n}{q}$ . Then  $W^{s,p}_K(\Omega) \hookrightarrow W^{t,q}_K(\Omega)$  for all  $K \in \mathcal{K}(\Omega)$ .*
- (3) *For all  $k_1, k_2 \in \mathbb{N}_0$  with  $k_1 \leq k_2$  and  $1 < p < \infty$ ,  $W^{k_2,p}(\Omega) \hookrightarrow W^{k_1,p}(\Omega)$ .*
- (4) *If  $0 \leq t \leq s < 1$  and  $1 < p < \infty$ , then  $W^{s,p}(\Omega) \hookrightarrow W^{t,p}(\Omega)$ .*
- (5) *If  $0 \leq t \leq s < \infty$  are such that  $[s] = [t]$  and  $1 < p < \infty$ , then  $W^{s,p}(\Omega) \hookrightarrow W^{t,p}(\Omega)$ .*
- (6) *If  $0 \leq t \leq s < \infty$ ,  $t \in \mathbb{N}_0$ , and  $1 < p < \infty$ , then  $W^{s,p}(\Omega) \hookrightarrow W^{t,p}(\Omega)$ .*

*Proof.*

(1) This item can be found in ([43], Section 4.6.1).

(2) For all  $u \in W^{s,p}_K(\Omega)$  we have

$$\|u\|_{W^{t,q}(\cdot)} \simeq \|\text{ext}^0_{\mathbb{R}^n} u\|_{W^{t,q}(\mathbb{R}^n)} \preceq \|\text{ext}^0_{\mathbb{R}^n} u\|_{W^{s,p}(\mathbb{R}^n)} \simeq \|u\|_{W^{s,p}(\cdot)}$$

(3) This item is a direct consequence of the definition of integer order Sobolev spaces.

- (4) Proof can be found in [35], Page 524.  
 (5) This is a direct consequence of the previous two items.  
 (6) This is true because  $W^{s,p}(\Omega) \hookrightarrow W^{\lfloor s \rfloor,p}(\Omega) \hookrightarrow W^{t,p}(\Omega)$ .

□

**Remark E.38.** For an arbitrary open set  $\Omega$  in  $\mathbb{R}^n$  and  $0 < t < 1$ , the embedding  $W^{1,p}(\Omega) \hookrightarrow W^{t,p}(\Omega)$  does NOT necessarily hold (see e.g. [35], Section 9.). Of course, as it was discussed, under the extra assumption that  $\Omega$  is Lipschitz, the latter embedding holds true. So, if  $\lfloor s \rfloor \neq \lfloor t \rfloor$  and  $t \notin \mathbb{N}_0$ , then in order to ensure that  $W^{s,p}(\Omega) \hookrightarrow W^{t,p}(\Omega)$  we need to assume some sort of regularity for the domain  $\Omega$  (for instance it is enough to assume  $\Omega$  is Lipschitz).

**Theorem E.39** (Multiplication by smooth functions). Let  $\Omega$  be any nonempty open set in  $\mathbb{R}^n$ . Let  $p \in (1, \infty)$ .

- (1) If  $0 \leq s < 1$  and  $\varphi \in BC^{0,1}(\Omega)$  (that is,  $\varphi \in L^\infty(\Omega)$  and  $\varphi$  is Lipschitz), then

$$m_\varphi : W^{s,p}(\Omega) \rightarrow W^{s,p}(\Omega), \quad u \mapsto \varphi u$$

is a well defined bounded linear map.

- (2) If  $k \in \mathbb{N}_0$  and  $\varphi \in BC^k(\Omega)$ , then

$$m_\varphi : W^{k,p}(\Omega) \rightarrow W^{k,p}(\Omega), \quad u \mapsto \varphi u$$

is a well defined bounded linear map.

- (3) If  $-1 < s < 0$  and  $\varphi \in BC^{0,1}(\Omega)$  or  $s \in \mathbb{Z}^-$  and  $\varphi \in BC^{-s}(\Omega)$ , then

$$m_\varphi : W^{s,p}(\Omega) \rightarrow W^{s,p}(\Omega), \quad u \mapsto \varphi u$$

is a well defined bounded linear map.

*Proof.*

- (1) Proof can be found in [35], Page 547.  
 (2) Proof can be found in [15], Page 995.  
 (3) The duality argument in Step 4. of the proof of Theorem E.26 works for this item too.

□

**Remark E.40.** Suppose  $\varphi \in BC^{\infty,1}(\Omega)$ . Note that the above theorem says nothing about the boundedness of the mapping  $m_\varphi : W^{s,p}(\Omega) \rightarrow W^{s,p}(\Omega)$  in the case where  $s$  is noninteger such that  $|s| > 1$ . Of course, if we assume  $\Omega$  is Lipschitz, then the continuity of  $m_\varphi$  follows from Theorem E.26. It is important to note that the proof of that theorem for the case  $s > 1$  (noninteger) uses the embedding  $W^{k+\theta,p}(\Omega) \hookrightarrow W^{k'+\theta,p}(\Omega)$  with  $k' < k$  which as we discussed does not hold for an arbitrary open set  $\Omega$ . The proof for the case  $s < -1$  (noninteger) uses duality to transfer the problem to  $s > 1$  and thus again we need the extra assumption of regularity of the boundary of  $\Omega$ .

**Theorem E.41.** Let  $\Omega$  be a nonempty open set in  $\mathbb{R}^n$ ,  $K \in \mathcal{K}(\Omega)$ ,  $p \in (1, \infty)$ , and  $-1 < s < 0$  or  $s \in \mathbb{Z}^-$  or  $s \in [0, \infty)$ . If  $\varphi \in C^\infty(\Omega)$ , then the linear map

$$W_K^{s,p}(\Omega) \rightarrow W_K^{s,p}(\Omega), \quad u \mapsto \varphi u$$

is well defined and bounded.

*Proof.* There exists  $\psi \in C_c^\infty(\Omega)$  such that  $\psi = 1$  on  $K$ . Clearly  $\psi\varphi \in C_c^\infty(\Omega)$  and if  $u \in W_K^{s,p}(\Omega)$ ,  $\psi\varphi u = \varphi u$  on  $\Omega$ . Thus without loss of generality we may assume that  $\varphi \in C_c^\infty(\Omega)$ . Since  $C_c^\infty(\Omega) \subseteq BC^\infty(\Omega)$  and  $C_c^\infty(\Omega) \subseteq BC^{\infty,1}(\Omega)$ , the cases where  $-1 < s < 0$  or  $s \in \mathbb{Z}^-$  follow from Theorem E.39. For  $s \geq 0$ , the proof of Theorem E.26 works for this theorem as well. The only place in that proof that the regularity of the boundary of  $\Omega$  was used was for the validity of the embedding  $W^{s,p}(\Omega) \hookrightarrow W^{\theta+|\beta|,p}(\Omega)$ . However, as we know (see Theorem E.37), this embedding holds for Sobolev spaces with support in a fixed compact set inside  $\Omega$  for a general open set  $\Omega$ , that is for  $W_K^{s,p}(\Omega) \hookrightarrow W_K^{\theta+|\beta|,p}(\Omega)$  to be true we do not need to assume  $\Omega$  is Lipschitz.  $\square$

**Remark E.42.** *Note that our proofs for  $s < 0$  are based on duality. As a result it seems that for the case where  $s$  is a noninteger less than  $-1$  we cannot have a multiplication by smooth functions result for  $W_K^{s,p}(\Omega)$  similar to the one stated in the above theorem. (Note that there is no fixed compact set  $K$  such that every  $v \in C_c^\infty(\Omega)$  has compact support in  $K$ . Thus the technique used in Step 4 of the proof of Theorem E.26 does not work in this case.)*

**Theorem E.43.** *Let  $s < 0$  and  $p \in (1, \infty)$ . Let  $\Omega$  and  $\Omega'$  be nonempty open sets in  $\mathbb{R}^n$  with  $\Omega' \subseteq \Omega$  and let  $K \in \mathcal{K}(\Omega')$ . Suppose  $u \in W_K^{s,p}(\Omega')$ . Then*

- (1) *If  $\text{ext}^0_{\Omega'} u \in W^{s,p}(\Omega)$ , then  $\|u\|_{W^{s,p}(\Omega')} \preceq \|\text{ext}^0_{\Omega'} u\|_{W^{s,p}(\Omega)}$  (the implicit constant may depend on  $K$ ).*
- (2) *If  $s \in (-\infty, -1] \cap \mathbb{Z}$  or  $-1 < s < 0$ , then  $\text{ext}^0_{\Omega'} u \in W^{s,p}(\Omega)$  and  $\|\text{ext}^0_{\Omega'} u\|_{W^{s,p}(\Omega)} \simeq \|u\|_{W^{s,p}(\Omega')}$ . This result holds for all  $s < 0$  if we further assume that  $\Omega$  is Lipschitz or  $\Omega = \mathbb{R}^n$ .*

*Proof.* To be completely rigorous, let  $i_{D,W} : D(\Omega') \rightarrow W_0^{-s,p'}(\Omega')$  be the identity map and let  $i_{D,W}^* : W^{s,p}(\Omega') \rightarrow D'(\Omega')$  be its dual with which we identify  $W^{s,p}(\Omega')$  with a subspace of  $D'(\Omega')$ . Previously we defined  $\text{ext}^0_{\Omega'}$  for distributions with compact support in  $\Omega'$ . For any  $u \in W_K^{s,p}(\Omega')$  we let

$$\text{ext}^0_{\Omega'} u := \text{ext}^0_{\Omega'} \circ i_{D,W}^* u$$

which by definition will be an element of  $D'(\Omega)$ . Note that (see Remark E.46)

$$\begin{aligned} \|\text{ext}^0_{\Omega'} u\|_{W^{s,p}(\Omega)} &= \sup_{0 \neq \psi \in D(\Omega)} \frac{|\langle \text{ext}^0_{\Omega'} u, \psi \rangle_{D'(\Omega) \times D(\Omega)}|}{\|\psi\|_{W^{-s,p'}(\Omega)}} \\ \|u\|_{W^{s,p}(\Omega')} &= \sup_{0 \neq \varphi \in D(\Omega')} \frac{|\langle u, \varphi \rangle_{D'(\Omega') \times D(\Omega')}|}{\|\varphi\|_{W^{-s,p'}(\Omega')}} \end{aligned}$$

So in order to prove the first item we just need to show that

$$\forall 0 \neq \varphi \in D(\Omega') \quad \exists \psi \in D(\Omega) \text{ s.t. } \frac{|\langle u, \varphi \rangle_{D'(\Omega') \times D(\Omega')}|}{\|\varphi\|_{W^{-s,p'}(\Omega')}} \preceq \frac{|\langle \text{ext}^0_{\Omega'} u, \psi \rangle_{D'(\Omega) \times D(\Omega)}|}{\|\psi\|_{W^{-s,p'}(\Omega)}}$$

Let  $\varphi \in D(\Omega')$ . Define  $\psi = \text{ext}^0_{\Omega'} \varphi$ . Clearly  $\psi \in D(\Omega)$  and  $\psi = \varphi$  on  $K$ . Therefore

$$\langle \text{ext}^0_{\Omega'} u, \psi \rangle_{D'(\Omega) \times D(\Omega)} = \langle u, \psi \rangle_{D'(\Omega') \times D(\Omega')} = \langle u, \varphi \rangle_{D'(\Omega') \times D(\Omega')}$$

Moreover, since  $-s > 0$

$$\|\psi\|_{W^{-s,p'}(\Omega)} = \|\text{ext}^0_{\Omega'} \varphi\|_{W^{-s,p'}(\Omega)} \preceq \|\varphi\|_{W^{-s,p'}(\Omega')}$$

This completes the proof of the first item. For the second item we just need to prove that under the given hypotheses

$$\forall 0 \neq \psi \in D(\Omega) \quad \exists \varphi \in D(\Omega') \text{ s.t. } \frac{|\langle \text{ext}^0_{\iota}, u, \psi \rangle_{D'(\cdot) \times D(\cdot)}|}{\|\psi\|_{W^{-s,p'}(\cdot)}} \preceq \frac{|\langle u, \varphi \rangle_{D'(\cdot) \times D(\cdot)}|}{\|\varphi\|_{W^{-s,p'}(\cdot)}}$$

To this end suppose  $\psi \in D(\Omega)$ . Choose a compact set  $\tilde{K}$  such that  $K \subset \overset{\circ}{\tilde{K}} \subset \tilde{K} \subset \Omega'$ . Fix  $\chi \in D(\Omega)$  such that  $\chi = 1$  on  $K$  and  $\chi = 0$  outside of  $\overset{\circ}{\tilde{K}}$ . Clearly if we set  $\varphi = \chi\psi|_{\cdot}$ , then  $\varphi \in D(\Omega')$  and  $\varphi = \psi|_{\cdot}$  on  $K$ . Therefore

$$\langle \text{ext}^0_{\iota}, u, \psi \rangle_{D'(\cdot) \times D(\cdot)} = \langle u, \psi|_{\cdot} \rangle_{\mathcal{E}'(\cdot) \times \mathcal{E}(\cdot)} = \langle u, \varphi \rangle_{D'(\cdot) \times D(\cdot)}$$

Also since  $-s > 0$ , we have

$$\|\varphi\|_{W^{-s,p'}(\cdot)} \leq \|\text{ext}^0_{\iota}, \varphi\|_{W^{-s,p'}(\cdot)} = \|\chi\psi\|_{W^{-s,p'}(\cdot)} \preceq \|\psi\|_{W^{-s,p'}(\cdot)}$$

The latter inequality is the place where we used the assumption that  $s \in (-\infty, -1] \cap \mathbb{Z}$  or  $-1 < s < 0$  or  $\Omega$  is Lipschitz or  $\Omega = \mathbb{R}^n$ . This completes the proof of the second item.  $\square$

**Corollary E.44.** *Let  $p \in (1, \infty)$ . Let  $\Omega$  and  $\Omega'$  be nonempty open sets in  $\mathbb{R}^n$  with  $\Omega' \subseteq \Omega$  and let  $K \in \mathcal{K}(\Omega')$ . Suppose  $u \in W_K^{s,p}(\Omega)$ . It follows from Corollary E.36 and Theorem E.43 that*

- if  $s \in \mathbb{R}$  is not a noninteger less than  $-1$ , then

$$\|u\|_{W^{s,p}(\cdot)} \simeq \|u\|_{W^{s,p}(\cdot)}$$

- if  $\Omega$  is Lipschitz or  $\Omega = \mathbb{R}^n$ , then for all  $s \in \mathbb{R}$

$$\|u\|_{W^{s,p}(\cdot)} \simeq \|u\|_{W^{s,p}(\cdot)}$$

Note that on the right hand sides of the above expressions,  $u$  stands for  $\text{res}_{\cdot} u$ . Clearly  $\text{ext}^0_{\iota} \circ \text{res}_{\cdot} u = u$ .

**Theorem E.45.** *Let  $\Omega$  be any nonempty open set in  $\mathbb{R}^n$ ,  $K \subseteq \Omega$  be compact,  $s > 0$ , and  $p \in (1, \infty)$ . Then the following norms on  $W_K^{s,p}(\Omega)$  are equivalent:*

$$\begin{aligned} \|u\|_{W^{s,p}(\cdot)} &:= \|u\|_{W^{k,p}(\cdot)} + \sum_{|\nu|=k} |\partial^\nu u|_{W^{\theta,p}(\cdot)} \\ [u]_{W^{s,p}(\cdot)} &:= \|u\|_{W^{k,p}(\cdot)} + \sum_{1 \leq |\nu| \leq k} |\partial^\nu u|_{W^{\theta,p}(\cdot)} \end{aligned}$$

where  $s = k + \theta$ ,  $k \in \mathbb{N}_0$ ,  $\theta \in (0, 1)$ . Moreover, if we further assume  $\Omega$  is Lipschitz, then the above norms are equivalent on  $W^{s,p}(\Omega)$ .

*Proof.* Clearly for all  $u \in W^{s,p}(\Omega)$ ,  $\|u\|_{W^{s,p}(\cdot)} \leq [u]_{W^{s,p}(\cdot)}$ . So it is enough to show that there is a constant  $C > 0$  such that for all  $u \in W_K^{s,p}(\Omega)$  (or  $u \in W^{s,p}(\Omega)$  if  $\Omega$  is Lipschitz)

$$[u]_{W^{s,p}(\cdot)} \leq C \|u\|_{W^{s,p}(\cdot)}$$

For each  $1 \leq i \leq k$  we have

$$\sum_{|\nu|=i} |\partial^\nu u|_{W^{\theta,p}(\cdot)} = \|u\|_{W^{i+\theta,p}(\cdot)} - \|u\|_{W^{i,p}(\cdot)}$$

Thus

$$\begin{aligned} [u]_{W^{s,p}(\Omega)} &= \|u\|_{W^{s,p}(\Omega)} + \sum_{1 \leq i < k} \sum_{|\nu|=i} |\partial^\nu u|_{W^{\theta,p}(\Omega)} \\ &= \|u\|_{W^{s,p}(\Omega)} + \sum_{1 \leq i < k} \left( \|u\|_{W^{i+\theta,p}(\Omega)} - \|u\|_{W^{i,p}(\Omega)} \right) \end{aligned}$$

Therefore it is enough to show that there exists a constant  $C \geq 1$  such that

$$\sum_{1 \leq i < k} \|u\|_{W^{i+\theta,p}(\Omega)} \leq (C-1)\|u\|_{W^{s,p}(\Omega)} + \sum_{1 \leq i < k} \|u\|_{W^{i,p}(\Omega)}$$

By Theorem E.37, for each  $1 \leq i < k$ ,  $W_K^{s,p}(\Omega) \hookrightarrow W_K^{i+\theta,p}(\Omega)$  (also we have  $W^{s,p}(\Omega) \hookrightarrow W^{i+\theta,p}(\Omega)$  with the extra assumption that  $\Omega$  is Lipschitz); so there is a constant  $C_i$  such that  $\|u\|_{W^{i+\theta,p}(\Omega)} \leq C_i \|u\|_{W^{s,p}(\Omega)}$ . Clearly with  $C = 1 + \sum_{i=1}^{k-1} C_i$  the desired inequality holds.  $\square$

**Remark E.46.** Let  $s \geq 0$  and  $1 < p < \infty$ . Here we summarize the connection between Sobolev spaces and space of distributions.

(1) **Question 1:** What does it mean to say  $u \in D'(\Omega)$  belongs to  $W^{-s,p'}(\Omega)$ ?

**Answer:**

$$\begin{aligned} u \in D'(\Omega) \text{ is in } W^{-s,p'}(\Omega) &\iff u : (D(\Omega), \|\cdot\|_{s,p}) \rightarrow \mathbb{R} \text{ is continuous} \\ &\iff u : D(\Omega) \rightarrow \mathbb{R} \text{ has a unique continuous extension to } \hat{u} : W_0^{s,p}(\Omega) \rightarrow \mathbb{R} \end{aligned}$$

(2) **Question 2:** How should we interpret  $W^{-s,p'}(\Omega) \subseteq D'(\Omega)$ ?

**Answer:**  $i : D(\Omega) \rightarrow W_0^{s,p}(\Omega)$  is continuous with dense image. Therefore  $i^* : W^{-s,p'}(\Omega) \rightarrow D'(\Omega)$  is an injective continuous linear map. If  $u \in W^{-s,p'}(\Omega)$ , then  $i^*u \in D'(\Omega)$  and

$$\langle i^*u, \varphi \rangle_{D'(\Omega) \times D(\Omega)} = \langle u, i\varphi \rangle_{W^{-s,p'}(\Omega) \times W_0^{s,p}(\Omega)} = \langle u, \varphi \rangle_{W^{-s,p'}(\Omega) \times W_0^{s,p}(\Omega)}$$

So  $i^*u = u|_{D(\Omega)}$  and if we identify with  $i^*u$  with  $u$  we can write

$$\langle u, \varphi \rangle_{D'(\Omega) \times D(\Omega)} = \langle u, \varphi \rangle_{W^{-s,p'}(\Omega) \times W_0^{s,p}(\Omega)}, \quad \|u\|_{W^{-s,p'}(\Omega)} = \sup_{0 \neq \varphi \in C_c^\infty(\Omega)} \frac{|\langle u, \varphi \rangle_{D'(\Omega) \times D(\Omega)}|}{\|\varphi\|_{W^{s,p}(\Omega)}}$$

(3) **Question 3:** What does it mean to say  $u \in D'(\Omega)$  belongs to  $W^{s,p}(\Omega)$ ?

**Answer:** It means there exists  $f \in W^{s,p}(\Omega)$  such that  $u = u_f$ .

(4) **Question 4:** How should we interpret  $W^{s,p}(\Omega) \subseteq D'(\Omega)$ ?

**Answer:** It is a direct consequence of the definition of  $W^{s,p}(\Omega)$  that  $W^{s,p}(\Omega) \hookrightarrow L^p(\Omega)$  for any open set  $\Omega$ . So any  $f \in W^{s,p}(\Omega)$  can be identified with the regular distribution  $u_f \in D'(\Omega)$  where

$$\langle u_f, \varphi \rangle = \int f \varphi \quad \forall \varphi \in D(\Omega)$$

**Remark E.47.** Let  $\Omega$  be a nonempty open set in  $\mathbb{R}^n$  and  $f, g \in C_c^\infty(\Omega)$ . Suppose  $s \in \mathbb{R}$  and  $p \in (1, \infty)$ .

• If  $s \geq 0$ , then

$$\|f\|_{W^{-s,p'}(\Omega)} = \sup_{0 \neq \varphi \in C_c^\infty(\Omega)} \frac{|\langle f, \varphi \rangle_{D'(\Omega) \times D(\Omega)}|}{\|\varphi\|_{W^{s,p}(\Omega)}} = \sup_{0 \neq \varphi \in C_c^\infty(\Omega)} \frac{|\int f \varphi dx|}{\|\varphi\|_{W^{s,p}(\Omega)}}$$

So for all  $\varphi \in C_c^\infty(\Omega)$

$$\left| \int f\varphi \, dx \right| \leq \|f\|_{W^{-s,p'}(\cdot)} \|\varphi\|_{W^{s,p}(\cdot)}$$

In particular, for  $g$ , we have

$$\left| \int fg \, dx \right| \leq \|f\|_{W^{-s,p'}(\cdot)} \|g\|_{W^{s,p}(\cdot)}$$

- If  $s < 0$ , we may replace the roles of  $f$  and  $g$ , and also  $(s, p)$  and  $(-s, p')$  in the above argument to get the exact same inequality:  $\left| \int fg \, dx \right| \leq \|f\|_{W^{-s,p'}(\cdot)} \|g\|_{W^{s,p}(\cdot)}$ .

### E.5. Invariance Under Change of Coordinates, Composition.

**Theorem E.48** ([45], Section 4.3). *Let  $s \in \mathbb{R}$  and  $1 < p < \infty$ . Suppose that  $T : \mathbb{R}^n \rightarrow \mathbb{R}^n$  is a  $C^\infty$ -diffeomorphism (i.e.  $T$  is bijective and  $T$  and  $T^{-1}$  are  $C^\infty$ ) with the property that the partial derivatives (of any order) of the components of  $T$  are bounded on  $\mathbb{R}^n$  (the bound may depend on the order of the partial derivative) and  $\inf_{\mathbb{R}^n} |\det T'| > 0$ . Then the linear map*

$$W^{s,p}(\mathbb{R}^n) \rightarrow W^{s,p}(\mathbb{R}^n), \quad u \mapsto u \circ T$$

is well defined and is bounded.

Now Let  $k \in \mathbb{N}$  and let  $U$  and  $V$  be two nonempty open sets in  $\mathbb{R}^n$ . Suppose  $T : U \rightarrow V$  is a bijective map. Similar to [2] we say  $T$  is  $k$ -**smooth** if all the components of  $T$  belong to  $BC^k(U)$  and all the components of  $T^{-1}$  belong to  $BC^k(V)$ .

**Remark E.49.** *It is useful to note that if  $T$  is 1-smooth, then*

$$\inf_U |\det T'| > 0 \quad \text{and} \quad \inf_V |\det (T^{-1})'| > 0$$

Indeed, since the first order partial derivatives of the components of  $T$  and  $T^{-1}$  are bounded, there exist positive numbers  $M$  and  $\tilde{M}$  such that for all  $x \in U$  and  $y \in V$

$$|\det T'(x)| < M, \quad |\det (T^{-1})'(y)| < \tilde{M}$$

Since  $|\det T'(x)| \times |\det (T^{-1})'(T(x))| = 1$ , we can conclude that for all  $x \in U$  and  $y \in V$

$$|\det T'(x)| > \frac{1}{\tilde{M}}, \quad |\det (T^{-1})'(y)| > \frac{1}{M}$$

which proves the claim.

**Remark E.50.** *Also it is interesting to note that as a consequence of the inverse function theorem, if  $T : U \rightarrow V$  is a bijective map that is  $C^k$  with the property that  $\det T'(x) \neq 0$  for all  $x \in U$ , then the inverse of  $T$  will be  $C^k$  as well, that is  $T$  will automatically be a  $C^k$ -diffeomorphism (see e.g. Appendix C in [33] for more details).*

**Remark E.51.** *Note that since we do not assume that  $U$  and  $V$  are necessarily convex, the continuity and boundedness of the partial derivatives of the components of  $T$  do not imply that the components of  $T$  are Lipschitz. (See the "Warning" immediately after Theorem B.10.)*

**Theorem E.52.** [(15], Page 1003), ([2], Pages 77 and 78)] *Let  $p \in (1, \infty)$  and  $k \in \mathbb{N}$ . Suppose that  $U$  and  $V$  are nonempty open subsets of  $\mathbb{R}^n$ .*

- (1) *If  $T : U \rightarrow V$  is a 1-smooth map, then the map*

$$L^p(V) \rightarrow L^p(U), \quad u \mapsto u \circ T$$

is well defined and is bounded.

(2) If  $T : U \rightarrow V$  is a  $k$ -smooth map, then the map

$$W^{k,p}(V) \rightarrow W^{k,p}(U), \quad u \mapsto u \circ T$$

is well defined and is bounded.

**Theorem E.53.** Let  $p \in (1, \infty)$  and  $k \in \mathbb{Z}^-$  ( $k$  is a negative integer). Suppose that  $U$  and  $V$  are nonempty open subsets of  $\mathbb{R}^n$ , and  $T : U \rightarrow V$  is  $|k|$ -smooth. Then the map

$$W^{k,p}(V) \rightarrow W^{k,p}(U), \quad u \mapsto u \circ T$$

is well defined and is bounded.

*Proof.* By definition we have ( $T^*u$  denotes the pullback of  $u$  by  $T$ )

$$\begin{aligned} \|T^*u\|_{W^{k,p}(U)} &= \sup_{\varphi \in C_c^\infty(U)} \frac{|\langle T^*u, \varphi \rangle_{D'(U) \times D(U)}|}{\|\varphi\|_{W_0^{-k,p'}(U)}} \\ &= \sup_{\varphi \in C_c^\infty(U)} \frac{|\langle u, |\det(T^{-1})'| \varphi \circ T^{-1} \rangle_{D'(V) \times D(V)}|}{\|\varphi\|_{W_0^{-k,p'}(U)}} \\ &\preceq \sup_{\varphi \in C_c^\infty(U)} \frac{\|u\|_{W^{k,p}(V)} \|\det(T^{-1})'| \varphi \circ T^{-1}\|_{W^{-k,p'}(V)}}{\|\varphi\|_{W_0^{-k,p'}(U)}} \\ &\stackrel{|\det(T^{-1})'| \in BC^{|k|}}{\preceq} \sup_{\varphi \in C_c^\infty(U)} \frac{\|u\|_{W^{k,p}(V)} \|\varphi \circ T^{-1}\|_{W^{-k,p'}(V)}}{\|\varphi\|_{W_0^{-k,p'}(U)}} \end{aligned}$$

Since  $-k$  is a positive integer, by Theorem E.52 we have  $\|\varphi \circ T^{-1}\|_{W^{-k,p'}(V)} \preceq \|\varphi\|_{W_0^{-k,p'}(U)}$ . Consequently

$$\|T^*u\|_{W^{k,p}(U)} \preceq \|u\|_{W^{k,p}(V)}$$

□

**Theorem E.54.** Let  $p \in (1, \infty)$  and  $0 < s < 1$ . Suppose that  $U$  and  $V$  are nonempty open subsets of  $\mathbb{R}^n$ ,  $T : U \rightarrow V$  is 1-smooth, and  $T$  is Lipschitz continuous on  $U$ . Then the map

$$W^{s,p}(V) \rightarrow W^{s,p}(U), \quad u \mapsto u \circ T$$

is well defined and is bounded.

*Proof.* Note that

$$\|u \circ T\|_{W^{s,p}(U)} = \|u \circ T\|_{L^p(U)} + |u \circ T|_{W^{s,p}(U)} \stackrel{\text{Theorem E.52}}{\preceq} \|u\|_{L^p(V)} + |u \circ T|_{W^{s,p}(U)}$$

So it is enough to show that  $|u \circ T|_{W^{s,p}(U)} \preceq |u|_{W^{s,p}(V)}$

$$\begin{aligned} |u \circ T|_{W^{s,p}(U)} &= \left( \int \int_{U \times U} \frac{|(u \circ T)(x) - (u \circ T)(y)|^p}{|x - y|^{n+sp}} dx dy \right)^{\frac{1}{p}} \\ &\stackrel{z=T(x), w=T(y)}{\preceq} \left( \int \int_{V \times V} \frac{|u(z) - u(w)|^p}{|T^{-1}(z) - T^{-1}(w)|^{n+sp}} \frac{1}{|\det T'(x)|} \frac{1}{|\det T'(y)|} dz dw \right)^{\frac{1}{p}} \\ &\preceq \left( \int \int_{V \times V} \frac{|u(z) - u(w)|^p}{|T^{-1}(z) - T^{-1}(w)|^{n+sp}} dz dw \right)^{\frac{1}{p}} \end{aligned}$$

$T$  is Lipschitz continuous on  $U$ ; so there exists a constant  $C > 0$  such that

$$|T(x) - T(y)| \leq C|x - y| \implies |z - w| \leq C|T^{-1}(z) - T^{-1}(w)|$$

Therefore

$$\|u \circ T\|_{W^{s,p}(U)} \leq \left( \int \int_{V \times V} \frac{|u(z) - u(w)|^p}{|z - w|^{n+sp}} dz dw \right)^{\frac{1}{p}} = \|u\|_{W^{s,p}(V)}$$

□

**Theorem E.55.** *Let  $p \in (1, \infty)$  and  $-1 < s < 0$ . Suppose that  $U$  and  $V$  are nonempty open subsets of  $\mathbb{R}^n$ ,  $T : U \rightarrow V$  is 1-smooth,  $T^{-1}$  is Lipschitz continuous on  $V$ , and  $|\det(T^{-1})'|$  is in  $BC^{0,1}(V)$ . Then the map*

$$W^{s,p}(V) \rightarrow W^{s,p}(U), \quad u \mapsto u \circ T$$

*is well defined and is bounded.*

*Proof.* The proof of Theorem E.53, with obvious modifications, shows the validity of the above claim. □

**Remark E.56.** *By assumption the first order partial derivatives of the components of  $T^{-1}$  are continuous and bounded. Also it is true that absolute value of a Lipschitz continuous function and the sum and product of bounded Lipschitz continuous functions will be Lipschitz continuous. Consequently, in order to ensure that  $|\det(T^{-1})'|$  is in  $BC^{0,1}(V)$ , it is enough to make sure that the first order partial derivatives of the components of  $T^{-1}$  are bounded and Lipschitz continuous.*

**Theorem E.57.** *Let  $s = k + \theta$  where  $k \in \mathbb{N}$ ,  $\theta \in (0, 1)$ , and let  $p \in (1, \infty)$ . Suppose that  $U$  and  $V$  are two nonempty open sets in  $\mathbb{R}^n$  and let  $T : U \rightarrow V$  be a  $k$ -smooth map that is Lipschitz continuous on  $U$ . Then*

(1) *for each  $K \in \mathcal{K}(V)$  the linear map*

$$T^* : W_K^{s,p}(V) \rightarrow W_{T^{-1}(K)}^{s,p}(U), \quad u \mapsto u \circ T$$

*is well defined and is bounded.*

(2) *if we further assume that  $V$  is Lipschitz (and so  $U$  is Lipschitz) and the partial derivatives up to and including order  $k$  of all the components of  $T$  are Lipschitz continuous on  $U$ , the linear map*

$$T^* : W^{s,p}(V) \rightarrow W^{s,p}(U), \quad u \mapsto u \circ T$$

*is well defined and is bounded.*

*Proof.* Recall that  $C^\infty(V) \cap W^{s,p}(V)$  is dense in  $W^{s,p}(V)$ . Our proof consists of two steps: in the first step we additionally assume that  $u \in C^\infty(V)$ . Then in the second step we prove the validity of the claim for  $u \in W_K^{s,p}(V)$  (or  $u \in W^{s,p}(V)$  with the assumption that  $V$  is Lipschitz).

• **Step 1:** We have

$$\begin{aligned} \|u \circ T\|_{W^{s,p}(U)} &= \|u \circ T\|_{W^{k,p}(U)} + \sum_{|\nu|=k} |\partial^\nu(u \circ T)|_{W^{\theta,p}(U)} \\ &\stackrel{\text{Theorem E.52}}{\leq} \|u\|_{W^{k,p}(V)} + \sum_{|\nu|=k} |\partial^\nu(u \circ T)|_{W^{\theta,p}(U)} \end{aligned}$$

Since  $u$  and  $T$  are both  $C^k$ , it can be proved by induction that (see e.g. [2])

$$\partial^\nu(u \circ T)(x) = \sum_{\beta \leq \nu, 1 \leq |\beta|} M_{\nu\beta}(x) [(\partial^\beta u) \circ T](x)$$



where  $M_{\nu\beta}(x)$  are polynomials of degree at most  $|\beta|$  in derivatives of order at most  $|\nu|$  of the components of  $T$ . In particular,  $M_{\nu\beta} \in BC^k(U)$  in case 1 and  $M_{\nu\beta} \in BC^{k,1}(U)$  in case 2. Therefore

$$\begin{aligned} |\partial^\nu(u \circ T)|_{W^{\theta,p}(U)} &\leq \|\partial^\nu(u \circ T)\|_{W^{\theta,p}(U)} = \left\| \sum_{\beta \leq \nu, 1 \leq |\beta|} M_{\nu\beta}(x) [(\partial^\beta u) \circ T](x) \right\|_{W^{\theta,p}(U)} \\ &\stackrel{\text{Theorem E.39 and E.41}}{\preceq} \sum_{\beta \leq \nu, 1 \leq |\beta|} \|(\partial^\beta u) \circ T\|_{W^{\theta,p}(U)} = \sum_{\beta \leq \nu, 1 \leq |\beta|} \|(\partial^\beta u) \circ T\|_{L^p(U)} + \|(\partial^\beta u) \circ T\|_{W^{\theta,p}(U)} \\ &\stackrel{\text{Theorem E.52 and E.54}}{\preceq} \sum_{\beta \leq \nu, 1 \leq |\beta|} \|\partial^\beta u\|_{L^p(V)} + |\partial^\beta u|_{W^{\theta,p}(V)} \leq \|u\|_{W^{k,p}(V)} + \sum_{\beta \leq \nu, 1 \leq |\beta|} |\partial^\beta u|_{W^{\theta,p}(V)} \end{aligned}$$

(The fact that  $\partial^\beta u$  belongs to  $W^{\theta,p}(V) \hookrightarrow L^p(V)$  is a consequence of the definition of the Slobodeckij norm combined with our embedding theorems for Sobolev spaces of functions with fixed compact support in an arbitrary domain or embedding theorems for Sobolev spaces of functions on a Lipschitz domain). Hence

$$\begin{aligned} \|u \circ T\|_{W^{s,p}(U)} &\preceq \|u\|_{W^{k,p}(V)} + \sum_{1 \leq |\nu| \leq k} \sum_{\beta \leq \nu, 1 \leq |\beta|} |\partial^\beta u|_{W^{\theta,p}(V)} \\ &\preceq \|u\|_{W^{k,p}(V)} + \sum_{1 \leq |\alpha| \leq k} |\partial^\alpha u|_{W^{\theta,p}(V)} \stackrel{\text{Theorem E.45}}{\simeq} \|u\|_{W^{s,p}(V)} \end{aligned}$$

Note that the last equivalence is due to the assumption that  $u \in W_K^{s,p}(V)$  (or  $u \in W^{s,p}(V)$  with  $V$  being Lipschitz).

- **Step 2:** Now suppose  $u$  is an arbitrary element of  $W_K^{s,p}(V)$  (or  $W^{s,p}(V)$  with  $V$  being Lipschitz). There exists a sequence  $\{u_m\}_{m \geq 1}$  in  $C^\infty(V)$  such that  $u_m \rightarrow u$  in  $W^{s,p}(V)$ . In particular,  $\{u_m\}$  is Cauchy. By the previous steps we have

$$\|T^*u_m - T^*u_l\|_{W^{s,p}(U)} \preceq \|u_m - u_l\|_{W^{s,p}(V)} \rightarrow 0 \quad (\text{as } m, l \rightarrow \infty)$$

Therefore  $\{T^*u_m\}$  is a Cauchy sequence in the Banach space  $W^{s,p}(U)$  and subsequently there exists  $v \in W^{s,p}(U)$  such that  $T^*u_m \rightarrow v$  as  $m \rightarrow \infty$ . It remains to show that  $v = T^*u$  as elements of  $W^{s,p}(U)$ . As a direct consequence of the definition of  $W^{s,p}$ -norm ( $s \geq 0$ ) we have

$$\begin{aligned} \|T^*u_m - v\|_{L^p(U)} &\leq \|T^*u_m - v\|_{W^{s,p}(U)} \rightarrow 0 \\ \|u_m - u\|_{L^p(V)} &\leq \|u_m - u\|_{W^{s,p}(V)} \rightarrow 0 \end{aligned}$$

Note that by Theorem E.52,  $u_m \rightarrow u$  in  $L^p(V)$  implies that  $T^*u_m \rightarrow T^*u$  in  $L^p(U)$ . Thus  $T^*u = v$  as elements of  $L^p(U)$  and hence as elements of  $W^{s,p}(U)$ .

□

**Theorem E.58.** *Let  $p \in (1, \infty)$  and  $s < -1$  be a **noninteger** number. Suppose that  $U$  and  $V$  are two nonempty **Lipschitz** open sets in  $\mathbb{R}^n$  and  $T : U \rightarrow V$  is a  $k$ -smooth map ( $k = \lfloor -s \rfloor$ ) such that  $T^{-1}$  is Lipschitz continuous on  $V$  and the partial derivatives up to and including order  $k$  of all the components of  $T^{-1}$  are Lipschitz continuous on  $V$ . Then the linear map*

$$T^* : W^{s,p}(V) \rightarrow W^{s,p}(U), \quad u \mapsto u \circ T$$

*is well defined and is bounded.*

*Proof.* The proof is completely analogous to the proof of Theorem E.53. We have

$$\begin{aligned}
\|T^*u\|_{W^{s,p}(U)} &= \sup_{\varphi \in C_c^\infty(U)} \frac{|\langle T^*u, \varphi \rangle_{D'(U) \times D(U)}|}{\|\varphi\|_{W_0^{-s,p'}(U)}} \\
&= \sup_{\varphi \in C_c^\infty(U)} \frac{|\langle u, |\det(T^{-1})'| \varphi \circ T^{-1} \rangle_{D'(V) \times D(V)}|}{\|\varphi\|_{W_0^{-s,p'}(U)}} \\
&\preceq \frac{\|u\|_{W^{s,p}(V)} \|\det(T^{-1})'| \varphi \circ T^{-1}\|_{W^{-s,p'}(V)}}{\|\varphi\|_{W_0^{-s,p'}(U)}} \\
&\stackrel{|\det(T^{-1})'| \in BC^{l-s,1}(V)}{\preceq} \frac{\|u\|_{W^{s,p}(V)} \|\varphi \circ T^{-1}\|_{W^{-s,p'}(V)}}{\|\varphi\|_{W_0^{-s,p'}(U)}}
\end{aligned}$$

Since  $-s > 0$ , it follows from the hypotheses of this theorem and the result of Theorem E.57 that  $\|\varphi \circ T^{-1}\|_{W^{-s,p'}(V)} \preceq \|\varphi\|_{W_0^{-s,p'}(U)}$ . Consequently

$$\|T^*u\|_{W^{s,p}(U)} \preceq \|u\|_{W^{s,p}(V)}$$

□

**Lemma E.59.** *Let  $U$  and  $V$  be two nonempty open sets in  $\mathbb{R}^n$ . Suppose  $T : U \rightarrow V$  ( $T = (T^1, \dots, T^n)$ ) is a  $(k+1)$ -diffeomorphism for some  $k \in \mathbb{N}_0$  and let  $B \subseteq U$  be a nonempty bounded open set such that  $B \subseteq \bar{B} \subseteq U$ . Then*

- (1)  $T : B \rightarrow T(B)$  is a  $(k+1)$ -map.
- (2)  $T : B \rightarrow T(B)$  and  $T^{-1} : T(B) \rightarrow B$  are Lipschitz (the Lipschitz constant may depend on  $B$ ).
- (3) For all  $1 \leq i \leq n$  and  $|\alpha| \leq k$ ,  $\partial^\alpha T^i \in BC^{k,1}(B)$  and  $\partial^\alpha (T^{-1})^i \in BC^{k,1}(T(B))$ .

*Proof.* Item 1. is true because  $\bar{B}$  is compact and so  $T(\bar{B})$  is compact and continuous functions are bounded on compact sets. Items 2. and 3. are direct consequences of Theorem B.11. □

**Theorem E.60.** *Let  $s \in \mathbb{R}$  and  $p \in (1, \infty)$ . Suppose that  $U$  and  $V$  are two nonempty open sets in  $\mathbb{R}^n$  and  $T : U \rightarrow V$  is a  $(\lfloor |s| \rfloor + 1)$ -diffeomorphism. Let  $B \subseteq U$  be a nonempty bounded open set such that  $B \subseteq \bar{B} \subseteq U$ . Let  $u \in W^{s,p}(V)$  be such that  $\text{supp } u \subseteq T(B)$ . (Note that if  $\text{supp } u$  is compact in  $V$ , then such a  $B$  exists.)*

- (1) If  $s$  is NOT a noninteger less than  $-1$ , then

$$\|u \circ T\|_{W^{s,p}(U)} \preceq \|u\|_{W^{s,p}(V)}$$

(the implicit constant may depend on  $B$  but otherwise is independent of  $u$ )

- (2) If  $U$  and  $V$  are Lipschitz, then the above result holds for all  $s \in \mathbb{R}$ .
- (3) If  $U = V = \mathbb{R}^n$  and we further assume that  $T$  is a  $C^\infty$ -diffeomorphism, then the above inequality holds for all  $s \in \mathbb{R}$ .

*Proof.* If  $s$  is an integer or  $-1 < s < 1$ , or if  $U$  and  $V$  are Lipschitz and  $s \in \mathbb{R}$  then as a consequence of the above lemma and the preceding theorems we may write

$$\|u \circ T\|_{W^{s,p}(U)} \stackrel{\text{Corollary E.44}}{\simeq} \|u \circ T\|_{W^{s,p}(B)} \preceq \|u\|_{W^{s,p}(T(B))} \stackrel{\text{Corollary E.44}}{\simeq} \|u\|_{W^{s,p}(V)}$$

For general  $U$  and  $V$ , if  $s = k + \theta$ , we let  $\hat{B}$  be an open set such that  $\bar{\hat{B}}$  is a compact subset of  $U$  and  $\bar{B} \subseteq \hat{B}$ . We can apply the previous lemma to  $\hat{B}$  and write

$$\|u \circ T\|_{W^{s,p}(U)} \stackrel{\text{Corollary E.44}}{\simeq} \|u \circ T\|_{W^{s,p}(\hat{B})} \stackrel{\text{Theorem E.57}}{\preceq} \|u\|_{W_{T(\hat{B})}^{s,p}(T(\hat{B}))} \stackrel{\text{Corollary E.44}}{\simeq} \|u\|_{W^{s,p}(V)}$$

□

**Theorem E.61.** [10] *Let  $s \in [1, \infty)$ ,  $1 < p < \infty$ , and let*

$$m = \begin{cases} s, & \text{if } s \text{ is an integer} \\ \lfloor s \rfloor + 1, & \text{otherwise} \end{cases}$$

*If  $F \in C^m(\mathbb{R})$  is such that  $F(0) = 0$  and  $F, F', \dots, F^{(m)} \in L^\infty(\mathbb{R})$  (in particular, note that every  $F \in C_c^\infty(\mathbb{R})$  with  $F(0) = 0$  satisfies these conditions), then the map  $u \mapsto F(u)$  is well-defined and continuous from  $W^{s,p}(\mathbb{R}^n) \cap W^{1,sp}(\mathbb{R}^n)$  into  $W^{s,p}(\mathbb{R}^n)$ .*

**Corollary E.62.** *Let  $s$ ,  $p$ , and  $F$  be as in the previous theorem. Moreover suppose  $sp > n$ . Then the map  $u \mapsto F(u)$  is well-defined and continuous from  $W^{s,p}(\mathbb{R}^n)$  into  $W^{s,p}(\mathbb{R}^n)$ . The reason is that when  $sp > n$ , we have  $W^{s,p}(\mathbb{R}^n) \hookrightarrow W^{1,sp}(\mathbb{R}^n)$ .*

## E.6. Differentiation.

**Theorem E.63** ([9], Pages 598-605), ([20], Section 1.4). *Let  $s \in \mathbb{R}$ ,  $1 < p < \infty$ , and  $\alpha \in \mathbb{N}_0^n$ . Suppose  $\Omega$  is a nonempty open set in  $\mathbb{R}^n$ . Then*

- (1) *the linear operator  $\partial^\alpha : W^{s,p}(\mathbb{R}^n) \rightarrow W^{s-|\alpha|,p}(\mathbb{R}^n)$  is well defined and bounded;*
- (2) *for  $s < 0$ , the linear operator  $\partial^\alpha : W^{s,p}(\Omega) \rightarrow W^{s-|\alpha|,p}(\Omega)$  is well defined and bounded;*
- (3) *for  $s \geq 0$  and  $|\alpha| \leq s$ , the linear operator  $\partial^\alpha : W^{s,p}(\Omega) \rightarrow W^{s-|\alpha|,p}(\Omega)$  is well defined and bounded;*
- (4) *if  $\Omega$  is bounded with Lipschitz continuous boundary, and if  $s \geq 0$ ,  $s - \frac{1}{p} \neq \text{integer}$  (i.e. the fractional part of  $s$  is not equal to  $\frac{1}{p}$ ), then the linear operator  $\partial^\alpha : W^{s,p}(\Omega) \rightarrow W^{s-|\alpha|,p}(\Omega)$  for  $|\alpha| > s$  is well defined and bounded;*

**Remark E.64.** *Comparing the first and last items of the previous theorem, we see that not all the properties of Sobolev-Slobodeckij spaces on  $\mathbb{R}^n$  are fully inherited by Sobolev-Slobodeckij spaces on bounded domains even when the domain has Lipschitz continuous boundary. (Note that the above difference is related to the more fundamental fact that for  $s > 0$ , even when  $\Omega$  is Lipschitz,  $C_c^\infty(\Omega)$  is not necessarily dense in  $W^{s,p}(\Omega)$  and subsequently  $W^{-s,p'}(\Omega)$  is defined as the dual of  $W_0^{s,p}(\Omega)$  rather than the dual of  $W^{s,p}(\Omega)$  itself.) For this reason, when working with Sobolev spaces on manifolds, we prefer super nice atlases (i.e. we prefer to work with coordinate charts whose image under the coordinate map is the entire  $\mathbb{R}^n$ ). The next best choice would be GGL or GL atlases.*

## APPENDIX F. SPACES OF LOCALLY SOBOLEV FUNCTIONS

Let  $s \in \mathbb{R}$ ,  $1 < p < \infty$ . Let  $\Omega$  be a nonempty open set in  $\mathbb{R}^n$ . We define

$$W_{loc}^{s,p}(\Omega) := \{u \in D'(\Omega) : \forall \varphi \in C_c^\infty(\Omega) \quad \varphi u \in W^{s,p}(\Omega)\}$$

**Remark F.1.** *Recall that  $C_c^\infty(\Omega) \subseteq BC^{\infty,1}(\Omega)$ . So it follows from Theorem E.26 and Theorem E.39 that*

- *if  $\Omega = \mathbb{R}^n$  or  $\Omega$  is a bounded Lipschitz domain, then for all  $s \in \mathbb{R}$  and  $p \in (1, \infty)$ ,  $W^{s,p}(\Omega) \subseteq W_{loc}^{s,p}(\Omega)$ ;*
- *for a general domain  $\Omega$  and  $p \in (1, \infty)$ , if  $s$  is an integer or  $|s| < 1$ , then  $W^{s,p}(\Omega) \subseteq W_{loc}^{s,p}(\Omega)$ .*

Two useful equivalent descriptions of locally Sobolev functions are described in the following theorems.

**Theorem F.2.** *Let  $s \in \mathbb{R}$ ,  $1 < p < \infty$ . Let  $\Omega$  be a nonempty open set in  $\mathbb{R}^n$ . Either assume  $\Omega = \mathbb{R}^n$  or  $\Omega$  is Lipschitz or else assume  $s$  is not a noninteger with magnitude greater than 1. Then  $u \in D'(\Omega)$  is in  $W_{loc}^{s,p}(\Omega)$  if and only if for every precompact open set  $V$  with  $\bar{V} \subseteq \Omega$  there is  $w \in W^{s,p}(\Omega)$  such that  $w = u$  on  $V$ .*

*Proof.* ( $\Rightarrow$ ) Suppose  $u \in W_{loc}^{s,p}(\Omega)$  and let  $V$  be a precompact open set such that  $\bar{V} \subseteq \Omega$ . Let  $\varphi \in C_c^\infty(\Omega)$  be such that  $\varphi = 1$  on  $\bar{V}$ . Let  $w = \varphi u$ .  $u$  is a locally Sobolev function, so  $w \in W^{s,p}(\Omega)$ ; also clearly  $w = u$  on  $V$ .

( $\Leftarrow$ ) Suppose  $u \in D'(\Omega)$  has the property that for every precompact open set  $V$  with  $\bar{V} \subseteq \Omega$  there is  $w \in W^{s,p}(\Omega)$  such that  $w = u$  on  $V$ . Let  $\varphi \in C_c^\infty(\Omega)$ . We need to show that  $\varphi u \in W^{s,p}(\Omega)$ . Note that  $\text{supp } \varphi$  is compact, so there exists a bounded open set  $V$  such that

$$\text{supp } \varphi \subseteq V \subseteq \bar{V} \subseteq \Omega$$

By assumption there exists a function  $w \in W^{s,p}(\Omega)$  such that  $w = u$  on  $V$ . It follows from the hypotheses that  $W^{s,p}(\Omega) \subseteq W_{loc}^{s,p}(\Omega)$ ; so  $w \in W_{loc}^{s,p}(\Omega)$  and thus  $\varphi w \in W^{s,p}(\Omega)$ . Clearly  $\varphi w = \varphi u$  on  $\Omega$ . Therefore  $\varphi u \in W^{s,p}(\Omega)$ .  $\square$

**Theorem F.3.** *Let  $s \in \mathbb{R}$ ,  $1 < p < \infty$ . Let  $\Omega$  be a nonempty open set in  $\mathbb{R}^n$ . Either assume  $\Omega = \mathbb{R}^n$  or  $\Omega$  is Lipschitz or else assume  $s$  is not a noninteger less than  $-1$ . If  $A$  is a subset of  $C_c^\infty(\Omega)$  with the following property:*

$$\forall x \in \Omega \quad \exists \varphi \in A \quad \text{such that} \quad \varphi \geq 0 \quad \text{and} \quad \varphi(x) \neq 0$$

*then we say  $A$  is **admissible**. If  $A$  is an admissible family of functions then*

$$W_{loc}^{s,p}(\Omega) = \{u \in D'(\Omega) : \forall \varphi \in A \quad \varphi u \in W^{s,p}(\Omega)\}$$

*Proof.* We will give an argument similar to the one presented in [3]. Let  $u \in D'(\Omega)$  be such that  $\varphi u \in W^{s,p}(\Omega)$  for all  $\varphi \in A$ . We need to show that if  $\psi \in C_c^\infty(\Omega)$ , then  $\psi u \in W^{s,p}(\Omega)$ . By the definition of  $A$ , for all  $x \in \text{supp } \psi$  there exists  $\varphi_x \in A$  such that  $\varphi_x(x) > 0$ . Define

$$U_x := \{y \in \Omega : \varphi_x(y) > \frac{1}{2} \varphi_x(x)\}$$

Clearly  $x \in U_x$  and since  $\varphi_x$  is continuous,  $U_x$  is an open set.  $\{U_x\}_{x \in \text{supp } \psi}$  is an open cover of the compact set  $\text{supp } \psi$ . So there exist points  $x_1, \dots, x_k$  such that  $\text{supp } \psi \subseteq U := U_{x_1} \cup \dots \cup U_{x_k}$ . If  $y \in U$ , then there exists  $1 \leq i \leq k$  such that  $y \in U_{x_i}$  and so  $\varphi_{x_i}(y) > 0$ . So the smooth function  $\sum_{i=1}^k \varphi_{x_i}$  is nonzero on  $U$ . Thus on  $U$  we have

$$\psi u = \frac{\psi}{\sum_{i=1}^k \varphi_{x_i}} \left( \sum_{i=1}^k \varphi_{x_i} u \right)$$

Indeed, if we define

$$\xi(z) = \begin{cases} \frac{\psi(z)}{\sum_{i=1}^k \varphi_{x_i}(z)} & \text{if } z \in U \\ 0 & \text{otherwise} \end{cases}$$

then  $\xi$  is smooth with compact support in  $U$  and

$$\psi u = \xi \sum_{i=1}^k \varphi_{x_i} u$$

on the entire  $\Omega$ . Now note that for each  $i$ ,  $\varphi_{x_i} u$  is in  $W^{s,p}(\Omega)$  (because by assumption  $\varphi u \in W^{s,p}(\Omega)$  for all  $\varphi \in A$ ). So  $\sum_{i=1}^k \varphi_{x_i} u \in W^{s,p}(\Omega)$ . Since  $\xi \in C_c^\infty(\Omega)$

and  $\sum_{i=1}^k \varphi_{x_i} u$  has compact support, it follows from the hypotheses of the theorem that  $\xi \sum_{i=1}^k \varphi_{x_i} u \in W^{s,p}(\Omega)$  (see Corollary E.27 and Theorem E.41).  $\square$

**Remark F.4.** *Note that if  $A$  is an admissible family of functions, then for all  $m \in \mathbb{N}$ , the set  $\{\varphi^m : \varphi \in A\}$  is also an admissible family of functions.*

We equip  $W_{loc}^{s,p}(\Omega)$  with the natural topology induced by the separating family of seminorms  $\{|\cdot|_\varphi\}_{\varphi \in C_c^\infty(\cdot)}$  (see Theorem B.38) where

$$\forall u \in W_{loc}^{s,p}(\Omega) \quad \varphi \in C_c^\infty(\Omega) \quad |u|_\varphi := \|\varphi u\|_{W^{s,p}(\cdot)}$$

As an immediate consequence, by item 1. of Theorem B.40,  $u_i \rightarrow u$  in  $W_{loc}^{s,p}(\Omega)$  if and only if  $\varphi u_i \rightarrow \varphi u$  in  $W^{s,p}(\Omega)$  for all  $\varphi \in C_c^\infty(\Omega)$ .

Theorem F.3 can be used to show that when  $\Omega = \mathbb{R}^n$  or  $\Omega$  is Lipschitz or  $s$  is not a noninteger less than  $-1$ , the topology of  $W_{loc}^{s,p}(\Omega)$  is completely determined by admissible family of test functions and it is possible to choose a countable separating subset of  $\{|\cdot|_\varphi\}_{\varphi \in C_c^\infty(\cdot)}$  that generates the topology of  $W_{loc}^{s,p}(\Omega)$ . Therefore, by Theorem B.42, if  $\Omega = \mathbb{R}^n$  or  $\Omega$  is Lipschitz or  $s$  is not a noninteger less than  $-1$ , then the topology of  $W_{loc}^{s,p}(\Omega)$  is metrizable.

**Theorem F.5.** *Let  $\Omega$  be a nonempty bounded open set in  $\mathbb{R}^n$  with Lipschitz continuous boundary or  $\Omega = \mathbb{R}^n$ . Let  $s \in \mathbb{R}$  and  $p \in (1, \infty)$ . Then  $W^{s,p}(\Omega) \hookrightarrow W_{loc}^{s,p}(\Omega)$ .*

*Proof.* By Remark F.1,  $W^{s,p}(\Omega) \subseteq W_{loc}^{s,p}(\Omega)$ . Since both spaces are metrizable, it suffices to show that if  $u_i \rightarrow u$  in  $W^{s,p}(\Omega)$ , then  $u_i \rightarrow u$  in  $W_{loc}^{s,p}(\Omega)$ . To this end, let  $\varphi$  be an arbitrary element of  $C_c^\infty(\Omega)$ . We need to show that if  $u_i \rightarrow u$  in  $W^{s,p}(\Omega)$ , then  $\varphi u_i \rightarrow \varphi u$  in  $W^{s,p}(\Omega)$ . But this is in fact a direct consequence of Theorem E.15 and Theorem E.26.  $\square$

**Theorem F.6.** *Let  $s \in \mathbb{R}$ ,  $1 < p < \infty$ , and  $\alpha \in \mathbb{N}_0^n$ . Suppose  $\Omega$  is a nonempty bounded open set in  $\mathbb{R}^n$  with Lipschitz continuous boundary. Then*

- (1) *the linear operator  $\partial^\alpha : W_{loc}^{s,p}(\mathbb{R}^n) \rightarrow W_{loc}^{s-|\alpha|,p}(\mathbb{R}^n)$  is well defined and bounded;*
- (2) *for  $s < 0$ , the linear operator  $\partial^\alpha : W_{loc}^{s,p}(\Omega) \rightarrow W_{loc}^{s-|\alpha|,p}(\Omega)$  is well defined and bounded;*
- (3) *for  $s \geq 0$  and  $|\alpha| \leq s$ , the linear operator  $\partial^\alpha : W_{loc}^{s,p}(\Omega) \rightarrow W_{loc}^{s-|\alpha|,p}(\Omega)$  is well defined and bounded;*
- (4) *if  $s \geq 0$ ,  $s - \frac{1}{p} \neq \text{integer}$  (i.e. the fractional part of  $s$  is not equal to  $\frac{1}{p}$ ), then the linear operator  $\partial^\alpha : W_{loc}^{s,p}(\Omega) \rightarrow W_{loc}^{s-|\alpha|,p}(\Omega)$  for  $|\alpha| > s$  is well defined and bounded;*

*Proof.* This is the counterpart of Theorem E.63 for locally Sobolev functions. Here we will prove the first item. The remaining items can be proved using a similar technique.

- **Step 1:** First we prove by induction on  $|\alpha|$  that if  $u \in W_{loc}^{s,p}(\mathbb{R}^n)$ , then  $\partial^\alpha u \in W_{loc}^{s-|\alpha|,p}(\mathbb{R}^n)$ . Let  $\varphi \in C_c^\infty(\mathbb{R}^n)$ ; we need to show that  $\varphi \partial^\alpha u \in W^{s-|\alpha|,p}(\mathbb{R}^n)$ . If  $|\alpha| = 0$ , there is nothing to prove. If  $|\alpha| = 1$ , there exists  $1 \leq i \leq n$  such that  $\partial^\alpha = \frac{\partial}{\partial x^i}$ . We have

$$\varphi \partial^\alpha u = \varphi \frac{\partial u}{\partial x^i} = \frac{\partial(\varphi u)}{\partial x^i} - \frac{\partial \varphi}{\partial x^i} u$$

By assumption  $\varphi u \in W^{s,p}(\mathbb{R}^n)$  and so it follows from Theorem E.63 that the first term on the right hand side is in  $W^{s-1,p}(\mathbb{R}^n)$ . Also, since  $u \in W_{loc}^{s,p}(\mathbb{R}^n)$ , the second term on the right hand side is in  $W^{s,p}(\mathbb{R}^n) \hookrightarrow W^{s-1,p}(\mathbb{R}^n)$ . Hence  $\varphi \partial^\alpha u \in W^{s-1,p}(\mathbb{R}^n)$ . Now suppose the claim holds for all  $|\alpha| \leq k$ . Suppose  $\alpha$  is a multi-index such that  $|\alpha| = k + 1$ . Clearly there exists  $1 \leq i \leq n$  such that  $\partial^\alpha = \frac{\partial}{\partial x^i}(\partial^\beta)$  where  $\beta$  is a multi-index with  $|\beta| = k$ . By the induction hypothesis,  $\partial^\beta u \in W_{loc}^{s-|\beta|,p}(\mathbb{R}^n)$  and so by the argument that was presented for the base case we have  $\frac{\partial}{\partial x^i} \partial^\beta u \in W_{loc}^{s-|\beta|-1,p}(\mathbb{R}^n) = W_{loc}^{s-|\alpha|,p}(\mathbb{R}^n)$ .

- **Step 2:** In this step we prove the continuity. Again we use induction on  $|\alpha|$ . Let  $|\alpha| = 1$ . Choose  $i$  as in the previous step. For every  $\varphi \in C_c^\infty(\mathbb{R}^n)$  we have

$$\begin{aligned} \|\varphi \frac{\partial}{\partial x^i} u\|_{s-1,p} &= \left\| \frac{\partial(\varphi u)}{\partial x^i} - \frac{\partial \varphi}{\partial x^i} u \right\|_{s-1,p} \\ &\leq \left\| \frac{\partial(\varphi u)}{\partial x^i} \right\|_{s-1,p} + \left\| \frac{\partial \varphi}{\partial x^i} u \right\|_{s-1,p} \\ &\leq \|\varphi u\|_{s,p} + \left\| \frac{\partial \varphi}{\partial x^i} u \right\|_{s,p} \end{aligned}$$

On the right hand side we have sum of two of the seminorms that define the topology of  $W_{loc}^{s,p}(\mathbb{R}^n)$ . It follows from item 2. of Theorem B.40 that  $\partial^\alpha : W_{loc}^{s,p}(\mathbb{R}^n) \rightarrow W_{loc}^{s-1,p}(\mathbb{R}^n)$  is continuous. Now suppose the claim holds for all  $|\alpha| \leq k$ . Suppose  $\alpha$  is a multi-index such that  $|\alpha| = k + 1$ . Clearly there exists  $1 \leq i \leq n$  such that  $\partial^\alpha = \frac{\partial}{\partial x^i}(\partial^\beta)$  where  $\beta$  is a multi-index with  $|\beta| = k$ . We have

$$\begin{aligned} \|\varphi \partial^\alpha u\|_{s-|\alpha|,p} &= \|\varphi \frac{\partial}{\partial x^i}(\partial^\beta u)\|_{s-|\alpha|,p} \\ &\stackrel{\text{argument of the base case}}{\leq} \|\varphi \partial^\beta u\|_{s-|\alpha|+1,p} + \left\| \frac{\partial \varphi}{\partial x^i} \partial^\beta u \right\|_{s-|\alpha|+1,p} \\ &\leq \|\varphi \partial^\beta u\|_{s-|\beta|,p} + \left\| \frac{\partial \varphi}{\partial x^i} \partial^\beta u \right\|_{s-|\beta|,p} \\ &\stackrel{\text{induction hypothesis; Theorem B.40}}{\leq} \max(\|\varphi_1 u\|_{s,p}, \dots, \|\varphi_k u\|_{s,p}) + \left\| \frac{\partial \varphi}{\partial x^i} \partial^\beta u \right\|_{s-|\beta|,p} \\ &\stackrel{\text{induction hypothesis; Theorem B.40}}{\leq} \max(\|\varphi_1 u\|_{s,p}, \dots, \|\varphi_k u\|_{s,p}) + \max(\|\psi_1 u\|_{s,p}, \dots, \|\psi_l u\|_{s,p}) \\ &\leq \max(\|\varphi_1 u\|_{s,p}, \dots, \|\varphi_k u\|_{s,p}, \|\psi_1 u\|_{s,p}, \dots, \|\psi_l u\|_{s,p}) \end{aligned}$$

for some  $\varphi_1, \dots, \varphi_k$  and  $\psi_1, \dots, \psi_l$  in  $C_c^\infty(\mathbb{R}^n)$ . It follows from item 2. of Theorem B.40 that  $\partial^\alpha : W_{loc}^{s,p}(\mathbb{R}^n) \rightarrow W_{loc}^{s-|\alpha|,p}(\mathbb{R}^n)$  is continuous. □

**Lemma F.7.** *Let  $\Omega$  be a nonempty open subset of  $\mathbb{R}^n$ . Suppose  $u : \Omega \rightarrow \mathbb{R}$  and  $\tilde{u} : \Omega \rightarrow \mathbb{R}$  are such that  $u = \tilde{u}$  a.e. If  $\tilde{u}$  is continuous then  $\text{supp } \tilde{u} \subseteq \text{supp } u$ .*

*Proof by Contradiction.* Suppose  $x \in \text{supp } \tilde{u} \setminus \text{supp } u$ . Since  $x$  belongs to the complement of  $\text{supp } u$ , which is an open set, there exists  $\epsilon > 0$  such that  $B_\epsilon(x) \subseteq \Omega$  and  $B_\epsilon(x) \cap \text{supp } u = \emptyset$ . Since  $x \in \text{supp } \tilde{u}$ , there exists  $y \in B_{\epsilon/4}(x)$  such that  $\tilde{u}(y) \neq 0$ .  $\tilde{u}$  is continuous, therefore there exists  $0 < \delta < \frac{\epsilon}{4}$  such that  $\tilde{u}(z) \neq 0$  for all  $z \in B_\delta(y) \subseteq B_\epsilon(x)$ . But  $u = 0$  on  $B_\epsilon(x)$ . This contradicts the fact that  $u = \tilde{u}$  a.e. □

The next two theorems play a key role in our study of Sobolev spaces on Riemannian manifolds with rough metrics.

**Theorem F.8.** *Let  $\Omega$  be a nonempty bounded open set in  $\mathbb{R}^n$  with Lipschitz continuous boundary or  $\Omega = \mathbb{R}^n$ . Suppose  $u \in W_{loc}^{s,p}(\Omega)$  where  $sp > n$ . Then  $u$  has a continuous version.*

*Proof.* Let  $\{V_j\}_{j \in \mathbb{N}_0}$  and  $\{\psi_j\}_{j \in \mathbb{N}_0}$  be as in Theorem B.2. Note that  $u = \sum_j \psi_j u$ . For all  $j$ ,  $\psi_j u \in W^{s,p}(\Omega)$  so by Theorem E.24 there exists  $\tilde{u}_j \in C(\Omega)$  such that  $\psi_j u = \tilde{u}_j$  on  $\Omega \setminus A_j$  where  $A_j$  is a set of measure zero. Also by Lemma F.7  $\text{supp } \tilde{u}_j \subseteq \text{supp } \psi_j$ . Therefore for any  $x \in \Omega$  only finitely many of  $\tilde{u}_j(x)$ 's are nonzero. So we may define  $\tilde{u} : \Omega \rightarrow \mathbb{R}$  by  $\tilde{u} = \sum_j \tilde{u}_j$ . Clearly  $\tilde{u} = u$  on  $\Omega \setminus A$  where  $A = \cup A_j$  (so  $A$  is a set of measure zero). Consequently  $\tilde{u} = u$  a.e. It remains to show that  $\tilde{u} : \Omega \rightarrow \mathbb{R}$  is indeed continuous. To this end suppose  $a_m \rightarrow a$  in  $\Omega$ . We need to prove that  $\tilde{u}(a_m) \rightarrow \tilde{u}(a)$ . The open set  $B_1(a) \cap \Omega$  intersects only finitely many of  $\text{supp } \tilde{u}_j$ 's; let's denote them by  $\tilde{u}_{r_1}, \dots, \tilde{u}_{r_l}$ . Also since  $a_m \rightarrow a$  there exists  $M$  such that for all  $m \geq M$ ,  $a_m \in B_1(a)$ . Hence

$$\begin{aligned} \tilde{u}(a) &= \sum_j \tilde{u}_j(a) = \tilde{u}_{r_1}(a) + \dots + \tilde{u}_{r_l}(a) \\ \forall m \geq M \quad \tilde{u}(a_m) &= \tilde{u}_{r_1}(a_m) + \dots + \tilde{u}_{r_l}(a_m) \end{aligned}$$

Recall that  $\tilde{u}_{r_1} + \dots + \tilde{u}_{r_l}$  is a finite sum of continuous functions and so it is continuous. Thus

$$\lim_{m \rightarrow \infty} \tilde{u}(a_m) = \lim_{m \rightarrow \infty} (\tilde{u}_{r_1} + \dots + \tilde{u}_{r_l})(a_m) = \tilde{u}_{r_1}(a) + \dots + \tilde{u}_{r_l}(a) = \tilde{u}(a)$$

□

**Lemma F.9.** *Let  $\Omega = \mathbb{R}^n$  or  $\Omega$  be a bounded open set in  $\mathbb{R}^n$  with Lipschitz continuous boundary. Suppose  $s_1, s_2, s \in \mathbb{R}$  and  $1 < p_1, p_2, p < \infty$  are such that*

$$W^{s_1, p_1}(\Omega) \times W^{s_2, p_2}(\Omega) \hookrightarrow W^{s, p}(\Omega).$$

Then

- (1)  $W_{loc}^{s_1, p_1}(\Omega) \times W_{loc}^{s_2, p_2}(\Omega) \hookrightarrow W_{loc}^{s, p}(\Omega)$ .
- (2)  $W_{loc}^{s_1, p_1}(\Omega) \times W_{comp}^{s_2, p_2}(\Omega) \hookrightarrow W^{s, p}(\Omega)$ .

**Remark F.10.** *In the above lemma, since the locally Sobolev spaces on  $\Omega$  are metrizable, the continuity of the mapping*

$$W_{loc}^{s_1, p_1}(\Omega) \times W_{loc}^{s_2, p_2}(\Omega) \rightarrow W_{loc}^{s, p}(\Omega), \quad (u, v) \mapsto uv$$

*can be interpreted as follows: if  $u_i \rightarrow u$  in  $W_{loc}^{s_1, p_1}(\Omega)$  and  $v_i \rightarrow v$  in  $W_{loc}^{s_2, p_2}(\Omega)$ , then  $u_i v_i \rightarrow uv$  in  $W_{loc}^{s, p}(\Omega)$ . Also since  $W_{comp}^{s_2, p_2}(\Omega)$  is considered as a normed subspace of  $W^{s_2, p_2}(\Omega)$ , we have a similar interpretation of the continuity of the mapping in item 2.*

*Proof.*

- (1) Suppose  $u \in W_{loc}^{s_1, p_1}(\Omega)$  and  $v \in W_{loc}^{s_2, p_2}(\Omega)$ . First we show that  $uv$  is in  $W_{loc}^{s, p}(\Omega)$ . Clearly the set  $A = \{\varphi^2 : \varphi \in C_c^\infty(\Omega)\}$  is an admissible family of test functions. So in order to show that  $uv \in W_{loc}^{s, p}(\Omega)$ , it is enough to show that for all  $\varphi \in C_c^\infty(\Omega)$ ,  $\varphi^2 uv = (\varphi u)(\varphi v)$  is in  $W^{s, p}(\Omega)$ . This is clearly true because  $\varphi u \in W^{s_1, p_1}(\Omega)$ ,  $\varphi v \in W^{s_2, p_2}(\Omega)$ , and by assumption

$$W^{s_1, p_1}(\Omega) \times W^{s_2, p_2}(\Omega) \hookrightarrow W^{s, p}(\Omega)$$

In order to prove the continuity of the map  $(u, v) \mapsto uv$ , suppose  $u_i \rightarrow u$  in  $W_{loc}^{s_1, p_1}(\Omega)$  and  $v_i \rightarrow v$  in  $W_{loc}^{s_2, p_2}(\Omega)$ . We need to show that  $u_i v_i \rightarrow uv$  in  $W_{loc}^{s, p}(\Omega)$ . That is, we

need to prove that for all  $\varphi \in C_c^\infty(\Omega)$

$$\varphi^2 u_i v_i \rightarrow \varphi^2 uv \quad \text{in } W^{s,p}(\Omega)$$

We have

$$\begin{aligned} u_i \rightarrow u \text{ in } W_{loc}^{s_1,p_1}(\Omega) &\implies \varphi u_i \rightarrow \varphi u \text{ in } W^{s_1,p_1}(\Omega) \\ v_i \rightarrow v \text{ in } W_{loc}^{s_2,p_2}(\Omega) &\implies \varphi v_i \rightarrow \varphi v \text{ in } W^{s_2,p_2}(\Omega) \end{aligned}$$

By assumption  $W^{s_1,p_1}(\Omega) \times W^{s_2,p_2}(\Omega) \hookrightarrow W^{s,p}(\Omega)$ , so

$$(\varphi u_i)(\varphi v_i) \rightarrow (\varphi u)(\varphi v) \quad \text{in } W^{s,p}(\Omega)$$

(2) Suppose  $u \in W_{loc}^{s_1,p_1}(\Omega)$  and  $v \in W_{comp}^{s_2,p_2}(\Omega)$ . First we show that  $uv$  is in  $W^{s,p}(\Omega)$ . To this end, let  $\varphi \in C_c^\infty(\Omega)$  be such that  $\varphi = 1$  on the compact support of  $v$ . We have

$$uv = u(\varphi v) = \underbrace{(\varphi u)}_{\in W^{s_1,p_1}(\cdot)} \underbrace{v}_{\in W^{s_2,p_2}(\cdot)} \in W^{s,p}(\Omega)$$

Now we prove the continuity. Suppose  $u_i \rightarrow u$  in  $W_{loc}^{s_1,p_1}(\Omega)$  and  $v_i \rightarrow v$  in  $W_{comp}^{s_2,p_2}(\Omega)$ . Let  $\tilde{K}$  be a compact set such that

$$\text{supp } v \subseteq \overset{\circ}{\tilde{K}} \subseteq \tilde{K} \subseteq \Omega$$

By Theorem D.17 there exists  $N$  such that for all  $i \geq N$ ,  $\text{supp } v_i \subseteq \tilde{K}$ . Let  $\varphi \in C_c^\infty(\Omega)$  be such that  $\varphi = 1$  on  $\tilde{K}$ . We have

$$\begin{aligned} u_i \rightarrow u \quad \text{in } W_{loc}^{s_1,p_1}(\Omega) &\implies \varphi u_i \rightarrow \varphi u \quad \text{in } W^{s_1,p_1}(\Omega) \\ v_i \rightarrow v \quad \text{in } W^{s_2,p_2}(\Omega) & \end{aligned}$$

This together with the assumption that  $W^{s_1,p_1}(\Omega) \times W^{s_2,p_2}(\Omega) \hookrightarrow W^{s,p}(\Omega)$  implies  $\varphi u_i v_i \rightarrow \varphi uv$  in  $W^{s,p}(\Omega)$ . Since  $\varphi v = v$  and for all  $i \geq N$ ,  $\varphi v_i = v_i$ , we conclude that  $u_i v_i \rightarrow uv$  in  $W^{s,p}(\Omega)$ . □

**Corollary F.11.** *Let  $\Omega$  be the same as the previous theorem. If  $sp > n$ , then  $W_{loc}^{s,p}(\Omega)$  is closed under multiplication. Moreover if*

$$(f_1)_m \rightarrow f_1 \quad \text{in } W_{loc}^{s,p}(\Omega), \dots, (f_l)_m \rightarrow f_l \quad \text{in } W_{loc}^{s,p}(\Omega)$$

then

$$(f_1)_m \cdots (f_l)_m \rightarrow f_1 \cdots f_l \quad \text{in } W_{loc}^{s,p}(\Omega)$$

**Lemma F.12.** *Let  $\Omega = \mathbb{R}^n$  or let  $\Omega$  be a nonempty bounded open set in  $\mathbb{R}^n$  with Lipschitz continuous boundary. Let  $s \geq 1$  and  $p \in (1, \infty)$  be such that  $sp > n$ . Let  $B : \Omega \rightarrow GL(k, \mathbb{R})$ . Suppose for all  $x \in \Omega$  and  $1 \leq i, j \leq k$ ,  $B_{ij}(x) \in W_{loc}^{s,p}(\Omega)$ . Then*

- (1)  $\det B \in W_{loc}^{s,p}(\Omega)$ .
- (2) *Moreover if for each  $m \in \mathbb{N}$   $B_m : \Omega \rightarrow GL(k, \mathbb{R})$  and for all  $1 \leq i, j \leq k$   $(B_m)_{ij} \rightarrow B_{ij}$  in  $W_{loc}^{s,p}(\Omega)$ , then  $\det B_m \rightarrow \det B$  in  $W_{loc}^{s,p}(\Omega)$ .*

*Proof.*

(1) By Leibniz formula we have

$$\det B(x) = \sum_{\sigma \in S_n} \text{sgn}(\sigma) B_{\sigma(1),1} \cdots B_{\sigma(k),k}$$



By assumption for all  $1 \leq i \leq k$ ,  $B_{\sigma(i),i}$  is in  $W_{loc}^{s,p}(\Omega)$ . Since  $sp > n$ ,  $s \geq 1$ , it follows from Corollary F.11 that  $\det B \in W_{loc}^{s,p}(\Omega)$ .

(2) Since  $(B_m)_{ij} \rightarrow B_{ij}$  in  $W_{loc}^{s,p}(\Omega)$  it again follows from Corollary F.11 that for all  $\sigma \in S_n$

$$(B_m)_{\sigma(1),1} \cdots (B_m)_{\sigma(k),k} \rightarrow B_{\sigma(1),1} \cdots B_{\sigma(k),k} \quad \text{in } W_{loc}^{s,p}(\Omega)$$

Thus  $\det B_m \rightarrow \det B$  in  $W_{loc}^{s,p}(\Omega)$ . □

**Theorem F.13.** *Let  $\Omega = \mathbb{R}^n$  or let  $\Omega$  be a nonempty bounded open set in  $\mathbb{R}^n$  with Lipschitz continuous boundary. Let  $s \geq 1$  and  $p \in (1, \infty)$  be such that  $sp > n$ .*

- (1) *Suppose that  $u \in W_{loc}^{s,p}(\Omega)$  and that  $u(x) \in I$  for all  $x \in \Omega$  where  $I$  is some interval in  $\mathbb{R}$ . If  $F : I \rightarrow \mathbb{R}$  is a smooth function, then  $F(u) \in W_{loc}^{s,p}(\Omega)$ .*
- (2) *Suppose that  $u_m \rightarrow u$  in  $W_{loc}^{s,p}(\Omega)$  and that for all  $m \geq 1$  and  $x \in \Omega$ ,  $u_m(x), u(x) \in I$  where  $I$  is some open interval in  $\mathbb{R}$ . If  $F : I \rightarrow \mathbb{R}$  is a smooth function, then  $F(u_m) \rightarrow F(u)$  in  $W_{loc}^{s,p}(\Omega)$ .*
- (3) *If  $F : \mathbb{R} \rightarrow \mathbb{R}$  is a smooth function, then the map taking  $u$  to  $F(u)$  is continuous from  $W_{loc}^{s,p}(\Omega)$  to  $W_{loc}^{s,p}(\Omega)$ .*

*Proof.* The proof of part (1) generalizes the argument given in [34]. Let  $k = \lfloor s \rfloor$ . First we show that  $F(u) \in W_{loc}^{k,p}(\Omega)$ . To this end we fix a multi-index  $|\alpha| = m \leq k$  and we show that  $\partial^\alpha(F(u)) \in L_{loc}^p(\Omega)$ .

It follows from the chain rule (and induction) that  $\partial^\alpha(F(u))$  is a sum of the terms of the form

$$F^{(l)}(u) \partial^{\beta_1} u \cdots \partial^{\beta_r} u$$

where  $l \in \mathbb{N}$  and  $\sum_{i=1}^r |\beta_i| = m$ . It is a consequence of Lemma F.9 that if  $s_1, s_2 \geq s_3 \geq 0$  and  $s_1 + s_2 - s_3 > \frac{n}{p}$ , then  $W_{loc}^{s_1,p}(\Omega) \times W_{loc}^{s_2,p}(\Omega) \hookrightarrow W_{loc}^{s_3,p}(\Omega)$ . As a consequence

$$\begin{aligned} W_{loc}^{s-|\beta_1|,p}(\Omega) \times W_{loc}^{s-|\beta_2|,p}(\Omega) &\hookrightarrow W_{loc}^{s-|\beta_1|-|\beta_2|,p}(\Omega) \\ W_{loc}^{s-|\beta_1|-|\beta_2|,p}(\Omega) \times W_{loc}^{s-|\beta_3|,p}(\Omega) &\hookrightarrow W_{loc}^{s-|\beta_1|-|\beta_2|-|\beta_3|,p}(\Omega) \\ &\vdots \\ W_{loc}^{s-|\beta_1|-\cdots-|\beta_{r-1}|,p}(\Omega) \times W_{loc}^{s-|\beta_r|,p}(\Omega) &\hookrightarrow W_{loc}^{s-|\beta_1|-\cdots-|\beta_r|,p}(\Omega) = W_{loc}^{s-m,p}(\Omega) \end{aligned}$$

Considering this and the fact that  $\partial^{\beta_i} u \in W_{loc}^{s-|\beta_i|,p}(\Omega)$ , we have

$$\partial^{\beta_1} u \cdots \partial^{\beta_r} u \in W_{loc}^{t,p}(\Omega)$$

for all  $0 \leq t \leq s - m$ . In particular,  $\partial^{\beta_1} u \cdots \partial^{\beta_r} u \in W_{loc}^{0,p}(\Omega) = L_{loc}^p(\Omega)$ . Also, since  $F$  is smooth and  $u$  is continuous,  $F^{(l)}(u) \in L_{loc}^\infty$ . Therefore

$$F^{(l)}(u) \partial^{\beta_1} u \cdots \partial^{\beta_r} u \in L_{loc}^p$$

So  $F(u) \in W_{loc}^{k,p}(\Omega)$  where  $k = \lfloor s \rfloor$ . Now, for noninteger  $s$ , we use a bootstrapping argument to show that  $F(u)$  in fact belongs to  $W_{loc}^{s,p}(\Omega)$ .

$F'$  is smooth, therefore  $F'(u) \in W_{loc}^{k,p}(\Omega)$ . Also  $\frac{\partial u}{\partial x^i} \in W_{loc}^{s-1,p}(\Omega)$  (note that  $s - 1 \geq 0$ ). By Lemma F.9 we have

$$W_{loc}^{k,p}(\Omega) \times W_{loc}^{s-1,p}(\Omega) \hookrightarrow W_{loc}^{t-1,p}(\Omega)$$

provided that

$$k \geq t - 1 \geq 0, \quad s - 1 \geq t - 1 \geq 0, \quad k + (s - 1) - (t - 1) > \frac{n}{p}$$

Therefore  $\frac{\partial}{\partial x^i}(F(u)) = F'(u) \frac{\partial u}{\partial x^i} \in W_{loc}^{t-1,p}(\Omega)$  for all  $1 \leq t \leq s$  such that  $t < k + (s - \frac{n}{p})$ . Consequently  $F(u) \in W_{loc}^{t,p}(\Omega)$  for all  $1 \leq t \leq s$  such that  $t < k + (s - \frac{n}{p})$ . Now we can repeat this argument by starting with "F' is smooth, therefore  $F'(u) \in W_{loc}^{t,p}(\Omega)$  for all  $1 \leq t \leq s$  such that  $t < k + (s - \frac{n}{p})$ ". This results in  $F(u) \in W_{loc}^{t,p}(\Omega)$  for all  $1 \leq t \leq s$  such that  $t < k + 2(s - \frac{n}{p})$ . Repeating this a finite number of times shows that  $F(u) \in W_{loc}^{s,p}(\Omega)$ .

Our next goal is to prove items 2 and 3. First we note that if  $0 \in I$  then WLOG we may assume that  $F(0) = 0$ . Indeed, the constant function  $F(0)$  is an element of  $W_{loc}^{s,p}(\Omega)$ . So

$$F(u_m) \rightarrow F(u) \quad \text{in } W_{loc}^{s,p}(\Omega) \iff \tilde{F}(u_m) \rightarrow \tilde{F}(u) \quad \text{in } W_{loc}^{s,p}(\Omega)$$

where  $\tilde{F}(t) = F(t) - F(0)$ . Thus WLOG we may assume that  $F(0) = 0$ .

Let  $\{K_j\}_{j \in \mathbb{N}_0}$ ,  $\{V_j\}_{j \in \mathbb{N}_0}$ , and  $\{\psi_j\}_{j \in \mathbb{N}_0}$  be as in Theorem B.2. Clearly  $\{\psi_j\}$  is also an admissible family of test functions. Therefore in order to show that  $F(u_m) \rightarrow F(u)$  in  $W_{loc}^{s,p}(\Omega)$  it is enough to prove that

$$\forall r \in \mathbb{N}_0 \quad \psi_r(F(u_m) - F(u)) \rightarrow 0 \quad \text{in } W^{s,p}(\Omega) \text{ as } m \rightarrow \infty$$

Let  $\psi_{r_1}, \dots, \psi_{r_k}$  be those admissible test functions whose support intersects the support of  $\psi_r$ . Therefore

$$\forall x \in \text{supp } \psi_r \quad \sum_{j \in \mathbb{N}_0} \psi_j u = \psi_{r_1} u + \dots + \psi_{r_k} u$$

Consequently

$$\psi_r(F(u_m) - F(u)) = \psi_r F(\psi_{r_1} u_m + \dots + \psi_{r_k} u_m) - \psi_r F(\psi_{r_1} u + \dots + \psi_{r_k} u)$$

Since  $u_m \rightarrow u$  in  $W_{loc}^{s,p}(\Omega)$ , for all  $1 \leq i \leq k$  we have

$$\psi_{r_i} u_m \rightarrow \psi_{r_i} u \quad \text{in } W^{s,p}(\Omega)$$

and so

$$\psi_{r_1} u_m + \dots + \psi_{r_k} u_m \rightarrow \psi_{r_1} u + \dots + \psi_{r_k} u \quad \text{in } W^{s,p}(\Omega)$$

Since  $W^{s,p}(\Omega) \hookrightarrow L^\infty(\Omega)$  also we have

$$\psi_{r_1} u_m + \dots + \psi_{r_k} u_m \rightarrow \psi_{r_1} u + \dots + \psi_{r_k} u \quad \text{in } L^\infty(\Omega) \quad (\text{F.1})$$

Consequently for the continuous versions of  $\psi_{r_1} u_m + \dots + \psi_{r_k} u_m$  and  $\psi_{r_1} u + \dots + \psi_{r_k} u$  we have uniform convergence. From this point, we work with these continuous versions. The continuous function  $\psi_{r_1} u + \dots + \psi_{r_k} u$  attains its max and min on the compact set  $\text{supp } \psi_r$  which we denote by  $A_{max}$  and  $A_{min}$ , respectively. Note that

$$\forall x \in \text{supp } \psi_r \quad (\psi_{r_1} u + \dots + \psi_{r_k} u)(x) = u(x) \in I$$

So  $A_{max}$  and  $A_{min}$  are in  $I$  (that is  $[A_{min}, A_{max}] \subseteq I$ ). Let  $\epsilon > 0$  be such that  $[A_{min} - 2\epsilon, A_{max} + 2\epsilon] \subseteq I$ . By (F.1) there exists  $M$  such that

$$\forall m \geq M, \forall x \in \text{supp } \psi_r \quad (\psi_{r_1} u_m + \dots + \psi_{r_k} u_m)(x) \in [A_{min} - \epsilon, A_{max} + \epsilon] \subseteq I$$

Let  $\xi \in C_c^\infty(\mathbb{R})$  be such that  $\xi = 1$  on  $[A_{min} - \epsilon, A_{max} + \epsilon]$  and  $\xi = 0$  outside of  $[A_{min} - 2\epsilon, A_{max} + 2\epsilon] \subseteq I$ . Define  $\hat{F} : \mathbb{R} \rightarrow \mathbb{R}$  by

$$\hat{F}(t) = \begin{cases} \xi(t)F(t) & \text{if } t \in I \\ 0 & \text{if } t \notin I \end{cases}$$

Clearly  $\hat{F} : \mathbb{R} \rightarrow \mathbb{R}$  is a smooth function and  $\hat{F}(0) = 0$ . Moreover  $\hat{F} = F$  on  $[A_{min} - \epsilon, A_{max} + \epsilon]$ . Also for all  $x \in \Omega$  and  $m \geq M$  we have

$$\begin{aligned} \psi_r(F(u_m) - F(u)) &= \psi_r F(\psi_{r_1} u_m + \cdots + \psi_{r_k} u_m) - \psi_r F(\psi_{r_1} u + \cdots + \psi_{r_k} u) \\ &= \psi_r \hat{F}(\psi_{r_1} u_m + \cdots + \psi_{r_k} u_m) - \psi_r \hat{F}(\psi_{r_1} u + \cdots + \psi_{r_k} u) \end{aligned}$$

Indeed, if  $x \notin \text{supp} \psi_r$ , then both sides are equal to zero. If  $x \in \text{supp} \psi_r$ , then

$$\begin{aligned} (\psi_{r_1} u + \cdots + \psi_{r_k} u)(x) &\in [A_{min}, A_{max}] \\ (\psi_{r_1} u_m + \cdots + \psi_{r_k} u_m)(x) &\in [A_{min} - \epsilon, A_{max} + \epsilon] \end{aligned}$$

and so

$$\begin{aligned} F((\psi_{r_1} u + \cdots + \psi_{r_k} u)(x)) &= \hat{F}((\psi_{r_1} u + \cdots + \psi_{r_k} u)(x)) \\ F((\psi_{r_1} u_m + \cdots + \psi_{r_k} u_m)(x)) &= \hat{F}((\psi_{r_1} u_m + \cdots + \psi_{r_k} u_m)(x)) \end{aligned}$$

$\hat{F}$  is a smooth function and its value at 0 is 0. Also by assumption  $sp > n$ . Therefore the mapping  $v \rightarrow \psi_r F(v)$  from  $W^{s,p}(\Omega)$  to  $W^{s,p}(\Omega)$  is continuous. Hence

$$\psi_r \hat{F}(\psi_{r_1} u_m + \cdots + \psi_{r_k} u_m) \rightarrow \psi_r \hat{F}(\psi_{r_1} u + \cdots + \psi_{r_k} u) \quad \text{in } W^{s,p}(\Omega)$$

That is

$$\psi_r(F(u_m) - F(u)) \rightarrow 0 \quad \text{in } W^{s,p}(\Omega)$$

So we proved item 2. Finally we note that  $W_{loc}^{s,p}(\Omega)$  is metrizable. So continuity of the mapping  $u \rightarrow F(u)$  is equivalent to sequential continuity which was proved in item 2.  $\square$

## APPENDIX G. LEBESGUE SPACES ON COMPACT RIEMANNIAN MANIFOLDS

Let  $M^n$  be a compact Riemannian manifold and  $E \rightarrow M$  be a vector bundle of rank  $r$ .

**Definition G.1.** A collection  $\{(U_\alpha, \varphi_\alpha, \rho_\alpha, \psi_\alpha)\}_{1 \leq \alpha \leq N}$  of 4-tuples is called an **augmented total trivialization atlas** for  $E \rightarrow M$  provided that  $\{(U_\alpha, \varphi_\alpha, \rho_\alpha)\}_{1 \leq \alpha \leq N}$  is a total trivialization atlas for  $E \rightarrow M$  and  $\{\psi_\alpha\}$  is a partition of unity subordinate to the open cover  $\{U_\alpha\}$ .

Let  $\{(U_\alpha, \varphi_\alpha, \rho_\alpha, \psi_\alpha)\}_{1 \leq \alpha \leq N}$  be an augmented total trivialization atlas for  $E \rightarrow M$ . Let  $g$  be a continuous Riemannian metric on  $M$  and  $\langle \cdot, \cdot \rangle_E$  be a fiber metric on  $E$  (we denote the corresponding norm by  $|\cdot|_E$ ). Suppose  $1 \leq q < \infty$ .

- (1) **Definition 1:** The space  $L^q(M, E)$  is the completion of  $C^\infty(M, E)$  with respect to the following norm

$$\|u\|_{L^q(M, E)} := \sum_{\alpha=1}^N \sum_{l=1}^r \|\rho_\alpha^l \circ (\psi_\alpha u) \circ \varphi_\alpha^{-1}\|_{L^q(\varphi_\alpha(U_\alpha))}$$

Note that for this definition to make sense it is not necessary to have metric on  $M$  or fiber metric on  $E$ .

- (2) **Definition 2:** The space  $L^q(M, E)$  is the completion of  $C^\infty(M, E)$  with respect to the following norm

$$|u|_{L^q(M, E)}^q := \int_M |u|_E^q dV_g$$

- (3) **Definition 3:** The metric  $g$  defines a Lebesgue measure on  $M$ . Define the following equivalence relation on  $\Gamma(M, E)$ :

$$u \sim v \iff u = v \text{ a.e.}$$

We define

$$L^q(M, E) := \frac{\{u \in \Gamma(M, E) : \|u\|_{L^q(M, E)}^q := \int_M |u|_E^q dV_g < \infty\}}{\sim}$$

For  $q = \infty$  we define

$$L^\infty(M, E) := \frac{\{u \in \Gamma(M, E) : \|u\|_{L^\infty(M, E)} := \text{esssup}|u|_E < \infty\}}{\sim}$$

**Note:** We may define negligible sets (sets of measure zero) on a compact manifold using charts. It can be shown that this definition is independent of the charts and equivalent to the one that is obtained using the metric  $g$ . So it is meaningful to write  $u = v$  a.e. even without using a metric.

**Theorem G.2.** *Definition 1 is equivalent to Definition 2 (i.e. the norms are equivalent).*

*Proof.* Our proof consists of four steps:

- **Step 1:** In the next section it will be proved that different total trivialization atlases and partitions of unity result in equivalent norms (note that  $L^q = W^{0,q}$ ). Therefore WLOG we may assume that  $\{(U_\alpha, \varphi_\alpha, \rho_\alpha)\}_{1 \leq \alpha \leq N}$  is a total trivialization atlas that trivializes the fiber metric  $\langle \cdot, \cdot \rangle_E$  (see Theorem C.22 and Corollary C.23). So on any bundle chart  $(U, \varphi, \rho)$  and for any section  $u$  we have

$$|u|_E^2 \circ \varphi^{-1} = \langle u, u \rangle_E \circ \varphi^{-1} = \sum_{l=1}^r (\rho^l \circ u \circ \varphi^{-1})^2$$

- **Step 2:** In this step we show that if there is  $1 \leq \beta \leq N$  such that  $\text{supp} u \subseteq U_\beta$ , then

$$\|u\|_{L^q(M, E)}^q = \int_M |u|_E^q dV_g \simeq \sum_{l=1}^r \|\rho_\beta^l \circ u \circ \varphi_\beta^{-1}\|_{L^q(\varphi_\beta(U_\beta))}^q$$

We have

$$\begin{aligned} \int_M |u|_E^q dV_g &= \int_{\varphi_\beta(U_\beta)} (|u|_E \circ \varphi_\beta^{-1})^q \sqrt{\det(g_{ij} \circ \varphi_\beta^{-1})(x)} dx^1 \cdots dx^n \\ &\simeq \int_{\varphi_\beta(U_\beta)} (|u|_E \circ \varphi_\beta^{-1})^q dx^1 \cdots dx^n \quad (\sqrt{\det(g_{ij} \circ \varphi_\beta^{-1})(x)} \text{ is bounded by positive constants}) \\ &= \int_{\varphi_\beta(U_\beta)} \left( \sqrt{\sum_{l=1}^r (\rho_\beta^l \circ u \circ \varphi_\beta^{-1})^2} \right)^q dx^1 \cdots dx^n \\ &\simeq \int_{\varphi_\beta(U_\beta)} \left[ \sum_{l=1}^r |\rho_\beta^l \circ u \circ \varphi_\beta^{-1}|^q dx^1 \cdots dx^n \right] \quad (\sqrt{\sum a_l^2} \simeq \sum |a_l|) \\ &\simeq \int_{\varphi_\beta(U_\beta)} \sum_{l=1}^r |\rho_\beta^l \circ u \circ \varphi_\beta^{-1}|^q dx^1 \cdots dx^n \quad ((\sum a_l)^q \simeq \sum a_l^q) \\ &= \sum_{l=1}^r \int_{\varphi_\beta(U_\beta)} |\rho_\beta^l \circ u \circ \varphi_\beta^{-1}|^q dx^1 \cdots dx^n = \sum_{l=1}^r \|\rho_\beta^l \circ u \circ \varphi_\beta^{-1}\|_{L^q(\varphi_\beta(U_\beta))}^q \end{aligned}$$

- **Step 3:** In this step we will prove that for all  $u \in C^\infty(M, E)$

$$|u|_{L^q(M,E)}^q \simeq \sum_{\alpha} |\psi_{\alpha} u|_{L^q(M,E)}^q$$

We have

$$\begin{aligned} |u|_{L^q(M,E)}^q &= \int_M |u|_E^q dV_g = \sum_{\alpha} \int_M \frac{\psi_{\alpha}^q}{\sum_{\beta} \psi_{\beta}^q} |u|_E^q dV_g \quad (\{\frac{\psi_{\alpha}^q}{\sum_{\beta} \psi_{\beta}^q}\} \text{ is a partition of unity subordinate to } \{U_{\alpha}\}) \\ &\simeq \sum_{\alpha} \int_{U_{\alpha}} \psi_{\alpha}^q |u|_E^q dV_g \quad (\frac{1}{\sum_{\beta} \psi_{\beta}^q} \text{ is bounded by positive constants}) \\ &= \sum_{\alpha} \int_{U_{\alpha}} |\psi_{\alpha} u|_E^q dV_g = \sum_{\alpha} \int_M |\psi_{\alpha} u|_E^q dV_g \\ &= \sum_{\alpha} |\psi_{\alpha} u|_{L^q(M,E)}^q \end{aligned}$$

- **Step 4:** Let  $u$  be an arbitrary element of  $C^\infty(M, E)$ . We have

$$|u|_{L^q(M,E)}^q \stackrel{\text{Step 3}}{\simeq} \sum_{\alpha} |\psi_{\alpha} u|_{L^q(M,E)}^q \stackrel{\text{Step 2}}{\simeq} \sum_{\alpha} \sum_l \|\rho_{\alpha}^l \circ (\psi_{\alpha} u) \circ \varphi_{\alpha}^{-1}\|_{L^q(\varphi_{\alpha}(U_{\alpha}))}^q \simeq \|u\|_{L^q(M,E)}^q$$

□

## APPENDIX H. SOBOLEV SPACES ON COMPACT MANIFOLDS AND ALTERNATIVE CHARACTERIZATIONS

**H.1. The Definition.** Let  $M^n$  be a compact smooth manifold. Let  $\pi : E \rightarrow M$  be a vector bundle of rank  $r$ . Let  $\Lambda = \{(U_{\alpha}, \varphi_{\alpha}, \rho_{\alpha}, \psi_{\alpha})\}_{1 \leq \alpha \leq N}$  be an augmented total trivialization atlas for  $E \rightarrow M$ . For each  $1 \leq \alpha \leq N$ , let  $H_{\alpha}$  denote the map  $H_{E^{\vee}, U_{\alpha}, \varphi_{\alpha}}$  which was introduced in Appendix D.

**Definition H.1.**

$$W^{e,q}(M, E; \Lambda) = \{u \in D'(M, E) : \|u\|_{W^{e,q}(M,E)} = \sum_{\alpha=1}^N \sum_{l=1}^r \|[H_{\alpha}(\psi_{\alpha} u)]^l\|_{W^{e,q}(\varphi_{\alpha}(U_{\alpha}))} < \infty\}$$

**Remark H.2.**

- (1) If  $u \in W^{e,q}(M, E; \Lambda)$  is a regular distribution, it follows from Remark D.27 that

$$\|u\|_{W^{e,q}(M,E)} = \sum_{\alpha=1}^N \sum_{l=1}^r \|(\rho_{\alpha})^l \circ (\psi_{\alpha} u) \circ \varphi_{\alpha}^{-1}\|_{W^{e,q}(\varphi_{\alpha}(U_{\alpha}))}$$

- (2) It is clear that the collection of functions from  $M$  to  $\mathbb{R}$  can be identified with sections of the vector bundle  $E = M \times \mathbb{R}$ . For this reason  $W^{e,q}(M; \Lambda)$  is defined as  $W^{e,q}(M, M \times \mathbb{R}; \Lambda)$ . Note that in this case, for each  $\alpha$ ,  $\rho_{\alpha}$  is the identity map. So we may consider an augmented total trivialization atlas  $\Lambda$  as a collection of 3-tuples  $\{(U_{\alpha}, \varphi_{\alpha}, \psi_{\alpha})\}_{1 \leq \alpha \leq N}$ . In particular, if  $u \in W^{e,q}(M; \Lambda)$  is a regular distribution, then

$$\|u\|_{W^{e,q}(M)} = \sum_{\alpha=1}^N \|(\psi_{\alpha} u) \circ \varphi_{\alpha}^{-1}\|_{W^{e,q}(\varphi_{\alpha}(U_{\alpha}))}$$

- (3) Sometimes, when the underlying manifold  $M$  and the augmented total trivialization atlas are clear from the context (or when they are irrelevant), we may write  $W^{e,q}(E)$  instead of  $W^{e,q}(M, E; \Lambda)$ . In particular, for tensor bundles, we may write  $W^{e,q}(T_l^k M)$  instead of  $W^{e,q}(M, T_l^k M; \Lambda)$ .

**Remark H.3.** *Here is a list of some alternative, not necessarily equivalent, characterizations of Sobolev spaces.*

(1) *Suppose  $e \geq 0$ .*

$$W^{e,q}(M, E; \Lambda) = \{u \in L^q(M, E) : \|u\|_{W^{e,q}(M, E; \Lambda)} = \sum_{\alpha=1}^N \sum_{l=1}^r \|(\rho_\alpha)^l \circ (\psi_\alpha u) \circ \varphi_\alpha^{-1}\|_{W^{e,q}(\varphi_\alpha(U_\alpha))} < \infty\}$$

(2)

$$W^{e,q}(M, E; \Lambda) = \{u \in D'(M, E) : \|u\|_{W^{e,q}(M, E; \Lambda)} = \sum_{\alpha=1}^N \sum_{l=1}^r \|\text{ext}_{\varphi_\alpha(U_\alpha), \mathbb{R}^n}^0 [H_\alpha(\psi_\alpha u)]^l\|_{W^{e,q}(\mathbb{R}^n)} < \infty\}$$

(3)

$$W^{e,q}(M, E; \Lambda) = \{u \in D'(M, E) : [H_\alpha(\psi_\alpha u)]^l \in W_{loc}^{e,q}(\varphi_\alpha(U_\alpha)), \forall 1 \leq \alpha \leq N, \forall 1 \leq l \leq r\}$$

(4)  *$W^{e,q}(M, E; \Lambda)$  is the completion of  $C^\infty(M, E)$  with respect to the norm*

$$\|u\|_{W^{e,q}(M, E; \Lambda)} = \sum_{\alpha=1}^N \sum_{l=1}^r \|(\rho_\alpha)^l \circ (\psi_\alpha u) \circ \varphi_\alpha^{-1}\|_{W^{e,q}(\varphi_\alpha(U_\alpha))}$$

(5) • *Let  $g$  be a smooth Riemannian metric (i.e a fiber metric on  $TM$ ). So  $g^{-1}$  is a fiber metric on  $T^*M$ .*

• *Let  $\langle \cdot, \cdot \rangle_E$  be a smooth fiber metric on  $E$ .*

• *Let  $\nabla^E$  be a metric connection in the vector bundle  $\pi : E \rightarrow M$ .*

*For  $k \in \mathbb{N}_0$ ,  $W^{k,q}(M, E; g, \nabla^E)$  is the completion of  $C^\infty(M, E)$  with respect to the following norm*

$$\|u\|_{W^{k,q}(M, E; g, \nabla^E)}^q = \sum_{i=0}^k |(\nabla^E)^i u|_{L^q}^q = \sum_{i=0}^k \int_M \underbrace{|\nabla^E \cdots \nabla^E u|}_{i \text{ times}}^q |_{(T^*M)^{\otimes i} \otimes E} dV_g$$

*In particular, if we denote the Levi Civita connection corresponding to the smooth Riemannian metric  $g$  by  $\nabla$ , then  $W^{k,q}(M; g)$  is the completion of  $C^\infty(M)$  with respect to the following norm*

$$\|u\|_{W^{k,q}(M; g)}^q = \sum_{i=0}^k |\nabla^i u|_{L^q}^q = \sum_{i=0}^k \int_M \underbrace{|\nabla \cdots \nabla u|}_{i \text{ times}}^q |_{T^i M} dV_g$$

*In the subsequent discussions we will study the relation between each of these alternative descriptions of Sobolev spaces and Definition H.1.*

An important question is whether our definition of Sobolev spaces (as topological spaces) depends on the augmented total trivialization atlas  $\Lambda$ . We will answer this question at 3 levels. Although each level can be considered as a generalization of the preceding level, the proofs will be independent of each other. The following theorems show that at least when  $e$  is not a noninteger less than  $-1$ , the space  $W^{e,q}(M, E; \Lambda)$  and its topology are independent of the choice of augmented total trivialization atlas.

**Remark H.4.** *In the following theorems, by the equivalence of two norms  $\|\cdot\|_1$  and  $\|\cdot\|_2$  we mean there exist constants  $C_1$  and  $C_2$  such that*

$$C_1 \|\cdot\|_1 \leq \|\cdot\|_2 \leq C_2 \|\cdot\|_1$$

*where  $C_1$  and  $C_2$  may depend on*

$$n, e, q, \varphi_\alpha, U_\alpha, \tilde{\varphi}_\beta, \tilde{U}_\beta, \psi_\alpha, \tilde{\psi}_\beta$$

**Theorem H.5** (Equivalence of norms for functions). *Let  $e \in \mathbb{R}$  and  $q \in (1, \infty)$ . Let  $\Lambda = \{(U_\alpha, \varphi_\alpha, \psi_\alpha)\}_{1 \leq \alpha \leq N}$  and  $\Upsilon = \{(\tilde{U}_\beta, \tilde{\varphi}_\beta, \tilde{\psi}_\beta)\}_{1 \leq \beta \leq N}$  be two augmented total trivialization atlases for the trivial bundle  $M \times \mathbb{R} \rightarrow M$ . Also let  $\mathcal{W}$  be any vector subspace of  $W^{e,q}(M; \Upsilon)$  whose elements are regular distributions (e.g.  $C^\infty(M)$ ).*

- (1) *If  $e$  is not a noninteger less than  $-1$ , then  $\mathcal{W}$  is a subspace of  $W^{e,q}(M; \Lambda)$  as well, and the norms produced by  $\Lambda$  and  $\Upsilon$  are equivalent on  $\mathcal{W}$ .*
- (2) *If  $e$  is a noninteger less than  $-1$ , further assume that the total trivialization atlases corresponding to  $\Lambda$  and  $\Upsilon$  are GLC. Then  $\mathcal{W}$  is a subspace of  $W^{e,q}(M; \Lambda)$  as well, and the norms produced by  $\Lambda$  and  $\Upsilon$  are equivalent on  $\mathcal{W}$ .*

*Proof.* Let  $u \in \Gamma_{reg}(M)$ . Our goal is to show that the following expressions are comparable:

$$\begin{aligned} & \sum_{\alpha=1}^N \|(\psi_\alpha u) \circ \varphi_\alpha^{-1}\|_{W^{e,q}(\varphi_\alpha(U_\alpha))} \\ & \sum_{\beta=1}^N \|(\tilde{\psi}_\beta u) \circ \tilde{\varphi}_\beta^{-1}\|_{W^{e,q}(\tilde{\varphi}_\beta(\tilde{U}_\beta))} \end{aligned}$$

To this end it suffices to show that for each  $1 \leq \alpha \leq N$

$$\|(\psi_\alpha u) \circ \varphi_\alpha^{-1}\|_{W^{e,q}(\varphi_\alpha(U_\alpha))} \preceq \sum_{\beta=1}^N \|(\tilde{\psi}_\beta u) \circ \tilde{\varphi}_\beta^{-1}\|_{W^{e,q}(\tilde{\varphi}_\beta(\tilde{U}_\beta))}$$

We have

$$\begin{aligned} \|(\psi_\alpha u) \circ \varphi_\alpha^{-1}\|_{W^{e,q}(\varphi_\alpha(U_\alpha))} &= \left\| \sum_{\beta=1}^N \tilde{\psi}_\beta (\psi_\alpha u) \circ \varphi_\alpha^{-1} \right\|_{W^{e,q}(\varphi_\alpha(U_\alpha))} \\ &\leq \sum_{\beta=1}^N \|\tilde{\psi}_\beta (\psi_\alpha u) \circ \varphi_\alpha^{-1}\|_{W^{e,q}(\varphi_\alpha(U_\alpha))} \\ &\simeq \sum_{\beta=1}^N \|(\tilde{\psi}_\beta \psi_\alpha u) \circ \varphi_\alpha^{-1}\|_{W^{e,q}(\varphi_\alpha(U_\alpha \cap \tilde{U}_\beta))} \end{aligned}$$

The last equality follows from Corollary E.44 because  $(\tilde{\psi}_\beta \psi_\alpha u) \circ \varphi_\alpha^{-1}$  has support in the compact set  $\varphi_\alpha(\text{supp } \psi_\alpha \cap \text{supp } \tilde{\psi}_\beta) \subseteq \varphi_\alpha(U_\alpha \cap \tilde{U}_\beta)$ . Note that here we used the assumption that if  $e$  is a noninteger less than  $-1$ , then  $\varphi_\alpha(U_\alpha)$  is Lipschitz or the entire  $\mathbb{R}^n$ . Clearly

$$\sum_{\beta=1}^N \|(\tilde{\psi}_\beta \psi_\alpha u) \circ \varphi_\alpha^{-1}\|_{W^{e,q}(\varphi_\alpha(U_\alpha \cap \tilde{U}_\beta))} = \sum_{\beta=1}^N \|(\tilde{\psi}_\beta \psi_\alpha u) \circ \tilde{\varphi}_\beta^{-1} \circ \tilde{\varphi}_\beta \circ \varphi_\alpha^{-1}\|_{W^{e,q}(\varphi_\alpha(U_\alpha \cap \tilde{U}_\beta))}$$

Since  $\tilde{\varphi}_\beta \circ \varphi_\alpha^{-1} : \varphi_\alpha(U_\alpha \cap \tilde{U}_\beta) \rightarrow \tilde{\varphi}_\beta(U_\alpha \cap \tilde{U}_\beta)$  is a  $C^\infty$ -diffeomorphism and  $(\tilde{\psi}_\beta \psi_\alpha u) \circ \tilde{\varphi}_\beta^{-1}$  has compact support in the compact set  $\tilde{\varphi}_\beta(\text{supp } \psi_\alpha \cap \text{supp } \tilde{\psi}_\beta) \subseteq \tilde{\varphi}_\beta(U_\alpha \cap \tilde{U}_\beta)$ , it follows from Theorem E.60 that

$$\sum_{\beta=1}^N \|(\tilde{\psi}_\beta \psi_\alpha u) \circ \tilde{\varphi}_\beta^{-1} \circ \tilde{\varphi}_\beta \circ \varphi_\alpha^{-1}\|_{W^{e,q}(\varphi_\alpha(U_\alpha \cap \tilde{U}_\beta))} \preceq \sum_{\beta=1}^N \|(\tilde{\psi}_\beta \psi_\alpha u) \circ \tilde{\varphi}_\beta^{-1}\|_{W^{e,q}(\tilde{\varphi}_\beta(U_\alpha \cap \tilde{U}_\beta))}$$

Note that here we used the assumption that if  $e$  is a noninteger less than  $-1$ , then the two total trivialization atlases are GL compatible. As a direct consequence of Corollary E.36 and Theorem E.43 we have

$$\begin{aligned} \|(\tilde{\psi}_\beta \psi_\alpha u) \circ \tilde{\varphi}_\beta^{-1}\|_{W^{e,q}(\varphi_\beta(U_\alpha \cap \tilde{\mathcal{C}}_\beta))} &\simeq \|(\tilde{\psi}_\beta \psi_\alpha u) \circ \tilde{\varphi}_\beta^{-1}\|_{W^{e,q}(\varphi_\beta(\tilde{\mathcal{C}}_\beta))} \\ &= \|(\psi_\alpha \circ \tilde{\varphi}_\beta^{-1})[(\tilde{\psi}_\beta u) \circ \tilde{\varphi}_\beta^{-1}]\|_{W^{e,q}(\varphi_\beta(\tilde{\mathcal{C}}_\beta))} \end{aligned}$$

Now note that  $\psi_\alpha \circ \tilde{\varphi}_\beta^{-1} \in C^\infty(\tilde{\varphi}_\beta(\tilde{U}_\beta))$  and  $(\tilde{\psi}_\beta u) \circ \tilde{\varphi}_\beta^{-1}$  has support in the compact set  $\tilde{\varphi}_\beta(\text{supp } \tilde{\psi}_\beta)$ . Therefore by Theorem E.41 (for the case where  $e$  is not a noninteger less than  $-1$ ) and Corollary E.27 (for the case where  $e$  is a noninteger less than  $-1$ ) we have

$$\|(\psi_\alpha \circ \tilde{\varphi}_\beta^{-1})[(\tilde{\psi}_\beta u) \circ \tilde{\varphi}_\beta^{-1}]\|_{W^{e,q}(\varphi_\beta(\tilde{\mathcal{C}}_\beta))} \preceq \|(\tilde{\psi}_\beta u) \circ \tilde{\varphi}_\beta^{-1}\|_{W^{e,q}(\varphi_\beta(\tilde{\mathcal{C}}_\beta))}$$

Hence

$$\|(\psi_\alpha u) \circ \varphi_\alpha^{-1}\|_{W^{e,q}(\varphi_\alpha(U_\alpha))} \preceq \sum_{\beta=1}^N \|(\tilde{\psi}_\beta u) \circ \tilde{\varphi}_\beta^{-1}\|_{W^{e,q}(\varphi_\beta(\tilde{\mathcal{C}}_\beta))}$$

□

**Theorem H.6** (Equivalence of norms for regular sections). *Let  $e \in \mathbb{R}$  and  $q \in (1, \infty)$ . Let  $\Lambda = \{(U_\alpha, \varphi_\alpha, \rho_\alpha, \psi_\alpha)\}_{1 \leq \alpha \leq N}$  and  $\Upsilon = \{(\tilde{U}_\beta, \tilde{\varphi}_\beta, \tilde{\rho}_\beta, \tilde{\psi}_\beta)\}_{1 \leq \beta \leq N}$  be two augmented total trivialization atlases for the vector bundle  $E \rightarrow M$ . Also let  $\mathcal{W}$  be any vector subspace of  $W^{e,q}(M, E; \Upsilon)$  whose elements are regular distributions (e.g  $C^\infty(M, E)$ ).*

- (1) *If  $e$  is not a noninteger less than  $-1$ , then  $\mathcal{W}$  is a subspace of  $W^{e,q}(M, E; \Lambda)$  as well, and the norms produced by  $\Lambda$  and  $\Upsilon$  are equivalent on  $\mathcal{W}$ .*
- (2) *If  $e$  is a noninteger less than  $-1$ , further assume that the total trivialization atlases corresponding to  $\Lambda$  and  $\Upsilon$  are GLC. Then  $\mathcal{W}$  is a subspace of  $W^{e,q}(M, E; \Lambda)$  as well, and the norms produced by  $\Lambda$  and  $\Upsilon$  are equivalent on  $\mathcal{W}$ .*

*Proof.* Let  $u \in \Gamma_{\text{reg}}(M, E)$ . Our goal is to show that the following expressions are comparable:

$$\begin{aligned} &\sum_{\alpha=1}^N \sum_{l=1}^r \|\rho_\alpha^l \circ (\psi_\alpha u) \circ \varphi_\alpha^{-1}\|_{W^{e,q}(\varphi_\alpha(U_\alpha))} \\ &\sum_{\beta=1}^N \sum_{l=1}^r \|\tilde{\rho}_\beta^l \circ (\tilde{\psi}_\beta u) \circ \tilde{\varphi}_\beta^{-1}\|_{W^{e,q}(\varphi_\beta(\tilde{\mathcal{C}}_\beta))} \end{aligned}$$

To this end, it is enough to show that for each  $1 \leq \alpha \leq N$  and  $1 \leq l \leq r$

$$\|\rho_\alpha^l \circ (\psi_\alpha u) \circ \varphi_\alpha^{-1}\|_{W^{e,q}(\varphi_\alpha(U_\alpha))} \preceq \sum_{\beta=1}^N \sum_{t=1}^r \|\tilde{\rho}_\beta^t \circ (\tilde{\psi}_\beta u) \circ \tilde{\varphi}_\beta^{-1}\|_{W^{e,q}(\varphi_\beta(\tilde{\mathcal{C}}_\beta))}$$



We have

$$\begin{aligned}
 \|\rho_\alpha^l \circ (\psi_\alpha u) \circ \varphi_\alpha^{-1}\|_{W^{e,q}(\varphi_\alpha(U_\alpha))} &= \|\rho_\alpha^l \circ \left(\sum_{\beta=1}^N \tilde{\psi}_\beta \psi_\alpha u\right) \circ \varphi_\alpha^{-1}\|_{W^{e,q}(\varphi_\alpha(U_\alpha))} \\
 &\leq \sum_{\beta=1}^N \|\rho_\alpha^l \circ (\tilde{\psi}_\beta \psi_\alpha u) \circ \varphi_\alpha^{-1}\|_{W^{e,q}(\varphi_\alpha(U_\alpha))} \\
 &\simeq \sum_{\beta=1}^N \|\rho_\alpha^l \circ (\tilde{\psi}_\beta \psi_\alpha u) \circ \varphi_\alpha^{-1}\|_{W^{e,q}(\varphi_\alpha(U_\alpha \cap \mathcal{U}_\beta))}
 \end{aligned}$$

The last equality follows from Corollary E.44 because  $\rho_\alpha^l \circ (\tilde{\psi}_\beta \psi_\alpha u) \circ \varphi_\alpha^{-1}$  has support in the compact set  $\varphi_\alpha(\text{supp } \psi_\alpha \cap \text{supp } \tilde{\psi}_\beta) \subseteq \varphi_\alpha(U_\alpha \cap \tilde{U}_\beta)$ . Note that here we used the assumption that if  $e$  is a noninteger less than  $-1$ , then  $\varphi_\alpha(U_\alpha)$  is either Lipschitz or equal to the entire  $\mathbb{R}^n$ . Note that

$$\begin{aligned}
 &\sum_{\beta=1}^N \|\rho_\alpha^l \circ (\tilde{\psi}_\beta \psi_\alpha u) \circ \varphi_\alpha^{-1}\|_{W^{e,q}(\varphi_\alpha(U_\alpha \cap \mathcal{U}_\beta))} \\
 &= \sum_{\beta=1}^N \|\rho_\alpha^l \circ (\tilde{\psi}_\beta \psi_\alpha u) \circ \tilde{\varphi}_\beta^{-1} \circ \tilde{\varphi}_\beta \circ \varphi_\alpha^{-1}\|_{W^{e,q}(\varphi_\alpha(U_\alpha \cap \mathcal{U}_\beta))} \\
 &\stackrel{\text{Theorem E.60}}{\preceq} \sum_{\beta=1}^N \|\rho_\alpha^l \circ (\tilde{\psi}_\beta \psi_\alpha u) \circ \tilde{\varphi}_\beta^{-1}\|_{W^{e,q}(\varphi_\beta(U_\alpha \cap \mathcal{U}_\beta))} \\
 &\simeq \sum_{\beta=1}^N \|\rho_\alpha^l \circ (\tilde{\psi}_\beta \psi_\alpha u) \circ \tilde{\varphi}_\beta^{-1}\|_{W^{e,q}(\varphi_\beta(\mathcal{U}_\beta))}
 \end{aligned}$$

(Here we used Corollary E.36 and Theorem E.43)

$$\begin{aligned}
 &= \sum_{\beta=1}^N \|(\psi_\alpha \circ \tilde{\varphi}_\beta^{-1})[\rho_\alpha^l \circ (\tilde{\psi}_\beta u) \circ \tilde{\varphi}_\beta^{-1}]\|_{W^{e,q}(\varphi_\beta(\mathcal{U}_\beta))} \\
 &\preceq \sum_{\beta=1}^N \|\rho_\alpha^l \circ (\tilde{\psi}_\beta u) \circ \tilde{\varphi}_\beta^{-1}\|_{W^{e,q}(\varphi_\beta(\mathcal{U}_\beta))}
 \end{aligned}$$

(Here we used Theorem E.41 and Corollary E.27)

$$\begin{aligned}
 &= \sum_{\beta=1}^N \|\pi_l \circ \underbrace{\pi'}_{\rho_\alpha} \circ \Phi_\alpha \circ (\tilde{\psi}_\beta u) \circ \tilde{\varphi}_\beta^{-1}\|_{W^{e,q}(\varphi_\beta(\mathcal{U}_\beta))} \\
 &= \sum_{\beta=1}^N \|\pi_l \circ \pi' \circ \Phi_\alpha \circ \Phi_\beta^{-1} \circ \Phi_\beta \circ (\tilde{\psi}_\beta u) \circ \tilde{\varphi}_\beta^{-1}\|_{W^{e,q}(\varphi_\beta(\mathcal{U}_\beta))}
 \end{aligned}$$

Let  $v_\beta : \tilde{\varphi}_\beta(\tilde{U}_\beta) \rightarrow E$  be defined by  $v_\beta(x) = (\tilde{\psi}_\beta u) \circ \tilde{\varphi}_\beta^{-1}$ . Clearly  $\pi(v_\beta(x)) = \tilde{\varphi}_\beta^{-1}(x)$ . Therefore

$$\Phi_\beta(v_\beta(x)) = (\pi(v_\beta(x)), \tilde{\rho}_\beta(v_\beta(x))) = (\tilde{\varphi}_\beta^{-1}(x), \tilde{\rho}_\beta(v_\beta(x)))$$

We have

$$\begin{aligned}
& \pi' \circ \Phi_\alpha \circ \Phi_\beta^{-1}(\Phi_\beta(v_\beta(x))) \\
&= \pi' \circ \Phi_\alpha \circ \Phi_\beta^{-1}(\tilde{\varphi}_\beta^{-1}(x), \tilde{\rho}_\beta(v_\beta(x))) \\
&\stackrel{\text{Lemma C.24}}{=} \pi' \circ (\tilde{\varphi}_\beta^{-1}(x), \tau_{\alpha\beta}(\tilde{\varphi}_\beta^{-1}(x))\tilde{\rho}_\beta(v_\beta(x))) \\
&= \underbrace{\tau_{\alpha\beta}(\tilde{\varphi}_\beta^{-1}(x))}_{\text{an } r \times r \text{ matrix}} \tilde{\rho}_\beta(v_\beta(x))
\end{aligned}$$

Let  $A_{\alpha\beta} = \tau_{\alpha\beta} \circ \tilde{\varphi}_\beta^{-1}$ . So we can write

$$\begin{aligned}
& \|\rho_\alpha^l \circ (\psi_\alpha u) \circ \varphi_\alpha^{-1}\|_{W^{e,q}(\varphi_\alpha(U_\alpha))} \\
&\preceq \sum_{\beta=1}^N \|\pi_l \circ A_{\alpha\beta}(x) \tilde{\rho}_\beta(v_\beta(x))\|_{W^{e,q}(\varphi_\beta(\mathcal{U}_\beta))} \\
&= \sum_{\beta=1}^N \left\| \sum_{t=1}^r (A_{\alpha\beta}(x))_{lt} \tilde{\rho}_\beta^t(v_\beta(x)) \right\|_{W^{e,q}(\varphi_\beta(\mathcal{U}_\beta))} \\
&\leq \sum_{\beta=1}^N \sum_{t=1}^r \|(A_{\alpha\beta}(x))_{lt} \tilde{\rho}_\beta^t(v_\beta(x))\|_{W^{e,q}(\varphi_\beta(\mathcal{U}_\beta))}
\end{aligned}$$

Now note that  $(A_{\alpha\beta}(x))_{lt}$  are in  $C^\infty(\varphi_\beta(U_\beta))$  and  $\tilde{\rho}_\beta^t(v_\beta(x))$  has support inside the compact set  $\tilde{\varphi}_\beta(\text{supp } \tilde{\psi}_\beta)$ . Therefore by Theorem E.41 (for the case where  $e$  is not a noninteger less than  $-1$ ) and Corollary E.27 (for the case where  $e$  is a noninteger less than  $-1$ ) we have

$$\sum_{t=1}^r \|(A_{\alpha\beta}(x))_{lt} \tilde{\rho}_\beta^t(v_\beta(x))\|_{W^{e,q}(\varphi_\beta(\mathcal{U}_\beta))} \preceq \sum_{t=1}^r \|\tilde{\rho}_\beta^t(v_\beta(x))\|_{W^{e,q}(\varphi_\beta(\mathcal{U}_\beta))}$$

Therefore

$$\begin{aligned}
& \|\rho_\alpha^l \circ (\psi_\alpha u) \circ \varphi_\alpha^{-1}\|_{W^{e,q}(\varphi_\alpha(U_\alpha))} \\
&\preceq \sum_{\beta=1}^N \sum_{t=1}^r \|\tilde{\rho}_\beta^t(v_\beta(x))\|_{W^{e,q}(\varphi_\beta(\mathcal{U}_\beta))} \\
&= \sum_{\beta=1}^N \sum_{t=1}^r \|\tilde{\rho}_\beta^t \circ (\tilde{\psi}_\beta u) \circ \tilde{\varphi}_\beta^{-1}\|_{W^{e,q}(\varphi_\beta(\mathcal{U}_\beta))}
\end{aligned}$$

□

**Theorem H.7** (Equivalence of norms for distributional sections). *Let  $e \in \mathbb{R}$  and  $q \in (1, \infty)$ . Let  $\Lambda = \{(U_\alpha, \varphi_\alpha, \rho_\alpha, \psi_\alpha)\}_{1 \leq \alpha \leq N}$  and  $\Upsilon = \{(\tilde{U}_\beta, \tilde{\varphi}_\beta, \tilde{\rho}_\beta, \tilde{\psi}_\beta)\}_{1 \leq \beta \leq N}$  be two augmented total trivialization atlases for the vector bundle  $E \rightarrow M$ .*

- (1) *If  $e$  is not a noninteger less than  $-1$ , then  $W^{e,q}(M, E; \Lambda)$  and  $W^{e,q}(M, E; \Upsilon)$  are equivalent normed spaces  $W^{e,q}(M, E)$ .*
- (2) *If  $e$  is a noninteger less than  $-1$ , further assume that the total trivialization atlases corresponding to  $\Lambda$  and  $\Upsilon$  are GLC. Then  $W^{e,q}(M, E; \Lambda)$  and  $W^{e,q}(M, E; \Upsilon)$  are equivalent normed spaces  $W^{e,q}(M, E)$ .*

*Proof.* Let  $u \in D'(M, E)$ . We want to show the following expressions are comparable:

$$\begin{aligned} & \sum_{\alpha=1}^N \sum_{l=1}^r \| [H_\alpha(\psi_\alpha u)]^l \|_{W^{e,q}(\varphi_\alpha(U_\alpha))} \\ & \sum_{\beta=1}^N \sum_{i=1}^r \| [\tilde{H}_\beta(\tilde{\psi}_\beta u)]^i \|_{W^{e,q}(\varphi_\beta(\tilde{U}_\beta))} \end{aligned}$$

To this end it is enough to show that for each  $1 \leq \alpha \leq N$  and  $1 \leq l \leq r$

$$\| [H_\alpha(\psi_\alpha u)]^l \|_{W^{e,q}(\varphi_\alpha(U_\alpha))} \preceq \sum_{\beta=1}^N \sum_{i=1}^r \| [\tilde{H}_\beta(\tilde{\psi}_\beta u)]^i \|_{W^{e,q}(\varphi_\beta(\tilde{U}_\beta))}$$

We have

$$[H_\alpha(\psi_\alpha u)]^l = [H_\alpha(\sum_{\beta=1}^N \tilde{\psi}_\beta \psi_\alpha u)]^l \stackrel{\text{Remark D.26}}{=} \sum_{\beta=1}^N [H_\alpha(\tilde{\psi}_\beta \psi_\alpha u)]^l$$

In what follows we will prove that

$$[H_\alpha(\tilde{\psi}_\beta \psi_\alpha u)]^l = \sum_{i=1}^r ((A_{\alpha\beta})_{il} [\tilde{H}_\beta(\tilde{\psi}_\beta \psi_\alpha u)]^i) \circ \tilde{\varphi}_\beta \circ \varphi_\alpha^{-1} \quad (\text{H.1})$$

for some functions  $(A_{\alpha\beta})_{il}$ , ( $1 \leq i \leq r$ ) in  $C^\infty(\tilde{\varphi}_\beta(\tilde{U}_\beta))$ . For now let's assume the validity of Equation **H.1** to prove the claim.

$$\begin{aligned} \| [H_\alpha(\psi_\alpha u)]^l \|_{W^{e,q}(\varphi_\alpha(U_\alpha))} &= \left\| \sum_{\beta=1}^N [H_\alpha(\tilde{\psi}_\beta \psi_\alpha u)]^l \right\|_{W^{e,q}(\varphi_\alpha(U_\alpha))} \\ &\leq \sum_{\beta=1}^N \| [H_\alpha(\tilde{\psi}_\beta \psi_\alpha u)]^l \|_{W^{e,q}(\varphi_\alpha(U_\alpha))} \\ &\stackrel{\text{Corollary E.44}}{\simeq} \sum_{\beta=1}^N \| [H_\alpha(\tilde{\psi}_\beta \psi_\alpha u)]^l \|_{W^{e,q}(\varphi_\alpha(U_\alpha \cap \tilde{U}_\beta))} \end{aligned}$$

(note that by Remark **D.26**  $[H_\alpha(\tilde{\psi}_\beta \psi_\alpha u)]^l$  has support in the compact set  $\varphi_\alpha(\text{supp } \psi_\alpha \cap \text{supp } \tilde{\psi}_\beta)$ )

$$\begin{aligned} &= \sum_{\beta=1}^N \left\| \sum_{i=1}^r ((A_{\alpha\beta})_{il} [\tilde{H}_\beta(\tilde{\psi}_\beta \psi_\alpha u)]^i) \circ \tilde{\varphi}_\beta \circ \varphi_\alpha^{-1} \right\|_{W^{e,q}(\varphi_\alpha(U_\alpha \cap \tilde{U}_\beta))} \\ &\leq \sum_{\beta=1}^N \sum_{i=1}^r \| ((A_{\alpha\beta})_{il} [\tilde{H}_\beta(\tilde{\psi}_\beta \psi_\alpha u)]^i) \circ \tilde{\varphi}_\beta \circ \varphi_\alpha^{-1} \|_{W^{e,q}(\varphi_\alpha(U_\alpha \cap \tilde{U}_\beta))} \end{aligned}$$

$$\begin{aligned}
& \stackrel{\text{Theorem E.60}}{\preceq} \sum_{\beta=1}^N \sum_{i=1}^r \|(A_{\alpha\beta})_{il} [\tilde{H}_\beta(\tilde{\psi}_\beta \psi_\alpha u)]^i\|_{W^{e,q}(\varphi_\beta(U_\alpha \cap \tilde{U}_\beta))} \\
& = \sum_{\beta=1}^N \sum_{i=1}^r \|(A_{\alpha\beta})_{il} (\psi_\alpha \circ \tilde{\varphi}_\beta^{-1}) [\tilde{H}_\beta(\tilde{\psi}_\beta u)]^i\|_{W^{e,q}(\varphi_\beta(U_\alpha \cap \tilde{U}_\beta))} \\
& \quad \sum_{\beta=1}^N \sum_{i=1}^r \|(A_{\alpha\beta})_{il} (\psi_\alpha \circ \tilde{\varphi}_\beta^{-1}) [\tilde{H}_\beta(\tilde{\psi}_\beta u)]^i\|_{W^{e,q}(\varphi_\beta(\tilde{U}_\beta))} \\
& \text{(Here we used Corollary E.36 and Theorem E.43)} \\
& \preceq \sum_{\beta=1}^N \sum_{i=1}^r \|\tilde{H}_\beta(\tilde{\psi}_\beta u)\|_{W^{e,q}(\varphi_\beta(\tilde{U}_\beta))} \\
& \text{(Here we used Theorem E.41 and Corollary E.27)}
\end{aligned}$$

So it remains to prove Equation H.1. Since  $\text{supp}[H_\alpha(\tilde{\psi}_\beta \psi_\alpha u)]^l$  is inside the compact set  $\varphi_\alpha(\text{supp}\psi_\alpha \cap \text{supp}\tilde{\psi}_\beta) \subseteq \varphi_\alpha(U_\alpha \cap \tilde{U}_\beta)$ , it is enough to consider the action of  $[H_\alpha(\tilde{\psi}_\beta \psi_\alpha u)]^l$  on elements of  $C_c^\infty(\varphi_\alpha(U_\alpha \cap \tilde{U}_\beta))$ .  $\tilde{\varphi}_\beta \circ \varphi_\alpha^{-1} : \varphi_\alpha(U_\alpha \cap \tilde{U}_\beta) \rightarrow \tilde{\varphi}_\beta(U_\alpha \cap \tilde{U}_\beta)$  is a  $C^\infty$ -diffeomorphism. Therefore the map

$$C_c^\infty[\tilde{\varphi}_\beta(U_\alpha \cap \tilde{U}_\beta)] \rightarrow C_c^\infty[\varphi_\alpha(U_\alpha \cap \tilde{U}_\beta)], \quad \eta \mapsto \eta \circ \tilde{\varphi}_\beta \circ \varphi_\alpha^{-1}$$

is bijective. In particular, an arbitrary element of  $C_c^\infty[\varphi_\alpha(U_\alpha \cap \tilde{U}_\beta)]$  has the form  $\eta \circ \tilde{\varphi}_\beta \circ \varphi_\alpha^{-1}$  where  $\eta$  is an element of  $C_c^\infty[\tilde{\varphi}_\beta(U_\alpha \cap \tilde{U}_\beta)]$ .

For all  $\eta \in C_c^\infty[\tilde{\varphi}_\beta(U_\alpha \cap \tilde{U}_\beta)]$  we have (see Section D.2.2)

$$\langle [H_\alpha(\tilde{\psi}_\beta \psi_\alpha u)]^l, \eta \circ \tilde{\varphi}_\beta \circ \varphi_\alpha^{-1} \rangle = \langle \tilde{\psi}_\beta \psi_\alpha u, g_{l, \eta \circ \tilde{\varphi}_\beta \circ \varphi_\alpha^{-1}}^\alpha \rangle \quad (\text{H.2})$$

where  $g_{l, \eta \circ \tilde{\varphi}_\beta \circ \varphi_\alpha^{-1}}^\alpha$  stands for  $g_{l, \eta \circ \tilde{\varphi}_\beta \circ \varphi_\alpha^{-1}, U_\alpha, \varphi_\alpha}$ .

For all  $y \in \varphi_\alpha(U_\alpha \cap \tilde{U}_\beta)$  we have ( $x = \varphi_\alpha^{-1}(y)$ )

$$\begin{aligned}
\rho_\alpha^\vee|_{E_x^\vee} \circ g_{l, \eta \circ \tilde{\varphi}_\beta \circ \varphi_\alpha^{-1}}^\alpha \circ \underbrace{\varphi_\alpha^{-1}(y)}_x &= (0, \dots, 0, \underbrace{\eta \circ \tilde{\varphi}_\beta \circ \varphi_\alpha^{-1}(y)}_{l^{\text{th}} \text{ position}}, 0, \dots, 0) \\
\tilde{\rho}_\beta^\vee \circ \tilde{g}_{l, \eta}^\beta \circ \underbrace{\tilde{\varphi}_\beta^{-1}(\tilde{\varphi}_\beta \circ \varphi_\alpha^{-1}(y))}_x &= (0, \dots, 0, \underbrace{\eta \circ \tilde{\varphi}_\beta \circ \varphi_\alpha^{-1}(y)}_{l^{\text{th}} \text{ position}}, 0, \dots, 0)
\end{aligned}$$

Therefore for all  $y \in \varphi_\alpha(U_\alpha \cap \tilde{U}_\beta)$

$$\rho_\alpha^\vee|_{E_x^\vee} \circ g_{l, \eta \circ \tilde{\varphi}_\beta \circ \varphi_\alpha^{-1}}^\alpha \circ \varphi_\alpha^{-1}(y) = \tilde{\rho}_\beta^\vee \circ \tilde{g}_{l, \eta}^\beta \circ \varphi_\alpha^{-1}(y)$$

which implies that on  $U_\alpha \cap \tilde{U}_\beta$

$$g_{l, \eta \circ \tilde{\varphi}_\beta \circ \varphi_\alpha^{-1}}^\alpha = [\rho_\alpha^\vee|_{E_x^\vee}]^{-1} \circ [\tilde{\rho}_\beta^\vee|_{E_x^\vee}] \circ \tilde{g}_{l, \eta}^\beta \quad (\text{H.3})$$

It follows from Lemma C.24 that for all  $a \in E_x^\vee$

$$[\tilde{\rho}_\beta^\vee|_{E_x^\vee}] \circ [\rho_\alpha^\vee|_{E_x^\vee}]^{-1} \circ [\tilde{\rho}_\beta^\vee|_{E_x^\vee}](a) = \underbrace{\tau^{\beta\alpha}(x)}_{r \times r} (\tilde{\rho}_\beta^\vee|_{E_x^\vee}(a))$$

That is

$$[\rho_\alpha^\vee|_{E_x^\vee}]^{-1} \circ [\tilde{\rho}_\beta^\vee|_{E_x^\vee}](a) = [\tilde{\rho}_\beta^\vee|_{E_x^\vee}]^{-1} [\tau^{\beta\alpha}(x) (\tilde{\rho}_\beta^\vee|_{E_x^\vee}(a))]$$

For  $a = \tilde{g}_{l,\eta}^\beta(x)$  we have

$$\tilde{\rho}_\beta^\vee|_{E_x^\vee}(a) = \tilde{\rho}_\beta^\vee|_{E_x^\vee}(\tilde{g}_{l,\eta}^\beta(x)) = (0, \dots, 0, \underbrace{\eta \circ \tilde{\varphi}_\beta(x)}_{l^{\text{th}} \text{ position}}, 0, \dots, 0)$$

So

$$\begin{aligned} [\rho_\alpha^\vee|_{E_x^\vee}]^{-1} \circ [\tilde{\rho}_\beta^\vee|_{E_x^\vee}] \circ \tilde{g}_{l,\eta}^\beta &= [\tilde{\rho}_\beta^\vee|_{E_x^\vee}]^{-1} [\tau^{\beta\alpha}(x)(\tilde{\rho}_\beta^\vee|_{E_x^\vee}(\tilde{g}_{l,\eta}^\beta(x)))] = [\tilde{\rho}_\beta^\vee|_{E_x^\vee}]^{-1} ((\eta \circ \tilde{\varphi}_\beta) \begin{bmatrix} \tau_{1l}^{\beta\alpha} \\ \vdots \\ \tau_{rl}^{\beta\alpha} \end{bmatrix}) \\ &= [\tilde{\rho}_\beta^\vee|_{E_x^\vee}]^{-1} \left( \begin{bmatrix} (\eta \circ \tilde{\varphi}_\beta) \tau_{1l}^{\beta\alpha} \\ 0 \\ \vdots \\ 0 \end{bmatrix} + \dots + \begin{bmatrix} 0 \\ \vdots \\ 0 \\ (\eta \circ \tilde{\varphi}_\beta) \tau_{rl}^{\beta\alpha} \end{bmatrix} \right) \\ &= \tilde{g}_{1,(\tau_{1l}^{\beta\alpha} \circ \varphi_\beta^{-1})\eta}^\beta + \dots + \tilde{g}_{r,(\tau_{rl}^{\beta\alpha} \circ \varphi_\beta^{-1})\eta}^\beta \end{aligned} \quad (\text{H.4})$$

It follows from (H.2), (H.3), and (H.4) that for all  $\eta \in C_c^\infty[\tilde{\varphi}_\beta(U_\alpha \cap \tilde{U}_\beta)]$

$$\begin{aligned} \langle [H_\alpha(\tilde{\psi}_\beta \psi_\alpha u)]^l, \eta \circ \tilde{\varphi}_\beta \circ \varphi_\alpha^{-1} \rangle &= \langle \tilde{\psi}_\beta \psi_\alpha u, [\rho_\alpha^\vee|_{E_x^\vee}]^{-1} \circ [\tilde{\rho}_\beta^\vee|_{E_x^\vee}] \circ \tilde{g}_{l,\eta}^\beta \rangle \\ &= \langle \tilde{\psi}_\beta \psi_\alpha u, \sum_{i=1}^r \tilde{g}_{i,(\tau_{il}^{\beta\alpha} \circ \varphi_\beta^{-1})\eta}^\beta \rangle \\ &= \sum_{i=1}^r \langle [\tilde{H}_\beta(\tilde{\psi}_\beta \psi_\alpha u)]^i, (\tau_{il}^{\beta\alpha} \circ \tilde{\varphi}_\beta^{-1})\eta \rangle \\ &= \sum_{i=1}^r \langle (\tau_{il}^{\beta\alpha} \circ \tilde{\varphi}_\beta^{-1})[\tilde{H}_\beta(\tilde{\psi}_\beta \psi_\alpha u)]^i, \eta \rangle \\ &= \sum_{i=1}^r \langle (\tau_{il}^{\beta\alpha} \circ \tilde{\varphi}_\beta^{-1})[\tilde{H}_\beta(\tilde{\psi}_\beta \psi_\alpha u)]^i, \eta \circ \tilde{\varphi}_\beta \circ \varphi_\alpha^{-1} \circ (\varphi_\alpha \circ \tilde{\varphi}_\beta^{-1}) \rangle \\ &= \sum_{i=1}^r \left\langle \frac{1}{\det(\varphi_\alpha \circ \tilde{\varphi}_\beta^{-1})} (\tau_{il}^{\beta\alpha} \circ \tilde{\varphi}_\beta^{-1})[\tilde{H}_\beta(\tilde{\psi}_\beta \psi_\alpha u)]^i \circ \tilde{\varphi}_\beta \circ \varphi_\alpha^{-1}, \eta \circ \tilde{\varphi}_\beta \circ \varphi_\alpha^{-1} \right\rangle \end{aligned}$$

For the last equality we used the following identity

$$\left\langle \frac{1}{\det T^{-1}}(u \circ T), \varphi \right\rangle = \langle u, \varphi \circ T^{-1} \rangle$$

Hence

$$[H_\alpha(\tilde{\psi}_\beta \psi_\alpha u)]^l = \sum_{i=1}^r \frac{1}{\det(\varphi_\alpha \circ \tilde{\varphi}_\beta^{-1})} (\tau_{il}^{\beta\alpha} \circ \tilde{\varphi}_\beta^{-1})[\tilde{H}_\beta(\tilde{\psi}_\beta \psi_\alpha u)]^i \circ \tilde{\varphi}_\beta \circ \varphi_\alpha^{-1}$$

and consequently letting

$$(A_{\alpha\beta})_{il} = \frac{1}{\det(\varphi_\alpha \circ \tilde{\varphi}_\beta^{-1})} (\tau_{il}^{\beta\alpha} \circ \tilde{\varphi}_\beta^{-1})$$

leads to (H.1).  $\square$

**Remark H.8.** Note that the above theorems establish the full independence of  $W^{e,q}(M, E; \cdot)$  from  $\Lambda$  at least when  $e$  is not a noninteger less than  $-1$ . So it is justified to write

$W^{e,q}(M, E)$  instead of  $W^{e,q}(M, E; \Lambda)$  at least when  $e$  is not a noninteger less than  $-1$ . Also see Remark H.30.

## H.2. The Properties.

### H.2.1. Multiplication Properties.

**Theorem H.9.** *Let  $M^n$  be a compact manifold and  $E \rightarrow M$  be a vector bundle with rank  $r$ . Let  $\Lambda = \{(U_\alpha, \varphi_\alpha, \rho_\alpha, \psi_\alpha)\}_{1 \leq \alpha \leq N}$  be an augmented total trivialization atlas for  $E$ . Suppose  $e \in \mathbb{R}$ ,  $q \in (1, \infty)$ ,  $\eta \in C^\infty(M)$ . If  $e$  is a noninteger less than  $-1$ , further assume that the total trivialization atlas of  $\Lambda$  is GGL. Then the linear map*

$$m_\eta : W^{e,q}(M, E; \Lambda) \rightarrow W^{e,q}(M, E; \Lambda), \quad u \mapsto \eta u$$

is well defined and bounded.

*Proof.*

$$\begin{aligned} \|\eta u\|_{W^{e,q}(M,E)} &:= \sum_{\alpha=1}^N \sum_{l=1}^r \|(H_\alpha(\psi_\alpha \eta u))^l\|_{W^{e,q}(\varphi_\alpha(U_\alpha))} \\ &\stackrel{\text{Remark D.26}}{=} \sum_{\alpha=1}^N \sum_{l=1}^r \|(\eta \circ \varphi_\alpha^{-1})(H_\alpha(\psi_\alpha u))^l\|_{W^{e,q}(\varphi_\alpha(U_\alpha))} \\ &\lesssim \sum_{\alpha=1}^N \sum_{l=1}^r \|(H_\alpha(\psi_\alpha u))^l\|_{W^{e,q}(\varphi_\alpha(U_\alpha))} = \|u\|_{W^{e,q}(M,E)} \end{aligned}$$

For the case where  $e$  is not a noninteger less than  $-1$ , the last inequality follows from Theorem E.41. If  $e$  is a noninteger less than  $-1$ , then by assumption  $\varphi_\alpha(U_\alpha)$  is either entire  $\mathbb{R}^n$  or is Lipschitz, and the last inequality is due to Theorem E.15 and Corollary E.27.  $\square$

**Theorem H.10.** *Let  $M^n$  be a compact manifold and  $E \rightarrow M$  be a vector bundle with rank  $r$ . Let  $\Lambda$  be an augmented total trivialization atlas for  $E$ . Let  $s_1, s_2, s \in \mathbb{R}$  and  $p_1, p_2, p \in (1, \infty)$ . If any of  $s_1, s_2$ , or  $s$  is a noninteger less than  $-1$ , further assume that the total trivialization atlas in  $\Lambda$  is GL compatible with itself.*

- (1) *If  $s_1, s_2$ , and  $s$  are not nonintegers less than  $-1$ , and if  $W^{s_1,p_1}(\mathbb{R}^n) \times W^{s_2,p_2}(\mathbb{R}^n) \hookrightarrow W^{s,p}(\mathbb{R}^n)$ , then*

$$W^{s_1,p_1}(M; \Lambda) \times W^{s_2,p_2}(M, E; \Lambda) \hookrightarrow W^{s,p}(M, E; \Lambda)$$

- (2) *If  $s_1, s_2$ , and  $s$  are not nonintegers less than  $-1$ , and if  $W^{s_1,p_1}(\Omega) \times W^{s_2,p_2}(\Omega) \hookrightarrow W^{s,p}(\Omega)$ , for any open ball  $\Omega$ , then*

$$W^{s_1,p_1}(M; \Lambda) \times W^{s_2,p_2}(M, E; \Lambda) \hookrightarrow W^{s,p}(M, E; \Lambda)$$

- (3) *If any of  $s_1, s_2$ , or  $s$  is a noninteger less than  $-1$ , and if  $W^{s_1,p_1}(\Omega) \times W^{s_2,p_2}(\Omega) \hookrightarrow W^{s,p}(\Omega)$  for  $\Omega = \mathbb{R}^n$  **and** for any bounded open set  $\Omega$  with Lipschitz continuous boundary, then*

$$W^{s_1,p_1}(M; \Lambda) \times W^{s_2,p_2}(M, E; \Lambda) \hookrightarrow W^{s,p}(M, E; \Lambda)$$

*Proof.* (1) Let  $\Lambda_1 = \{(U_\alpha, \varphi_\alpha, \rho_\alpha, \psi_\alpha)\}_{1 \leq \alpha \leq N}$  be any augmented total trivialization atlas which is super nice. Let  $\Lambda_2 = \{(U_\alpha, \varphi_\alpha, \rho_\alpha, \tilde{\psi}_\alpha)\}_{1 \leq \alpha \leq N}$  where for each

$1 \leq \alpha \leq N$ ,  $\tilde{\psi}_\alpha = \frac{\psi_\alpha^2}{\sum_{\beta=1}^N \psi_\beta^2}$ . Note that  $\frac{1}{\sum_{\beta=1}^N \psi_\beta^2} \circ \varphi_\alpha^{-1} \in BC^\infty(\varphi_\alpha(U_\alpha))$ . For  $f \in W^{s_1, p_1}(M; \Lambda)$  and  $u \in W^{s_2, p_2}(M, E; \Lambda)$  we have

$$\begin{aligned} \|fu\|_{W^{s,p}(M,E;\Lambda)} &\simeq \|fu\|_{W^{s,p}(M,E;\Lambda_2)} = \sum_{\alpha=1}^N \sum_{j=1}^r \|[H_\alpha(\tilde{\psi}_\alpha(fu))]^j\|_{W^{s,p}(\varphi_\alpha(U_\alpha))} \\ &\leq \sum_{\alpha=1}^N \sum_{j=1}^r \|((\psi_\alpha f) \circ \varphi_\alpha^{-1})[H_\alpha(\psi_\alpha u)]^j\|_{W^{s,p}(\varphi_\alpha(U_\alpha))} \\ &\leq \left( \sum_{\alpha=1}^N \|(\psi_\alpha f) \circ \varphi_\alpha^{-1}\|_{W^{s_1, p_1}(\varphi_\alpha(U_\alpha))} \right) \left( \sum_{\alpha=1}^N \sum_{j=1}^r \|[H_\alpha(\psi_\alpha u)]^j\|_{W^{s_2, p_2}(\varphi_\alpha(U_\alpha))} \right) \\ &= \|f\|_{W^{s_1, p_1}(M; \Lambda_1)} \|u\|_{W^{s_2, p_2}(M, E; \Lambda_1)} \simeq \|f\|_{W^{s_1, p_1}(M; \Lambda)} \|u\|_{W^{s_2, p_2}(M, E; \Lambda)} \end{aligned}$$

- (2) We can use the exact same argument as item 1. Just choose  $\Lambda_1$  to be "nice" instead of "super nice".
- (3) The exact same argument as item 1. works. Just choose  $\Lambda_1 = \Lambda$ . (The equality  $\|fu\|_{W^{s,p}(M,E;\Lambda)} \simeq \|fu\|_{W^{s,p}(M,E;\Lambda_2)}$  holds due to the assumption that  $\Lambda = \Lambda_1$  is GL compatible with itself.) □

**Remark H.11.** Suppose  $e$  is a noninteger less than  $-1$  and  $q \in (1, \infty)$ . We will prove that if  $\Lambda$  and  $\tilde{\Lambda}$  are two augmented total trivialization atlases and each of  $\Lambda$  and  $\tilde{\Lambda}$  is GL compatible with itself, then  $W^{e,q}(M, E; \Lambda) = W^{e,q}(M, E; \tilde{\Lambda})$  (see Remark H.30). Considering this and the fact that we can choose  $\Lambda_1$  to be super nice (or nice) and GL compatible with itself (see Theorem C.16 and Corollary C.17), we can remove the assumption "s<sub>1</sub>, s<sub>2</sub>, and s are not nonintegers less than  $-1$ " from part 1 and part 2 of the preceding theorem.

### H.2.2. Embedding Properties.

**Theorem H.12.** Let  $M^n$  be a compact smooth manifold. Let  $\pi : E \rightarrow M$  be a smooth vector bundle of rank  $r$  over  $M$ . Let  $\Lambda$  be an augmented total trivialization atlas for  $E$ . Let  $e_1, e_2 \in \mathbb{R}$  and  $q_1, q_2 \in (1, \infty)$ . If any of  $e_1$  or  $e_2$  is a noninteger less than  $-1$ , further assume that the total trivialization atlas in  $\Lambda$  is GGL.

- (1) If  $e_1$  and  $e_2$  are not nonintegers less than  $-1$  and if  $W^{e_1, q_1}(\mathbb{R}^n) \hookrightarrow W^{e_2, q_2}(\mathbb{R}^n)$ , then  $W^{e_1, q_1}(M, E; \Lambda) \hookrightarrow W^{e_2, q_2}(M, E; \Lambda)$ .
- (2) If  $e_1$  and  $e_2$  are not nonintegers less than  $-1$  and if  $W^{e_1, q_1}(\Omega) \hookrightarrow W^{e_2, q_2}(\Omega)$  for all open balls  $\Omega \subseteq \mathbb{R}^n$ , then  $W^{e_1, q_1}(M, E; \Lambda) \hookrightarrow W^{e_2, q_2}(M, E; \Lambda)$ .
- (3) If any of  $e_1$  or  $e_2$  is a noninteger less than  $-1$  and if  $W^{e_1, q_1}(\Omega) \hookrightarrow W^{e_2, q_2}(\Omega)$  for  $\Omega = \mathbb{R}^n$  and for any bounded domain  $\Omega \subseteq \mathbb{R}^n$  with Lipschitz continuous boundary, then  $W^{e_1, q_1}(M, E; \Lambda) \hookrightarrow W^{e_2, q_2}(M, E; \Lambda)$ .

*Proof.* (1) Let  $\Lambda_1 = \{(U_\alpha, \varphi_\alpha, \rho_\alpha, \psi_\alpha)\}_{1 \leq \alpha \leq N}$  be any augmented total trivialization atlas for  $E$  which is super nice. We have

$$\begin{aligned} \|u\|_{W^{e_2, q_2}(M, E;)} &\simeq \|u\|_{W^{e_2, q_2}(M, E; \_1)} = \sum_{\alpha=1}^N \sum_{l=1}^r \| [H_\alpha(\psi_\alpha u)]^l \|_{W^{e_2, q_2}(\varphi_\alpha(U_\alpha))} \\ &\lesssim \sum_{\alpha=1}^N \sum_{l=1}^r \| [H_\alpha(\psi_\alpha u)]^l \|_{W^{e_1, q_1}(\varphi_\alpha(U_\alpha))} \\ &= \|u\|_{W^{e_1, q_1}(M, E; \_1)} \simeq \|u\|_{W^{e_1, q_1}(M, E;)} \end{aligned}$$

(2) We can use the exact same argument as item 1. Just choose  $\Lambda_1$  to be "nice" instead of "super nice".

(3) The exact same argument as item 1. works. Just choose  $\Lambda_1 = \Lambda$ . □

**Remark H.13.** *If we further assume that  $\Lambda$  is GL compatible with itself, then we can remove the assumption "e<sub>1</sub> and e<sub>2</sub> are not nonintegers less than -1" from part 1 and part 2 of the preceding theorem. (See the explanation in Remark H.11.)*

**Theorem H.14.** *Let  $M^n$  be a compact smooth manifold. Let  $\pi : E \rightarrow M$  be a smooth vector bundle of rank  $r$  over  $M$  equipped with fiber metric  $\langle \cdot, \cdot \rangle_E$  (so it is meaningful to talk about  $L^\infty(M, E)$ ). Suppose  $s \in \mathbb{R}$  and  $p \in (1, \infty)$  are such that  $sp > n$ . Then  $W^{s,p}(M, E) \hookrightarrow L^\infty(M, E)$ . Moreover every element  $u$  in  $W^{s,p}(M, E)$  has a continuous version. (Note that since  $s$  is not a noninteger less than -1, the choice of the augmented total trivialization atlas is immaterial.)*

*Proof.* Let  $\{(U_\alpha, \varphi_\alpha, \rho_\alpha)\}_{1 \leq \alpha \leq N}$  be a nice total trivialization atlas for  $E \rightarrow M$  that trivializes the fiber metric. Let  $\{\psi_\alpha\}_{1 \leq \alpha \leq N}$  be a partition of unity subordinate to  $\{U_\alpha\}$ . We need to show that for every  $u \in W^{s,p}(M, E)$

$$|u|_{L^\infty(M, E)} \preceq \|u\|_{W^{s,p}(M, E)}$$

Note that since  $s > 0$ ,  $W^{s,p}(M, E) \hookrightarrow L^p(M, E)$  and we can treat  $u$  as an ordinary section of  $E$ . We prove the above inequality in two steps:

• **Step 1:** Suppose there exists  $1 \leq \beta \leq N$  such that  $\text{supp } u \subseteq U_\beta$ . We have

$$\begin{aligned} |u|_{L^\infty(M, E)} &= \sup_{x \in M} |u|_E = \sup_{x \in U_\beta} |u|_E \\ &= \sup_{y \in \varphi_\beta(U_\beta)} \sqrt{\sum_{l=1}^r |\rho_\beta^l \circ u \circ \varphi_\beta^{-1}|^2} \quad (\text{by assumption the triples trivialize the metric}) \\ &\leq \sup_{y \in \varphi_\beta(U_\beta)} \sum_{l=1}^r |\rho_\beta^l \circ u \circ \varphi_\beta^{-1}| = \sum_{l=1}^r \sup_{y \in \varphi_\beta(U_\beta)} |\rho_\beta^l \circ u \circ \varphi_\beta^{-1}| \\ &= \sum_{l=1}^r \| \rho_\beta^l \circ u \circ \varphi_\beta^{-1} \|_{L^\infty(\varphi_\beta(U_\beta))} \\ &\preceq \sum_{l=1}^r \| \rho_\beta^l \circ u \circ \varphi_\beta^{-1} \|_{W^{s,p}(\varphi_\beta(U_\beta))} \quad (sp > n \text{ so } W^{s,p}(\varphi_\beta(U_\beta)) \hookrightarrow L^\infty(\varphi_\beta(U_\beta))) \end{aligned}$$



• **Step 2:** Now suppose  $u$  is an arbitrary element of  $W^{s,p}(M, E)$ . We have

$$\begin{aligned} \|u\|_{L^\infty(M,E)} &= \left\| \sum_{\alpha=1}^N \psi_\alpha u \right\|_{L^\infty(M,E)} \leq \sum_{\alpha=1}^N \|\psi_\alpha u\|_{L^\infty(M,E)} \\ &\stackrel{\text{Step 1}}{\leq} \sum_{\alpha=1}^N \sum_{l=1}^r \|\rho_\alpha^l \circ \psi_\alpha u \circ \varphi_\alpha^{-1}\|_{W^{s,p}(\varphi_\alpha(U_\alpha))} \simeq \|u\|_{W^{s,p}(M,E)} \end{aligned}$$

Next we prove that every element  $u$  of  $W^{s,p}(M, E)$  has a continuous version. Note that for all  $x \in U_\alpha$

$$\psi_\alpha u(x) = \Phi_\alpha^{-1}(x, \rho_\alpha^1 \circ \psi_\alpha u, \dots, \rho_\alpha^r \circ \psi_\alpha u)$$

Also for all  $1 \leq l \leq r$  and  $1 \leq \alpha \leq N$  we have

$$\rho_\alpha^l \circ \psi_\alpha u \circ \varphi_\alpha^{-1} \in W^{s,p}(\varphi_\alpha(U_\alpha))$$

Therefore  $\rho_\alpha^l \circ \psi_\alpha u \circ \varphi_\alpha^{-1}$  has a continuous version which we denote by  $v_\alpha^l$ . Suppose  $A_\alpha^l$  is the set of measure zero on which  $v_\alpha^l \neq \rho_\alpha^l \circ \psi_\alpha u \circ \varphi_\alpha^{-1}$ . Let  $A_\alpha = \cup_{1 \leq l \leq r} A_\alpha^l$ . Clearly  $A_\alpha$  is a set of measure zero. Since  $\varphi_\alpha : U_\alpha \rightarrow \varphi_\alpha(U_\alpha)$  is a diffeomorphism,  $B_\alpha := \varphi_\alpha^{-1}(A_\alpha)$  is a set of measure zero in  $U_\alpha$ . (In general, if  $M$  and  $N$  are smooth  $n$ -manifolds,  $F : M \rightarrow N$  is a smooth map, and  $A \subseteq M$  is a subset of measure zero, then  $F(A)$  has measure zero in  $N$ . See Page 128 in [33].)

Clearly

$$(x, v_\alpha^1 \circ \varphi_\alpha, \dots, v_\alpha^r \circ \varphi_\alpha) = (x, \rho_\alpha^1 \circ \psi_\alpha u, \dots, \rho_\alpha^r \circ \psi_\alpha u)$$

on  $U_\alpha \setminus B_\alpha$ . So

$$w_\alpha := \Phi_\alpha^{-1}(x, v_\alpha^1 \circ \varphi_\alpha, \dots, v_\alpha^r \circ \varphi_\alpha) = \Phi_\alpha^{-1}(x, \rho_\alpha^1 \circ \psi_\alpha u, \dots, \rho_\alpha^r \circ \psi_\alpha u) = \psi_\alpha u$$

on  $U_\alpha \setminus B_\alpha$ . Note that  $w_\alpha : U_\alpha \rightarrow E$  is a composition of continuous functions and so it is continuous on  $U_\alpha$ . Let  $\xi_\alpha \in C_c^\infty(U_\alpha)$  be such that  $\xi_\alpha = 1$  on  $\text{supp} \psi_\alpha$ . So  $\xi_\alpha w_\alpha = \psi_\alpha u$  on  $M \setminus B_\alpha$ . Consequently if we let  $w = \sum_{\alpha=1}^N \xi_\alpha w_\alpha$ , then  $w$  is a continuous function that agrees with  $u = \sum_{\alpha=1}^N \psi_\alpha u$  on  $M \setminus B$  where  $B = \cup_{1 \leq \alpha \leq N} B_\alpha$ .  $\square$

**H.2.3. Observations Concerning the Local Representation of Sobolev Functions.** Let  $M^n$  be a compact smooth manifold. Let  $E \rightarrow M$  be a smooth vector bundle of rank  $r$  over  $M$ . As it was discussed in Appendix D, Given a total trivialization triple  $(U_\alpha, \varphi_\alpha, \rho_\alpha)$ , we can associate with every  $u \in D'(M, E)$  and every  $f \in \Gamma(M, E)$ , a local representation with respect to  $(U_\alpha, \varphi_\alpha, \rho_\alpha)$ :

$$\begin{aligned} u &\mapsto (\tilde{u}^1, \dots, \tilde{u}^r) \in [D'(\varphi_\alpha(U_\alpha))]^{\times r}, & \tilde{u}^l &= [H_\alpha(u|_{U_\alpha})]^l \\ f &\mapsto (\tilde{f}^1, \dots, \tilde{f}^r) \in [\text{Func}(\varphi_\alpha(U_\alpha), \mathbb{R})]^{\times r}, & \tilde{f}^l &= \rho_\alpha^l \circ (f|_{U_\alpha}) \circ \varphi_\alpha^{-1} \end{aligned}$$

and of course as it was pointed out in Remark D.27, the two representations agree when  $u$  is a regular distribution. The goal of this section is to list some useful facts about the local representations of elements of Sobolev spaces. In what follows, when there is no possibility of confusion, we may write  $H_\alpha(u)$  instead of  $H_\alpha(u|_{U_\alpha})$ , or  $\rho_\alpha^l \circ f \circ \varphi_\alpha^{-1}$  instead of  $\rho_\alpha^l \circ (f|_{U_\alpha}) \circ \varphi_\alpha^{-1}$ .

**Theorem H.15.** *Let  $M^n$  be a compact smooth manifold and  $E \rightarrow M$  be a vector bundle of rank  $r$ . Suppose  $\{(U_\alpha, \varphi_\alpha, \rho_\alpha, \psi_\alpha)\}_{\alpha=1}^N$  is an augmented total trivialization atlas for  $E \rightarrow M$ . Let  $u \in D'(M, E)$ ,  $e \in \mathbb{R}$ , and  $q \in (1, \infty)$ . If for all  $1 \leq \alpha \leq N$  and  $1 \leq j \leq r$ ,  $[H_\alpha(u)]^j \in W_{loc}^{e,q}(\varphi_\alpha(U_\alpha))$ , then  $u \in W^{e,q}(M, E; \Lambda)$ .*

*Proof.*

$$\begin{aligned} \|u\|_{W^{e,q}(M,E)} &= \sum_{\alpha=1}^N \sum_{j=1}^r \| [H_\alpha(\psi_\alpha u)]^j \|_{W^{e,q}(\varphi_\alpha(U_\alpha))} \\ &= \sum_{\alpha=1}^N \sum_{j=1}^r \| (\psi_\alpha \circ \varphi_\alpha^{-1}) \cdot ([H_\alpha(u)]^j) \|_{W^{e,q}(\varphi_\alpha(U_\alpha))} \end{aligned}$$

Now note that  $\psi_\alpha \circ \varphi_\alpha^{-1} : \varphi_\alpha(U_\alpha) \rightarrow \mathbb{R}$  is smooth with compact support (its support is in the compact set  $\varphi_\alpha(\text{supp } \psi_\alpha)$ ). Therefore it follows from the assumption that each term on the right hand side of the above equality is finite.  $\square$

**Remark H.16.** *Note that, as opposed to what is claimed in some references, it is NOT true in general that if  $u \in W^{e,q}(M, E; \Lambda)$ , then the components of the local representations of  $u$  will be in the corresponding Euclidean Sobolev space; that is  $u \in W^{e,q}(M, E; \Lambda)$  does not imply that for all  $1 \leq \alpha \leq N$  and  $1 \leq j \leq r$ ,  $[H_\alpha(u)]^j \in W^{e,q}(\varphi_\alpha(U_\alpha))$ . Consider the following example:*

$M = S^1$ ,  $e = 0$ ,  $q = 1$ , and  $f : M \rightarrow \mathbb{R}$  defined by  $f \equiv 1$ . Clearly  $f \in W^{0,1}(M) = L^1(S^1)$ . Now consider the atlas  $\mathcal{A} = \{(U_1, \varphi_1), (U_2, \varphi_2)\}$  where

$$\begin{aligned} U_1 &= S^1 \setminus \{(0, 1)\}, & \varphi_1(x, y) &= \frac{x}{1-y} \\ U_2 &= S^1 \setminus \{(0, -1)\}, & \varphi_2(x, y) &= \frac{x}{1+y} \quad (\text{stereographic projection}) \end{aligned}$$

Clearly  $f \circ \varphi_1^{-1} = f \circ \varphi_2^{-1} = 1$  and  $\varphi_1(U_1) = \varphi_2(U_2) = \mathbb{R}$ . So  $f \circ \varphi_1^{-1}$  and  $f \circ \varphi_2^{-1}$  do not belong to  $L^1(\varphi_1(U_1))$  or  $L^1(\varphi_2(U_2))$ .

However, the following theorem holds true.

**Theorem H.17.** *Let  $M^n$  be a compact smooth manifold and  $E \rightarrow M$  be a vector bundle of rank  $r$ . Let  $e \in \mathbb{R}$  and  $q \in (1, \infty)$ . Suppose  $\Lambda = \{(U_\alpha, \varphi_\alpha, \rho_\alpha, \psi_\alpha)\}_{\alpha=1}^N$  is an augmented total trivialization atlas for  $E \rightarrow M$ . If  $e$  is a noninteger less than  $-1$  further assume that  $\Lambda$  is GL compatible with itself. Let  $u \in W^{e,q}(M, E; \Lambda)$  be such that  $\text{supp } u \subseteq V \subseteq \bar{V} \subseteq U_\beta$  for some open set  $V$  and some  $1 \leq \beta \leq N$ . Then for all  $1 \leq i \leq r$ ,  $[H_\beta(u)]^i \in W^{e,q}(\varphi_\beta(U_\beta))$ . Indeed,*

$$\| [H_\beta(u)]^i \|_{W^{e,q}(\varphi_\beta(U_\beta))} \leq \| u \|_{W^{e,q}(M,E)}$$

*Proof.* Let  $\Lambda_1 = \{(U_\alpha, \varphi_\alpha, \rho_\alpha, \tilde{\psi}_\alpha)\}_{\alpha=1}^N$  where  $\{\tilde{\psi}_\alpha\}_{1 \leq \alpha \leq N}$  is a partition of unity subordinate to the cover  $\{U_\alpha\}_{1 \leq \alpha \leq N}$  such that  $\tilde{\psi}_\beta = 1$  on a neighborhood of  $\bar{V}$  (see Lemma C.11). We have

$$\begin{aligned} \| [H_\beta(u)]^i \|_{W^{e,q}(\varphi_\beta(U_\beta))} &= \| [H_\beta(\tilde{\psi}_\beta u)]^i \|_{W^{e,q}(\varphi_\beta(U_\beta))} \\ &\leq \sum_{\alpha=1}^N \sum_{j=1}^r \| [H_\alpha(\tilde{\psi}_\alpha u)]^j \|_{W^{e,q}(\varphi_\alpha(U_\alpha))} \\ &= \| u \|_{W^{e,q}(M,E)} \simeq \| u \|_{W^{e,q}(M,E)} \end{aligned}$$

$\square$

**Corollary H.18.** *Let  $M^n$  be a compact smooth manifold and  $E \rightarrow M$  be a vector bundle of rank  $r$ . Let  $e \in \mathbb{R}$  and  $q \in (1, \infty)$ . Suppose  $\Lambda = \{(U_\alpha, \varphi_\alpha, \rho_\alpha, \psi_\alpha)\}_{\alpha=1}^N$  is an augmented total trivialization atlas for  $E \rightarrow M$ . If  $e$  is a noninteger less than  $-1$  further assume that  $\Lambda$  is GL compatible with itself. If  $u \in W^{e,q}(M, E; \Lambda)$ , then for all*

$1 \leq \alpha \leq N$  and  $1 \leq i \leq r$ ,  $[H_\alpha(u)]^i$  (i.e. each component of the local representation of  $u$  with respect to  $(U_\alpha, \varphi_\alpha, \rho_\alpha)$ ) belongs to  $W_{loc}^{e,q}(\varphi_\alpha(U_\alpha))$ . Moreover, if  $\xi \in C_c^\infty(\varphi_\alpha(U_\alpha))$ , then

$$\|\xi[H_\alpha(u)]^i\|_{W^{e,q}(\varphi_\alpha(U_\alpha))} \preceq \|u\|_{W^{e,q}(M,E)}$$

where the implicit constant may depend on  $\xi$ .

*Proof.* Define  $G : M \rightarrow \mathbb{R}$  by

$$G(p) = \begin{cases} \xi \circ \varphi_\alpha & \text{if } p \in U_\alpha \\ 0 & \text{if } p \notin U_\alpha \end{cases}$$

Clearly  $G \in C^\infty(M)$ . So, by Theorem H.9,  $Gu \in W^{e,q}(M, E; \Lambda)$ . Also since  $\xi \in C_c^\infty(\varphi_\alpha(U_\alpha))$ , there exists a compact set  $K$  such that

$$\text{supp } \xi \subseteq \overset{\circ}{K} \subseteq K \subseteq \varphi_\alpha(U_\alpha)$$

Consequently there exists an open set  $V_\alpha$  (e.g.  $V_\alpha = \varphi_\alpha^{-1}(\overset{\circ}{K})$ ) such that

$$\text{supp}(Gu) \subseteq \text{supp}(\xi \circ \varphi_\alpha) \subseteq V_\alpha \subseteq \bar{V}_\alpha \subseteq U_\alpha$$

So by Theorem H.17,  $[H_\alpha(Gu)]^i \in W^{e,q}(\varphi_\alpha(U_\alpha))$  and

$$\|[H_\alpha(Gu)]^i\|_{W^{e,q}(\varphi_\alpha(U_\alpha))} \preceq \|Gu\|_{W^{e,q}(M,E)} \preceq \|u\|_{W^{e,q}(M,E)}$$

Now we just need to notice that on  $\varphi_\alpha(U_\alpha)$ ,

$$[H_\alpha(Gu)]^i = (G \circ \varphi_\alpha^{-1})[H_\alpha(u)]^i = \xi[H_\alpha(u)]^i$$

□

**H.2.4. Observations Concerning the Riemannian Metric.** The sobolev spaces that appear in this section all have nonnegative smoothness exponents; therefore the choice of the augmented total trivialization atlas is immaterial and will not appear in the notation.

**Corollary H.19.** *Let  $(M, g)$  be a compact Riemannian manifold with  $g \in W^{s,p}(T^2M)$ ,  $sp > n$ . Let  $\{(U_\alpha, \varphi_\alpha, \rho_\alpha)\}_{1 \leq \alpha \leq N}$  be a standard total trivialization atlas for  $T^2M \rightarrow M$ . Fix some  $\alpha$  and denote the components of the metric with respect to  $(U_\alpha, \varphi_\alpha, \rho_\alpha)$  by  $g_{ij} : U_\alpha \rightarrow \mathbb{R}$  ( $g_{ij} = \rho_\alpha^{ij} \circ g$ ). As an immediate consequence of Corollary H.18 we have*

$$g_{ij} \circ \varphi_\alpha^{-1} \in W_{loc}^{s,p}(\varphi_\alpha(U_\alpha))$$

**Theorem H.20.** *Let  $(M, g)$  be a compact Riemannian manifold with  $g \in W^{s,p}(T^2M)$ ,  $sp > n$ ,  $s \geq 1$ . Let  $\{(U_\alpha, \varphi_\alpha, \rho_\alpha)\}_{1 \leq \alpha \leq N}$  be a GGL standard total trivialization atlas for  $T^2M \rightarrow M$ . Fix some  $\alpha$  and denote the components of the metric with respect to  $(U_\alpha, \varphi_\alpha, \rho_\alpha)$  by  $g_{ij} : U_\alpha \rightarrow \mathbb{R}$  ( $g_{ij} = \rho_\alpha^{ij} \circ g$ ). Then*

- (1)  $\det g_\alpha \in W_{loc}^{s,p}(\varphi_\alpha(U_\alpha))$  where  $g_\alpha(x)$  is the matrix whose  $(i, j)$ -entry is  $g_{ij} \circ \varphi_\alpha^{-1}$ .
- (2)  $\sqrt{\det g} \circ \varphi_\alpha^{-1} = \sqrt{\det g_\alpha} \in W_{loc}^{s,p}(\varphi_\alpha(U_\alpha))$ .
- (3)  $\frac{1}{\sqrt{\det g \circ \varphi_\alpha^{-1}}} \in W_{loc}^{s,p}(\varphi_\alpha(U_\alpha))$ .

*Proof.*

- (1) By Corollary H.18,  $g_{ij} \circ \varphi_\alpha^{-1}$  is in  $W_{loc}^{s,p}(\varphi_\alpha(U_\alpha))$ . So it follows from Lemma F.12 that  $\det g_\alpha \in W_{loc}^{s,p}(\varphi_\alpha(U_\alpha))$ .
- (2) This is a direct consequence of item 1 and Theorem F.13.
- (3) This is a direct consequence of item 1 and Theorem F.13.

□

**Theorem H.21.** *Let  $(M, g)$  be a compact Riemannian manifold with  $g \in W^{s,p}(T^2M)$ ,  $sp > n$ ,  $s \geq 1$ . Then the inverse metric tensor  $g^{-1}$  (which is a  $\binom{0}{2}$  tensor field) is in  $W^{s,p}(T_2M)$ .*

*Proof.* Let  $\{(U_\alpha, \varphi_\alpha, \rho_\alpha)\}_{1 \leq \alpha \leq N}$  be a GGL standard total trivialization atlas for  $T^2M \rightarrow M$ . Let  $\{\psi_\alpha\}_{1 \leq \alpha \leq N}$  be a partition of unity subordinate to  $\{U_\alpha\}_{1 \leq \alpha \leq N}$ . We have

$$\|g^{-1}\|_{W^{s,p}(T_2M)} = \sum_{\alpha=1}^N \sum_{i,j} \|\psi_\alpha g^{ij} \circ \varphi_\alpha^{-1}\|_{W^{s,p}(\varphi_\alpha(U_\alpha))}$$

So it is enough to show that for all  $i, j$  and  $\alpha$ ,  $g^{ij} \circ \varphi_\alpha^{-1}$  is in  $W_{loc}^{s,p}(\varphi_\alpha(U_\alpha))$ . Let  $B = (B_{ij})$  where  $B_{ij} = g_{ij} \circ \varphi_\alpha^{-1}$ . By assumption  $g \in W^{s,p}(T^2M)$ ; so it follows from Corollary H.18 that  $B_{ij} \in W_{loc}^{s,p}(\varphi_\alpha(U_\alpha))$ . Our goal is to show that the entries of the inverse of  $B$  are in  $W_{loc}^{s,p}(\varphi_\alpha(U_\alpha))$ . Recall that

$$(B^{-1})_{ij} = \frac{(-1)^{i+j}}{\det B} M_{ij}$$

where  $M_{ij}$  is the determinant of the  $(n-1) \times (n-1)$  matrix formed by removing the  $j^{\text{th}}$  row and  $i^{\text{th}}$  column of  $B$ . Since the entries of  $B$  are in  $W_{loc}^{s,p}(\varphi_\alpha(U_\alpha))$ , it follows from Lemma F.12 that  $\det B$  and  $M_{ij}$  are in  $W_{loc}^{s,p}(\varphi_\alpha(U_\alpha))$ . Also  $sp > n$ , so  $W_{loc}^{s,p}(\varphi_\alpha(U_\alpha))$  is closed under multiplication. Consequently  $(B^{-1})_{ij}$  is in  $W_{loc}^{s,p}(\varphi_\alpha(U_\alpha))$ .  $\square$

**Corollary H.22.** *Let  $(M, g)$  be a compact Riemannian manifold with  $g \in W^{s,p}(T^2M)$ ,  $sp > n$ ,  $s \geq 1$ .  $\{(U_\alpha, \varphi_\alpha)\}_{1 \leq \alpha \leq N}$  be a GGL smooth atlas for  $M$ . Denote the standard components of the inverse metric with respect to this chart by  $g^{ij} : U_\alpha \rightarrow \mathbb{R}$ . As an immediate consequence of Theorem H.21 and Corollary H.18 we have*

$$g^{ij} \circ \varphi_\alpha^{-1} \in W_{loc}^{s,p}(\varphi_\alpha(U_\alpha))$$

Also since

$$\Gamma_{ij}^k \circ \varphi_\alpha^{-1} = \frac{1}{2} g^{kl} (\partial_i g_{jl} + \partial_j g_{il} - \partial_l g_{ij}) \circ \varphi_\alpha^{-1}$$

it follows from Corollary H.19, Lemma F.9, Theorem F.6, and the fact that  $W^{s,p}(\varphi_\alpha(U_\alpha)) \times W^{s-1,p}(\varphi_\alpha(U_\alpha)) \hookrightarrow W^{s-1,p}(\varphi_\alpha(U_\alpha))$  that

$$\Gamma_{ij}^k \circ \varphi_\alpha^{-1} \in W_{loc}^{s-1,p}(\varphi_\alpha(U_\alpha))$$

**H.2.5. A Useful Isomorphism.** Let  $M^n$  be a compact smooth manifold and  $E \rightarrow M$  be a vector bundle of rank  $r$ . Let  $e \in \mathbb{R}$  and  $q \in (1, \infty)$ . Suppose  $\Lambda = \{(U_\alpha, \varphi_\alpha, \rho_\alpha, \psi_\alpha)\}_{\alpha=1}^N$  is an augmented total trivialization atlas for  $E \rightarrow M$ . Given a closed subset  $A \subseteq M$ ,  $W_A^{e,q}(M, E; \Lambda)$  is defined to be the subspace of  $W^{e,q}(M, E; \Lambda)$  consisting of  $u \in W^{e,q}(M, E; \Lambda)$  with  $\text{supp } u \subseteq A$ . Fix  $1 \leq \beta \leq N$  and suppose  $K \subseteq U_\beta$  is compact. Then each element of  $W_K^{e,q}(M, E; \Lambda)$  can be identified with an element of  $D'(U_\beta, E_{U_\beta})$  under the injective map  $u \in W_K^{e,q}(M, E; \Lambda) \subseteq D'(M, E) \mapsto u|_U \in D'(U_\beta, E_{U_\beta})$ . So we can restrict the domain of  $H_\beta : [D(U_\beta, E_{U_\beta}^\vee)]^* \rightarrow (D'(\varphi_\beta(U_\beta)))^{\times r}$  to  $W_K^{e,q}(M, E; \Lambda)$  which associates with each element  $u \in W_K^{e,q}(M, E; \Lambda)$ , the  $r$  components of  $H_\beta(u) = (\tilde{u}_\beta^1, \dots, \tilde{u}_\beta^r)$ . (Here  $H_\beta$  stands for  $H_{E^\vee, U_\beta, \varphi_\beta}$ .)

**Lemma H.23.** *Consider the above setting and further assume that if  $e$  is a noninteger less than  $-1$ , then the total trivialization atlas in  $\Lambda$  is GL compatible with itself. Then the*

linear topological isomorphism  $H_\beta : [D(U_\beta, E_{U_\beta}^\vee)]^* = D'(U_\beta, E_{U_\beta}) \rightarrow (D'(\varphi_\beta(U_\beta)))^{\times r}$  restricts to a linear topological isomorphism

$$\hat{H}_\beta : W_{K'}^{e,q}(M, E; \Lambda) \rightarrow [W_{\varphi_\beta(K)}^{e,q}(\varphi_\beta(U_\beta))]^{\times r}$$

*Proof.* In order to simplify the notations we will use  $(U, \varphi, \rho)$ ,  $H$ ,  $\hat{H}$ , and  $\tilde{u}^l$  instead of  $(U_\beta, \varphi_\beta, \rho_\beta)$ ,  $H_\beta$ ,  $\hat{H}_\beta$ , and  $\tilde{u}_\beta^l$ . In order to prove this claim, we proceed as follows:

- (1) First we show that  $\text{supp } \tilde{u}^l \subseteq \varphi(K)$ .
- (2) Next we show that if  $u \in W_{K'}^{e,q}(M, E; \Lambda)$ , then  $\|u\|_{W^{e,q}(M,E;\Lambda)} \simeq \sum_{l=1}^r \|\tilde{u}^l\|_{W^{e,q}(\varphi(U))}$  which proves that
  - (i.)  $\tilde{u}^l$  is indeed an element of  $W^{e,q}(\varphi(U))$  and
  - (ii.)  $\hat{H}$  is continuous.
 Note that (i) together with the fact that  $\text{supp } \tilde{u}^l \subseteq \varphi(K)$  shows that  $\tilde{u}^l$  is indeed an element of  $W_{\varphi(K)}^{e,q}(\varphi(U))$  so  $\hat{H}$  is well defined.
- (3) We prove that  $\hat{H}$  is injective.
- (4) In order to prove that  $\hat{H}$  is surjective we use our explicit formula for  $H^{-1}$  (see Remark D.26).

Note that the fact that  $\hat{H}$  is bijective combined with the equality  $\|u\|_{W^{e,q}(M,E)} \simeq \sum_{l=1}^r \|\tilde{u}^l\|_{W^{e,q}(\varphi(U))}$  implies that  $\hat{H}^{-1}$  is continuous as well.

Here are the proofs:

- (1) This item is a direct consequence of item 1. in Remark D.26.
- (2) Define the augmented total trivialization atlas  $\Lambda_1$  by  $\Lambda_1 = \{(U_\alpha, \varphi_\alpha, \rho_\alpha, \tilde{\psi}_\alpha)\}_{\alpha=1}^N$  where  $\{\tilde{\psi}_\alpha\}_{1 \leq \alpha \leq N}$  is a partition of unity subordinate to  $\{U_\alpha\}_{1 \leq \alpha \leq N}$  such that  $\tilde{\psi}_\beta = 1$  on a neighborhood of  $K$ . Note that for each  $\alpha$ ,  $\tilde{\psi}_\alpha \geq 0$  and  $\sum_{\alpha=1}^N \tilde{\psi}_\alpha = 1$ . Thus the assumption  $\tilde{\psi}_\beta = 1$  on  $K$  implies that  $\tilde{\psi}_\alpha = 0$  on  $K$  for all  $\alpha \neq \beta$ . We have

$$\begin{aligned} \|u\|_{W^{e,q}(M,E)} &\simeq \|u\|_{W^{e,q}(M,E; \Lambda_1)} \simeq \sum_{\alpha=1}^N \sum_{l=1}^r \|(H_\alpha(\tilde{\psi}_\alpha u))^l\|_{W^{e,q}(\varphi_\alpha(U_\alpha))} \\ &= \sum_{l=1}^r \|(H(\tilde{\psi}_\beta u))^l\|_{W^{e,q}(\varphi_\alpha(U_\alpha))} = \sum_{l=1}^r \|[H(u)]^l\|_{W^{e,q}(\varphi_\alpha(U_\alpha))} \end{aligned}$$

Note that  $\text{supp } u \subseteq K$  and  $\tilde{\psi}_\beta = 1$  on  $K$ , so  $\tilde{\psi}_\beta u = u|_U$  as elements of  $D'(U, E_U)$ . Therefore  $H(\tilde{\psi}_\beta u) = H(u) = (\tilde{u}^1, \dots, \tilde{u}^r)$ .

- (3)  $\hat{H}$  is injective because it is a restriction of the injective map  $H$ .
- (4) Let  $(v^1, \dots, v^r) \in [W_{\varphi(K)}^{e,q}(\varphi(U))]^{\times r}$ . Our goal is to show that  $H^{-1}(v^1, \dots, v^r) \in W_{K'}^{e,q}(M, E; \Lambda) \simeq W_{K'}^{e,q}(M, E; \Lambda_1)$  (this implies that  $\hat{H}$  is surjective). By Remark D.26, for all  $\xi \in D(U, E_U^\vee)$

$$H^{-1}(v^1, \dots, v^r)(\xi) = \sum_i v^i [(\rho^\vee)^i \circ \xi \circ \varphi^{-1}]$$

First note it follows from Remark D.23 that  $\text{supp } H^{-1}(v^1, \dots, v^r) \subseteq K$ ; indeed, if  $\text{supp } \xi \subseteq U \setminus K$ , then  $\xi \circ \varphi^{-1} = 0$  on  $\varphi(K)$ . So  $(\rho^\vee)^i \circ \xi \circ \varphi^{-1} = 0$  on  $\varphi(K)$ . That is  $\text{supp}[(\rho^\vee)^i \circ \xi \circ \varphi^{-1}] \subseteq \varphi(U) \setminus \varphi(K)$ . Thus for all  $i$ ,  $v^i [(\rho^\vee)^i \circ \xi \circ \varphi^{-1}] = 0$  (because by assumption  $\text{supp } v^i \subseteq \varphi(K)$ ). This shows that if  $\text{supp } \xi \subseteq U \setminus K$ , then

$H^{-1}(v^1, \dots, v^r)(\xi) = 0$ . Consequently  $\text{supp}H^{-1}(v^1, \dots, v^r) \subseteq K$ .

Also we have

$$\|H^{-1}(v^1, \dots, v^r)\|_{W^{e,q}(M,E; \Lambda)} \simeq \sum_{l=1}^r \|v^l\|_{W^{e,q}(\varphi(U))} < \infty$$

So  $H^{-1}(v^1, \dots, v^r) \in W^{e,q}(M, E; \Lambda)$ .

□

It is clear that  $u \in W^{e,q}(M, E; \Lambda)$  if and only if for all  $\alpha$ ,  $\psi_\alpha u \in W_{K_\alpha}^{e,q}(M, E; \Lambda)$  where  $K_\alpha$  can be taken as any compact set such that  $\text{supp}\psi_\alpha \subseteq K_\alpha \subseteq U_\alpha$ . In fact as a direct consequence of the definition of Sobolev spaces and the above mentioned isomorphism we have

$$\begin{aligned} u \in W^{e,q}(M, E; \Lambda) &\iff \forall 1 \leq \alpha \leq N \quad H_\alpha(\psi_\alpha u) \in [W_{\varphi_\alpha(\text{supp}\psi_\alpha)}^{e,q}(\varphi_\alpha(U_\alpha))]^{\times r} \\ &\iff \forall 1 \leq \alpha \leq N \quad \psi_\alpha u \in W_{\text{supp}\psi_\alpha}^{e,q}(M, E; \Lambda) \end{aligned}$$

**H.2.6. Completeness; Density of Smooth Functions.** Our proofs for completeness of Sobolev spaces and density of smooth functions are based on the argument given in [38].

**Lemma H.24.** *Let  $M^n$  be a compact smooth manifold and  $E \rightarrow M$  be a vector bundle of rank  $r$ . Let  $e \in \mathbb{R}$  and  $q \in (1, \infty)$ . Suppose  $\Lambda = \{(U_\alpha, \varphi_\alpha, \rho_\alpha, \psi_\alpha)\}_{\alpha=1}^N$  is an augmented total trivialization atlas for  $E \rightarrow M$ . If  $e$  is a noninteger less than  $-1$  further assume that  $\Lambda$  is GL compatible with itself. Let  $K_\alpha$  be a compact subset of  $U_\alpha$  that contains the support of  $\psi_\alpha$ . Let  $S : W^{e,q}(M, E; \Lambda) \rightarrow \prod_{\alpha=1}^N W_{K_\alpha}^{e,q}(M, E; \Lambda)$  be the linear map defined by  $S(u) = (\psi_1 u, \dots, \psi_N u)$ . Then  $S : W^{e,q}(M, E; \Lambda) \rightarrow S(W^{e,q}(M, E; \Lambda)) \subseteq \prod_{\alpha=1}^N W_{K_\alpha}^{e,q}(M, E; \Lambda)$  is a linear topological isomorphism. Moreover  $S(W^{e,q}(M, E; \Lambda))$  is closed in  $\prod_{\alpha=1}^N W_{K_\alpha}^{e,q}(M, E; \Lambda)$ .*

*Proof.*

Each component of  $S$  is continuous (see Theorem H.9), therefore  $S$  is continuous. Define  $P : \prod_{\alpha=1}^N W_{K_\alpha}^{e,q}(M, E) \rightarrow W^{e,q}(M, E)$  by

$$P(v_1, \dots, v_N) = \sum_i v_i$$

Clearly  $P$  is continuous. Also  $P \circ S = id$ . Now the claim follows from Theorem B.45. □

**Theorem H.25.** *Let  $M^n$  be a compact smooth manifold and  $E \rightarrow M$  be a vector bundle of rank  $r$ . Let  $e \in \mathbb{R}$  and  $q \in (1, \infty)$ . Suppose  $\Lambda = \{(U_\alpha, \varphi_\alpha, \rho_\alpha, \psi_\alpha)\}_{\alpha=1}^N$  is an augmented total trivialization atlas for  $E \rightarrow M$ . If  $e$  is a noninteger less than  $-1$  further assume that  $\Lambda$  is GL compatible with itself. Then  $W^{e,q}(M, E; \Lambda)$  is a Banach space.*

*Proof.* According to Lemma H.23, for each  $1 \leq \alpha \leq N$ ,  $W_{K_\alpha}^{e,q}(M, E; \Lambda)$  is isomorphic to the Banach space  $[W_{\varphi_\alpha(K_\alpha)}^{e,q}(\varphi_\alpha(U_\alpha))]^{\times r}$ . So  $\prod_{\alpha=1}^N W_{K_\alpha}^{e,q}(M, E; \Lambda)$  is a Banach space. A closed subspace of a Banach space is Banach. Therefore  $S(W^{e,q}(M, E; \Lambda))$  is a Banach space. Since  $S$  is a linear topological isomorphism onto its image,  $W^{e,q}(M, E; \Lambda)$  is also a Banach space. □

**Theorem H.26.** *Let  $M^n$  be a compact smooth manifold and  $E \rightarrow M$  be a vector bundle of rank  $r$ . Let  $e \in \mathbb{R}$  and  $q \in (1, \infty)$ . Suppose  $\Lambda = \{(U_\alpha, \varphi_\alpha, \rho_\alpha, \psi_\alpha)\}_{\alpha=1}^N$  is an augmented total trivialization atlas for  $E \rightarrow M$ . If  $e$  is a noninteger less than  $-1$  further assume that  $\Lambda$  is GL compatible with itself. Then  $D(M, E)$  is dense in  $W^{e,q}(M, E; \Lambda)$ .*

*Proof.* Let  $K_\alpha = \text{supp}\psi_\alpha$ . For each  $1 \leq \alpha \leq N$ , let  $V_\alpha$  be an open set such that

$$K_\alpha \subseteq V_\alpha \subseteq \bar{V}_\alpha \subseteq U_\alpha$$

Suppose  $u \in W^{e,q}(M, E; \Lambda)$  and let  $u_\alpha = \psi_\alpha u$ . Clearly  $\text{supp}u_\alpha \subseteq K_\alpha$ . Also according to Lemma H.23, for each  $\alpha$  there exists a linear topological isomorphism

$$\hat{H}_\alpha : W_{V_\alpha}^{e,q}(M, E) \rightarrow [W_{\varphi_\alpha(V_\alpha)}^{e,q}(\varphi_\alpha(U_\alpha))]^{\times r}$$

Note that  $\hat{H}_\alpha(u_\alpha) \in [W_{\varphi_\alpha(K_\alpha)}^{e,q}(\varphi_\alpha(U_\alpha))]^{\times r}$ . Therefore by Lemma E.28 there exists a sequence  $\{(\eta_\alpha)_i\}$  in  $[C_{\varphi_\alpha(V_\alpha)}^\infty(\varphi_\alpha(U_\alpha))]^{\times r}$  (of course we view each component of  $(\eta_\alpha)_i$  as a distribution) that converges to  $\hat{H}_\alpha(u_\alpha)$  in  $W^{e,q}$  norm as  $i \rightarrow \infty$ . Since  $\hat{H}_\alpha$  is a linear topological isomorphism, we can conclude that

$$\hat{H}_\alpha^{-1}((\eta_\alpha)_i) \rightarrow u_\alpha, \quad (\text{in } W_{V_\alpha}^{e,q}(M, E; \Lambda) \text{ as } i \rightarrow \infty)$$

(Note that if a sequence converges in  $W_A^{e,q}(M, E; \Lambda)$  where  $A$  is a closed subset of  $M$ , it also obviously converges in  $W^{e,q}(M, E; \Lambda)$ .) Let  $\xi_i = \sum_{\alpha=1}^N \hat{H}_\alpha^{-1}((\eta_\alpha)_i)$ . Clearly  $\xi_i \rightarrow \sum_\alpha u_\alpha = u$  in  $W^{e,q}(M, E; \Lambda)$ . It remains to show that for each  $i$ ,  $\xi_i$  is in  $C^\infty(M, E)$ . To this end, it suffices to show that if  $\chi = (\chi^1, \dots, \chi^r) \in [C_c^\infty(\varphi_\alpha(U_\alpha))]^{\times r}$ , then  $\hat{H}_\alpha^{-1}(\chi)$  is in  $C_c^\infty(U_\alpha, E_\alpha)$  and so can be considered as an element of  $C^\infty(M, E)$  (by extension by zero). Note that  $\hat{H}_\alpha^{-1}(\chi)$  is compactly supported in  $U_\alpha$  because by definition of  $\hat{H}_\alpha$  any distribution in the codomain of  $\hat{H}_\alpha^{-1}$  has compact support in  $\bar{V}_\alpha$ . So we just need to prove the smoothness of  $\hat{H}_\alpha^{-1}(\chi)$ . That is, we need to show that there is a smooth section  $f \in C^\infty(U_\alpha, E_{U_\alpha})$  such that  $u_f = \hat{H}_\alpha^{-1}(\chi)$ . It seems that the natural candidate for  $f(x)$  should be  $(\rho_\alpha|_{E_x})^{-1} \circ \chi \circ \varphi_\alpha(x)$ . In fact, if we define  $f$  by this formula, then  $\hat{H}_\alpha(u_f) = H_\alpha(u_f)$  and by Remark D.27  $H_\alpha(u_f)$  is a distribution that corresponds to the regular function  $(\tilde{f}^1, \dots, \tilde{f}^r) = \rho_\alpha \circ f \circ \varphi_\alpha^{-1}$ . Obviously

$$\rho_\alpha \circ f \circ \varphi_\alpha^{-1}|_{\varphi_\alpha(x)} = \rho_\alpha \circ (\rho_\alpha|_{E_x})^{-1} \circ \chi \circ \varphi_\alpha \circ \varphi_\alpha^{-1}|_{\varphi_\alpha(x)} = \chi|_{\varphi_\alpha(x)}$$

So the regular section  $f(x) = \rho_\alpha|_{E_x}^{-1} \circ \chi \circ \varphi_\alpha(x)$  corresponds to  $\hat{H}_\alpha^{-1}(\chi)$  and we just need to show that  $f$  is smooth; this is true because  $f$  is a composition of smooth functions. Indeed,

$$f(x) = \rho_\alpha|_{E_x}^{-1} \circ \chi \circ \varphi_\alpha(x) = \Phi_\alpha^{-1}(x, \chi \circ \varphi_\alpha(x)) \implies f = \Phi_\alpha^{-1} \circ (Id, \chi \circ \varphi_\alpha)$$

and all the maps involved in the above expression are smooth.  $\square$

### H.2.7. Dual of Sobolev Spaces.

**Lemma H.27.** *Let  $M^n$  be a compact smooth manifold and let  $\pi : E \rightarrow M$  be a vector bundle of rank  $r$  equipped with a fiber metric  $\langle \cdot, \cdot \rangle_E$ . Let  $e \in \mathbb{R}$  and  $q \in (1, \infty)$ . Suppose  $\Lambda = \{(U_\alpha, \varphi_\alpha, \rho_\alpha, \psi_\alpha)\}_{\alpha=1}^N$  is an augmented total trivialization atlas for  $E \rightarrow M$  which trivializes the fiber metric. If  $e$  is a noninteger less than  $-1$  further assume that the total trivialization atlas in  $\Lambda$  is GGL.*

*Fix a positive smooth density  $\mu$  on  $M$  (for instance we can equip  $M$  with a smooth Riemannian metric and consider the corresponding Riemannian density). Let  $T : D(M, E) \rightarrow D(M, E^\vee)$  be a map that sends  $\xi$  to  $T_\xi$  where  $T_\xi$  is defined by*

$$\forall x \in M \quad T_\xi(x) : E_x \rightarrow \mathcal{D}_x, \quad a \mapsto \langle a, \xi(x) \rangle_E \mu(x)$$

*Then  $T$  is a linear bijective continuous map. (So the adjoint of  $T$  is a well defined bijective continuous map that can be used to identify  $D'(M, E) = [D(M, E^\vee)]^*$  with  $[D(M, E)]^*$ .) Moreover,  $T : (C^\infty(M, E), \|\cdot\|_{W^{e,q}(M, E; \Lambda)}) \rightarrow (C^\infty(M, E^\vee), \|\cdot\|_{W^{e,q}(M, E^\vee; \Lambda^\vee)})$  is a topological isomorphism.*

*Proof.* The fact that  $T$  is linear is obvious.

- **T is one-to-one:** Suppose  $\xi \in D(M, E)$  is such that  $T_\xi = 0$ . Then

$$\begin{aligned} \forall x \in M \quad T_\xi(x) = 0 &\implies \forall x \in M, \forall a \in E_x \quad [T_\xi(x)](a) = 0 \\ &\implies \forall x \in M, \forall a \in E_x \quad \langle a, \xi(x) \rangle_E = 0 \\ &\implies \forall x \in M \quad \langle \xi(x), \xi(x) \rangle_E = 0 \implies \forall x \in M \quad \xi(x) = 0 \end{aligned}$$

- **T is onto:** Let  $u \in D(M, E^\vee)$ . Our goal is to show that there exists  $\xi \in D(M, E)$  such that  $u = T_\xi$ . Note that

$$\forall x \in M \quad u(x) = T_\xi(x) \iff \forall x \in M \forall a \in E_x \quad \langle a, \xi(x) \rangle_E \mu(x) = [u(x)](a)$$

Since  $\mathcal{D}_x$  is 1-dimensional and both  $\mu(x)$  (which is a positive smooth density) and  $[u(x)][a]$  belong to  $\mathcal{D}_x$ , there exists a number  $b(x, a)$  such that

$$[u(x)](a) = b(x, a)\mu(x)$$

So we need to show that there exists  $\xi \in D(M, E)$  such that

$$\forall x \in M \forall a \in E_x \quad \langle a, \xi(x) \rangle_E = b(x, a)$$

The above equality uniquely defines a functional on  $E_x$  which gives us a unique element  $\xi(x) \in E_x$  by the Riesz representation theorem. It remains to prove that  $\xi$  is smooth. To this end, we will show that for each  $\alpha$ ,  $\xi|_{U_\alpha}$  is smooth. Let  $(s_1, \dots, s_r)$  be a smooth orthonormal frame for  $E_{U_\alpha}$ .

$$\forall x \in U_\alpha \quad \xi(x) = \xi^1(x)s_1(x) + \dots + \xi^r(x)s_r(x)$$

It suffices to show that  $\xi^1, \dots, \xi^r$  are smooth functions (see Theorem C.20). We have

$$\xi^i(x) = \langle \xi(x), s_i(x) \rangle_E$$

It follows from the definition of  $\xi(x)$  that

$$[u(x)][s_i(x)] = \langle s_i(x), \xi(x) \rangle_E \mu(x)$$

Therefore  $\xi^i(x)$  satisfies the following equality

$$[u(x)][s_i(x)] = \xi^i(x)\mu(x)$$

That is, if we define a section of  $\mathcal{D} \rightarrow U_\alpha$  by

$$[u, s_i] : U_\alpha \rightarrow \mathcal{D}, \quad x \mapsto [u(x)][s_i(x)]$$

then  $\xi^i$  is the component of this section with respect to the smooth frame  $\{\mu(x)\}$  on  $U_\alpha$ . The smoothness of  $\xi^i$  follows from the fact that if  $N$  is any manifold,  $E \rightarrow N$  is a vector bundle and  $u$  and  $v$  are in  $\mathcal{E}(N, E^\vee)$  and  $\mathcal{E}(N, E)$ , respectively, then  $[u, v]$  is in  $\mathcal{E}(N, \mathcal{D})$ ; indeed, the local representation of  $[u, v]$  is  $\sum_l \tilde{u}^l \tilde{v}^l$  which is a smooth function because  $\tilde{u}^l$  and  $\tilde{v}^l$  are smooth functions.

- **$T : D(M, E) \rightarrow D(M, E^\vee)$  is continuous:**

We make use of Theorem B.40. Recall that

- (1) The topology on  $D(M, E)$  is induced by the seminorms:

$$\forall 1 \leq l \leq r, \forall 1 \leq \alpha \leq N, \forall k \in \mathbb{N}, \forall K \subseteq U_\alpha(\text{compact}) \quad p_{l, \alpha, k, K}(\xi) = \|\rho_\alpha^l \circ \xi \circ \varphi_\alpha^{-1}\|_{\varphi_\alpha(K), k}$$

- (2) The topology on  $D(M, E^\vee)$  is induced by the seminorms:

$$\forall 1 \leq l \leq r, \forall 1 \leq \alpha \leq N, \forall k \in \mathbb{N}, \forall K \subseteq U_\alpha(\text{compact}) \quad q_{l, \alpha, k, K}(\eta) = \|(\rho_\alpha^\vee)^l \circ \eta \circ \varphi_\alpha^{-1}\|_{\varphi_\alpha(K), k}$$



For all  $\xi \in D(M, E)$  we have

$$q_{l,\alpha,k,K}(T_\xi) = \|(\rho_\alpha^\vee)^l \circ T_\xi \circ \varphi_\alpha^{-1}\|_{\varphi_\alpha(K),k} = \|(\rho_{\mathcal{D},\varphi_\alpha}) \circ (T_\xi \circ \varphi_\alpha^{-1}) \circ \underbrace{(\rho|_{E_x})^{-1}(e_l)}_{s_l(x)}\|_{\varphi_\alpha(K),k}$$

where  $(e_1, \dots, e_l)$  is the standard basis for  $\mathbb{R}^r$ . Let  $y = \varphi_\alpha(x)$ . Note that

$$[T_\xi(\varphi_\alpha^{-1}(y))][s_l(x)] = \langle s_l(x), \xi(x) \rangle_E \mu(x)$$

Therefore if we define the smooth function  $f_\alpha$  on  $U_\alpha$  by  $\mu(x) = f_\alpha(x)|dx^1 \wedge \dots \wedge dx^n|$ , then

$$(\rho_{\mathcal{D},\varphi_\alpha}) \circ (T_\xi \circ \varphi_\alpha^{-1}) \circ s_l(x) = \langle s_l(x), \xi(x) \rangle_E f_\alpha(x) = \xi^l(x) f_\alpha(x) = (\rho_\alpha^l \circ \xi \circ \varphi_\alpha^{-1}(y))(f_\alpha \circ \varphi_\alpha^{-1}(y)) \quad (\text{H.5})$$

So if we let

$$C = \max_{y \in \varphi_\alpha(K), |\beta| \leq k} |\partial^\beta (f_\alpha \circ \varphi_\alpha^{-1}(y))|$$

Then

$$q_{l,\alpha,k,K}(T_\xi) = \|(\rho_\alpha^l \circ \xi \circ \varphi_\alpha^{-1}(y))(f_\alpha \circ \varphi_\alpha^{-1}(y))\|_{\varphi_\alpha(K),k} \leq C \|(\rho_\alpha^l \circ \xi \circ \varphi_\alpha^{-1}(y))\|_{\varphi(K),k} = C p_{l,\alpha,k,K}(\xi)$$

- $T : (C^\infty(M, E), \|\cdot\|_{e,q}) \rightarrow (C^\infty(M, E^\vee), \|\cdot\|_{e,q})$  is a topological isomorphism:

$$\|\xi\|_{W^{e,q}(M,E;)} = \sum_{\alpha=1}^N \sum_{l=1}^r \|(\rho_\alpha^l \circ \psi_\alpha \xi \circ \varphi_\alpha^{-1})\|_{W^{e,q}(\varphi_\alpha(U_\alpha))}$$

$$\|T_\xi\|_{W^{e,q}(M,E^\vee; \vee)} = \sum_{\alpha=1}^N \sum_{l=1}^r \|(\rho_\alpha^\vee)^l \circ \psi_\alpha T_\xi \circ \varphi_\alpha^{-1}\|_{W^{e,q}(\varphi_\alpha(U_\alpha))}$$

By Equation H.5, we have

$$(\rho_\alpha^\vee)^l \circ \psi_\alpha T_\xi \circ \varphi_\alpha^{-1} = \rho_{\mathcal{D},\varphi_\alpha} \circ (\psi_\alpha T_\xi \circ \varphi_\alpha^{-1}) \circ s_l(x) = (\rho_\alpha^l \circ \psi_\alpha \xi \circ \varphi_\alpha^{-1})(f_\alpha \circ \varphi_\alpha^{-1})$$

Therefore

$$\|T_\xi\|_{W^{e,q}(M,E^\vee; \vee)} = \sum_{\alpha=1}^N \sum_{l=1}^r \|(\rho_\alpha^l \circ \psi_\alpha \xi \circ \varphi_\alpha^{-1})(f_\alpha \circ \varphi_\alpha^{-1})\|_{W^{e,q}(\varphi_\alpha(U_\alpha))}$$

Now we just need to notice that  $f_\alpha \circ \varphi_\alpha^{-1}$  is a positive function and belongs to  $C^\infty(\varphi_\alpha(U_\alpha))$  (so  $\frac{1}{f_\alpha \circ \varphi_\alpha^{-1}}$  is also smooth) and  $\rho_\alpha^l \circ \psi_\alpha \xi \circ \varphi_\alpha^{-1}$  has support in the compact set  $\varphi_\alpha(\text{supp}(\psi_\alpha))$  to conclude that

$$\|\xi\|_{W^{e,q}(M,E;)} \simeq \|T_\xi\|_{W^{e,q}(M,E^\vee; \vee)}$$

□

**Lemma H.28.** *Let  $M^n$  be a compact smooth manifold and let  $\pi : E \rightarrow M$  be a vector bundle of rank  $r$  equipped with a fiber metric  $\langle \cdot, \cdot \rangle_E$ . Let  $e \in \mathbb{R}$  and  $q \in (1, \infty)$ . Suppose  $\Lambda = \{(U_\alpha, \varphi_\alpha, \rho_\alpha, \psi_\alpha)\}_{\alpha=1}^N$  is an augmented total trivialization atlas for  $E \rightarrow M$ . If  $e$  is a noninteger less than  $-1$  further assume that the total trivialization atlas in  $\Lambda$  is GGL. Then  $D(M, E) \hookrightarrow W^{e,q}(M, E) \hookrightarrow D'(M, E)$ .*

*Proof.* For  $e \in \mathbb{Z}$  the claim is proved in [38]. For  $e \in \mathbb{R} \setminus \mathbb{Z}$  we have

$$W^{e,q}(M, E; \Lambda) \hookrightarrow W^{\lfloor e \rfloor, q}(M, E; \Lambda) \hookrightarrow D'(M, E)$$

$$D(M, E) \hookrightarrow W^{\lfloor e \rfloor + 1, q}(M, E; \Lambda) \hookrightarrow W^{e,q}(M, E; \Lambda)$$

□

**Theorem H.29.** *Let  $M^n$  be a compact smooth manifold and let  $\pi : E \rightarrow M$  be a vector bundle of rank  $r$  equipped with a fiber metric  $\langle \cdot, \cdot \rangle_E$ . Let  $e \in \mathbb{R}$  and  $q \in (1, \infty)$ . Suppose  $\Lambda = \{(U_\alpha, \varphi_\alpha, \rho_\alpha, \psi_\alpha)\}_{\alpha=1}^N$  is an augmented total trivialization atlas for  $E \rightarrow M$  which trivializes the fiber metric. If  $e$  is a noninteger whose magnitude is greater than 1 further assume that the total trivialization atlas in  $\Lambda$  is GL compatible with itself. Fix a positive smooth density  $\mu$  on  $M$ .*

*Consider the  $L^2$  inner product on  $D(M, E)$  defined by*

$$\langle u, v \rangle_2 = \int_M \langle u, v \rangle_E \mu$$

*Then*

- (i)  $\langle \cdot, \cdot \rangle_2$  extends uniquely to a continuous bilinear pairing  $\langle \cdot, \cdot \rangle_2 : W^{-e, q'}(M, E; \Lambda) \times W^{e, q}(M, E; \Lambda) \rightarrow \mathbb{R}$ . (We are using the same notation (i.e.  $\langle \cdot, \cdot \rangle_2$ ) for the extended bilinear map!)
- (ii) The map  $S : W^{-e, q'}(M, E, \Lambda) \rightarrow [W^{e, q}(M, E; \Lambda)]^*$  defined by  $S(u) = l_u$  where

$$l_u : W^{e, q}(M, E; \Lambda) \rightarrow \mathbb{R}, \quad l_u(v) = \langle u, v \rangle_2$$

*is a well defined topological isomorphism.*

*In particular,  $[W^{e, q}(M, E; \Lambda)]^*$  can be identified with  $W^{-e, q'}(M, E; \Lambda)$ .*

*Proof.*

- (1) By Theorem B.15, in order to prove (i) it is enough to show that

$$\langle \cdot, \cdot \rangle_2 : (C^\infty(M, E), \|\cdot\|_{-e, q'}) \times (C^\infty(M, E), \|\cdot\|_{e, q}) \rightarrow \mathbb{R}$$

is a **continuous** bilinear map. Denote the corresponding standard trivialization map for the density bundle  $D \rightarrow M$  by  $\rho_{\mathcal{D}, \varphi_\alpha}$ . Let  $\Lambda_1 = \{(U_\alpha, \varphi_\alpha, \rho_\alpha, \tilde{\psi}_\alpha)\}_{\alpha=1}^N$  be an augmented total trivialization atlas for  $E$  where  $\tilde{\psi}_\alpha = \frac{\psi_\alpha^3}{\sum_{\beta=1}^N \psi_\beta^3}$ . Note that  $\frac{1}{\sum_{\beta=1}^N \psi_\beta^3} \circ \varphi_\alpha^{-1} \in BC^\infty(\varphi_\alpha(U_\alpha))$ . Let  $K_\alpha = \text{supp} \psi_\alpha$ . Recall that on  $U_\alpha$  we may write  $\mu = h_\alpha |dx^1 \wedge \dots \wedge dx^n|$  where  $h_\alpha = \rho_{\mathcal{D}, \varphi_\alpha} \circ \mu$  is smooth. Moreover, for any continuous function  $f : M \rightarrow \mathbb{R}$

$$\begin{aligned} \int_M f \mu &= \sum_{\alpha=1}^N \int_M \tilde{\psi}_\alpha f \mu \\ &= \sum_{\alpha=1}^N \int_{\varphi_\alpha(U_\alpha)} (\varphi_\alpha^{-1})^* (\tilde{\psi}_\alpha f \mu) \\ &= \sum_{\alpha=1}^N \int_{\varphi_\alpha(U_\alpha)} (\tilde{\psi}_\alpha f \circ \varphi_\alpha^{-1}) (\varphi_\alpha^{-1})^* \mu \\ &= \sum_{\alpha=1}^N \int_{\varphi_\alpha(U_\alpha)} (\tilde{\psi}_\alpha f \circ \varphi_\alpha^{-1}) (h_\alpha \circ \varphi_\alpha^{-1}) dV \\ &\stackrel{1.4}{=} \sum_{\alpha=1}^N \int_{\varphi_\alpha(U_\alpha)} (\psi_\alpha^2 f \circ \varphi_\alpha^{-1}) (\psi_\alpha h_\alpha \circ \varphi_\alpha^{-1}) dV \quad \left( \frac{1}{\sum_{\beta=1}^N \psi_\beta^3} \circ \varphi_\alpha^{-1} \in BC^\infty(\varphi_\alpha(U_\alpha)) \right) \end{aligned}$$

Therefore we have

$$\begin{aligned} \left| \int_M \langle u, v \rangle_E \mu \right| &= \left| \sum_{\alpha=1}^N \int_M \tilde{\psi}_\alpha \langle u, v \rangle_E \mu \right| \\ &\leq \left| \sum_{\alpha=1}^N \int_{\varphi_\alpha(U_\alpha)} (\psi_\alpha^2 \langle u, v \rangle_E \circ \varphi_\alpha^{-1}) (\psi_\alpha h_\alpha \circ \varphi_\alpha^{-1}) dV \right| \end{aligned}$$

Consequently, since by assumption the total trivialization atlas in  $\Lambda$  trivializes the metric, we get

$$\begin{aligned} \left| \int_M \langle u, v \rangle_E \mu \right| &\leq \sum_{\alpha=1}^N \sum_{i=1}^r \left| \int_{\varphi_\alpha(U_\alpha)} (\psi_\alpha \circ \varphi_\alpha^{-1} \tilde{u}_i) (\psi_\alpha \circ \varphi_\alpha^{-1} \tilde{v}_i) (\psi_\alpha h_\alpha \circ \varphi_\alpha^{-1}) dV \right| \\ &\stackrel{\text{Remark E.47}}{\leq} \sum_{\alpha=1}^N \sum_{i=1}^r \left\| (\psi_\alpha \circ \varphi_\alpha^{-1} \tilde{u}_i) \right\|_{W^{-e, q'}(\varphi_\alpha(U_\alpha))} \left\| (\psi_\alpha \circ \varphi_\alpha^{-1} \tilde{v}_i) (\psi_\alpha h_\alpha \circ \varphi_\alpha^{-1}) \right\|_{W^{e, q}(\varphi_\alpha(U_\alpha))} \\ &\preceq \sum_{\alpha=1}^N \sum_{i=1}^r \left\| (\psi_\alpha \circ \varphi_\alpha^{-1} \tilde{u}_i) \right\|_{W^{-e, q'}(\varphi_\alpha(U_\alpha))} \left\| (\psi_\alpha \circ \varphi_\alpha^{-1} \tilde{v}_i) \right\|_{W^{e, q}(\varphi_\alpha(U_\alpha))} \\ &\preceq \left[ \sum_{\alpha=1}^N \sum_{i=1}^r \left\| (\psi_\alpha \circ \varphi_\alpha^{-1} \tilde{u}_i) \right\|_{W^{-e, q'}(\varphi_\alpha(U_\alpha))} \right] \left[ \sum_{\alpha=1}^N \sum_{i=1}^r \left\| (\psi_\alpha \circ \varphi_\alpha^{-1} \tilde{v}_i) \right\|_{W^{e, q}(\varphi_\alpha(U_\alpha))} \right] \\ &= \|u\|_{W^{-e, q'}(M, E; \Lambda)} \|v\|_{W^{e, q}(M, E; \Lambda)} \end{aligned}$$

(2) For each  $u \in W^{-e, q'}(M, E; \Lambda)$ ,  $l_u$  is continuous because  $\langle \cdot, \cdot \rangle_2$  is continuous. So  $S$  is well defined.

(3)  $S$  is a continuous linear map because

$$\begin{aligned} \forall u \in W^{-e, q'}(M, E; \Lambda) \quad \|S(u)\|_{(W^{e, q}(M, E; \Lambda))^*} &= \sup_{0 \neq v \in W^{e, q}(M, E; \Lambda)} \frac{|S(u)v|}{\|v\|_{W^{e, q}(M, E; \Lambda)}} \\ &= \sup_{0 \neq v \in W^{e, q}(M, E; \Lambda)} \frac{|\langle u, v \rangle_2|}{\|v\|_{W^{e, q}(M, E; \Lambda)}} \leq C \|u\|_{W^{-e, q'}(M, E; \Lambda)} \end{aligned}$$

where  $C$  is the norm of the continuous bilinear form  $\langle \cdot, \cdot \rangle_2$ .

(4)  $S$  is injective: suppose  $u \in W^{-e, q'}(M, E; \Lambda)$  is such that  $S(u) = 0$ , then

$$\forall v \in W^{e, q}(M, E; \Lambda) \quad l_u(v) = \langle u, v \rangle_2 = 0$$

We need to show that  $u = 0$ .

• **Step 1:** For  $\xi$  and  $\eta$  in  $D(M, E)$  we have

$$\langle \xi, \eta \rangle_2 = \langle u_\xi, T\eta \rangle_{[D(M, E^\vee)]^* \times D(M, E^\vee)}$$

where  $T$  is the map introduced in Lemma H.27. (Note that if we identify  $D(M, E)$  with a subset of  $[D(M, E^\vee)]^*$ , then we may write  $\xi$  instead of  $u_\xi$  on the right hand side of the above equality.) The reason is as follows

$$\langle u_\xi, T\eta \rangle_{[D(M, E^\vee)]^* \times D(M, E^\vee)} = \int_M [T_\eta(x)][\xi(x)] \quad \text{by definition of } u_\xi$$

Recall that by definition of  $T_\eta$  we have

$$\forall x \in M \quad \forall a \in E_x \quad [T_\eta(x)][a] = \langle a, \eta(x) \rangle_E \mu$$

In particular

$$[T_\eta(x)][\xi(x)] = \langle \xi(x), \eta(x) \rangle_E \mu$$

Therefore

$$\langle u_\xi, T\eta \rangle_{[D(M, E^\vee)]^* \times D(M, E^\vee)} = \int_M \langle \xi(x), \eta(x) \rangle_E \mu = \langle \xi, \eta \rangle_2$$

- **Step 2:** For  $w \in W^{-e, q'}(M, E; \Lambda)$  and  $\eta \in D(M, E) \subseteq W^{e, q}(M, E; \Lambda)$  we have

$$\langle w, \eta \rangle_2 = \langle w, T\eta \rangle_{[D(M, E^\vee)]^* \times D(M, E^\vee)}$$

Indeed, let  $\{\xi_m\}$  be a sequence in  $D(M, E)$  that converges to  $w$  in  $W^{-e, q'}(M, E; \Lambda)$ . Note that  $W^{-e, q'}(M, E; \Lambda) \hookrightarrow [D(M, E^\vee)]^*$ , so the sequence converges to  $w$  in  $[D(M, E^\vee)]^*$  as well. By what was proved in the first step, for all  $m$

$$\langle \xi_m, \eta \rangle_2 = \langle \xi_m, T\eta \rangle_{[D(M, E^\vee)]^* \times D(M, E^\vee)}$$

Taking the limit as  $m \rightarrow \infty$  proves the claim.

- **Step 3:** Finally note that for all  $v \in D(M, E) \subseteq W^{e, q}(M, E; \Lambda)$

$$\langle T^*u, v \rangle_{[D(M, E)]^* \times D(M, E)} = \langle u, Tv \rangle_{[D(M, E^\vee)]^* \times D(M, E^\vee)} = \langle u, v \rangle_2 = 0$$

Therefore  $T^*u = 0$  as an element of  $[D(M, E)]^*$ .  $T$  is a continuous bijective map, so  $T^*$  is injective. It follows that  $u = 0$  as an element of  $[D(M, E^\vee)]^*$  and so  $u = 0$  as an element of  $W^{-e, q'}(M, E; \Lambda)$ .

- (5)  $S$  is surjective. Let  $F \in [W^{e, q}(M, E; \Lambda)]^*$ . We need to show that there is an element  $u \in W^{-e, q'}(M, E; \Lambda)$  such that  $S(u) = F$ . Since  $D(M, E)$  is dense in  $W^{e, q}(M, E; \Lambda)$ , it is enough to show that there exists an element  $u \in W^{-e, q'}(M, E; \Lambda)$  with the property that

$$\forall \xi \in D(M, E) \quad F(\xi) = \langle u, \xi \rangle_2$$

Note that according to what was proved in Step 2

$$\langle u, \xi \rangle_2 = \langle u, T\xi \rangle_{[D(M, E^\vee)]^* \times D(M, E^\vee)} = \langle T^*u, \xi \rangle_{[D(M, E)]^* \times D(M, E)}$$

So we need to show that there exists an element  $u \in W^{-e, q'}(M, E; \Lambda)$  such that

$$\forall \xi \in D(M, E) \quad F(\xi) = \langle T^*u, \xi \rangle_{[D(M, E)]^* \times D(M, E)}$$

Since  $D(M, E) \hookrightarrow W^{e, q}(M, E; \Lambda)$ ,  $F|_{D(M, E)}$  is an element of  $[D(M, E)]^*$ . We let

$$u := [T^{-1}]^*(F|_{D(M, E)}) \in [D(M, E^\vee)]^*$$

Clearly  $u$  satisfies the desired equality (note that  $[T^{-1}]^* = [T^*]^{-1}$ ). So we just need to show that  $u$  is indeed an element of  $W^{-e, q'}(M, E; \Lambda)$ . Note that

$$u \in W^{-e, q'}(M, E; \Lambda) \iff \forall 1 \leq \alpha \leq N \quad H_\alpha(\psi_\alpha u) \in [W_{\varphi_\alpha(\text{supp } \psi_\alpha)}^{-e, q'}(\varphi_\alpha(U_\alpha))]^{\times r}$$

Since  $\text{supp}(\psi_\alpha u) \subseteq \text{supp } \psi_\alpha$ , it follows from Remark D.26 that

$$\forall 1 \leq l \leq r \quad \text{supp}([H_\alpha(\psi_\alpha u)]^l) \subset \varphi_\alpha(\text{supp } \psi_\alpha)$$

It remains to prove that  $[H_\alpha(\psi_\alpha u)]^l \in W^{-e, q'}(\varphi_\alpha(U_\alpha))$ . Note that

$$\text{for } e \geq 0 \quad [W_0^{e, q}(\varphi_\alpha(U_\alpha))]^* = W^{-e, q'}(\varphi_\alpha(U_\alpha))$$

$$\text{for } e < 0 \quad [W_0^{e, q}(\varphi_\alpha(U_\alpha))]^* = [W^{e, q}(\varphi_\alpha(U_\alpha))]^* = W_0^{-e, q'}(\varphi_\alpha(U_\alpha)) \subseteq W^{-e, q'}(\varphi_\alpha(U_\alpha))$$

Consequently for all  $e$

$$[W_0^{e, q}(\varphi_\alpha(U_\alpha))]^* \subseteq W^{-e, q'}(\varphi_\alpha(U_\alpha))$$

Therefore it is enough to show that

$$[H_\alpha(\psi_\alpha u)]^l \in [W_0^{e,q}(\varphi_\alpha(U_\alpha))]^*$$

To this end, we need to prove that

$$[H_\alpha(\psi_\alpha u)]^l : (C_c^\infty(\varphi_\alpha(U_\alpha)), \|\cdot\|_{e,q}) \rightarrow \mathbb{R}$$

is continuous. For all  $\xi \in C_c^\infty(\varphi_\alpha(U_\alpha))$  we have

$$\begin{aligned} [H_\alpha(\psi_\alpha u)]^l(\xi) &= \langle \psi_\alpha u, g_{l,\xi,U_\alpha,\varphi_\alpha} \rangle_{[D(U_\alpha, E_{U_\alpha}^\vee)]^* \times D(U_\alpha, E_{U_\alpha}^\vee)} = \langle u, \psi_\alpha g_{l,\xi,U_\alpha,\varphi_\alpha} \rangle_{[D(M, E^\vee)]^* \times D(M, E^\vee)} \\ &= \langle [T^{-1}]^* F|_{D(M, E)}, \psi_\alpha g_{l,\xi,U_\alpha,\varphi_\alpha} \rangle_{[D(M, E^\vee)]^* \times D(M, E^\vee)} \\ &= \langle F|_{D(M, E)}, T^{-1}(\psi_\alpha g_{l,\xi}) \rangle_{D^*(M, E) \times D(M, E)} = F(T^{-1}(\psi_\alpha g_{l,\xi,U_\alpha,\varphi_\alpha})) \end{aligned}$$

Thus  $[H_\alpha(\psi_\alpha u)]^l$  is the composition of the following maps

$$\begin{aligned} (C_c^\infty(\varphi_\alpha(U_\alpha)), \|\cdot\|_{e,q}) &\rightarrow [W_{\varphi_\alpha(\text{supp}\psi_\alpha)}^{e,q}(\varphi_\alpha(U_\alpha))]^{\times r} \cap [C_c^\infty(\varphi_\alpha(U_\alpha))]^{\times r} \rightarrow W_{\text{supp}\psi_\alpha}^{e,q}(M, E^\vee; \vee) \cap C^\infty(M, E^\vee) \\ &\rightarrow (C^\infty(M, E), \|\cdot\|_{e,q}) \rightarrow \mathbb{R} \end{aligned}$$

$$\xi \mapsto (0, \dots, 0, \underbrace{(\psi_\alpha \circ \varphi_\alpha^{-1})\xi}_{l^{\text{th}} \text{ position}}, 0, \dots, 0) \mapsto H_{E^\vee, U_\alpha, \varphi_\alpha}^{-1}(0, \dots, 0, (\psi_\alpha \circ \varphi_\alpha^{-1})\xi, 0, \dots, 0) = \psi_\alpha g_{l,\xi,U_\alpha,\varphi_\alpha}$$

$$\mapsto T^{-1}(\psi_\alpha g_{l,\xi,U_\alpha,\varphi_\alpha}) \mapsto F(T^{-1}(\psi_\alpha g_{l,\xi}))$$

which is a composition of continuous maps.

- (6)  $S : W^{-e,q'}(M, E; \Lambda) \rightarrow [W^{e,q}(M, E; \Lambda)]^*$  is a continuous bijective map, so by the Banach isomorphism theorem, it is a topological isomorphism.  $\square$

### Remark H.30.

- (1) The result of Theorem H.29 remains valid even if  $\Lambda = \{(U_\alpha, \varphi_\alpha, \rho_\alpha, \psi_\alpha)\}$  does not trivialize the fiber metric. Indeed, if  $e$  is not a noninteger whose magnitude is greater than 1, then the Sobolev spaces  $W^{e,q}$  and  $W^{-e,q'}$  are independent of the choice of augmented total trivialization atlas. If  $e$  is a noninteger whose magnitude is greater than 1, then by Theorem C.22 there exists an augmented total trivialization atlas  $\tilde{\Lambda} = \{(U_\alpha, \varphi_\alpha, \tilde{\rho}_\alpha, \psi_\alpha)\}$  that trivializes the metric and has the same base atlas as  $\Lambda$  (so it is GL compatible with  $\Lambda$  because by assumption  $\Lambda$  is GL compatible with itself). So we can replace  $\Lambda$  by  $\tilde{\Lambda}$ .
- (2) Let  $\Lambda$  be an augmented total trivialization atlas that is GL compatible with itself. Let  $e$  be a noninteger less than  $-1$  and  $q \in (1, \infty)$ . By Theorem H.29 and the above observation,  $W^{e,q}(M, E; \Lambda)$  is topologically isomorphic to  $[W^{-e,q'}(M, E; \Lambda)]^*$ . However, the space  $W^{-e,q'}(M, E; \Lambda)$  is independent of  $\Lambda$ . So we may conclude that even when  $e$  is a noninteger less than  $-1$ , the space  $W^{e,q}(M, E; \Lambda)$  is independent of the choice of the augmented total trivialization atlas as long as the corresponding total trivialization atlas is **GL compatible** with itself.

**H.3. On the Relationship Between Various Characterizations.** Here we discuss the relationship between the characterizations of Sobolev spaces given in Remark H.3 and our original definition (Definition H.1).

- (1) Suppose  $e \geq 0$ .

$$W^{e,q}(M, E; \Lambda) = \{u \in L^q(M, E) : \|u\|_{W^{e,q}(M, E; \Lambda)} = \sum_{\alpha=1}^N \sum_{l=1}^r \|(\rho_\alpha)^l \circ (\psi_\alpha u) \circ \varphi_\alpha^{-1}\|_{W^{e,q}(\varphi_\alpha(U_\alpha))} < \infty\}$$

As a direct consequence of Theorem H.12, for  $e \geq 0$ ,  $W^{e,q}(M, E; \Lambda) \hookrightarrow L^q(M, E)$ . Therefore the above characterization is completely consistent with the original definition.

(2)

$$W^{e,q}(M, E; \Lambda) = \{u \in D'(M, E) : \|u\|_{W^{e,q}(M, E; \Lambda)} = \sum_{\alpha=1}^N \sum_{l=1}^r \|\text{ext}_{\varphi_\alpha(U_\alpha), \mathbb{R}^n}^0 [H_\alpha(\psi_\alpha u)]^l\|_{W^{e,q}(\mathbb{R}^n)} < \infty\}$$

It follows from Corollary E.44 that

- if  $e$  is not a noninteger less than  $-1$ , then

$$\| [H_\alpha(\psi_\alpha u)]^l \|_{W^{e,q}(\varphi_\alpha(U_\alpha))} \simeq \| \text{ext}_{\varphi_\alpha(U_\alpha), \mathbb{R}^n}^0 [H_\alpha(\psi_\alpha u)]^l \|_{W^{e,q}(\mathbb{R}^n)},$$

- if  $e$  is a noninteger less than  $-1$  and  $\varphi_\alpha(U_\alpha)$  is  $\mathbb{R}^n$  or a bounded open set with Lipschitz continuous boundary, then again the above equality holds.

Therefore when  $e$  is not a noninteger less than  $-1$ , the above characterization completely agrees with the original definition. If  $e$  is a noninteger less than  $-1$  and the total trivialization atlas corresponding to  $\Lambda$  is GGL, then again the two definitions agree.

(3)

$$W^{e,q}(M, E; \Lambda) = \{u \in D'(M, E) : [H_\alpha(\psi_\alpha u)]^l \in W_{loc}^{e,q}(\varphi_\alpha(U_\alpha)), \forall 1 \leq \alpha \leq N, \forall 1 \leq l \leq r\}$$

It follows immediately from Theorem H.15 and Corollary H.18 that the above characterization of the set of Sobolev functions is equivalent to the set given in the original definition provided we assume that if  $e$  is a noninteger less than  $-1$ , then  $\Lambda$  is GL compatible with itself.

- (4)  $W^{e,q}(M, E; \Lambda)$  is the completion of  $C^\infty(M, E)$  with respect to the norm

$$\|u\|_{W^{e,q}(M, E; \Lambda)} = \sum_{\alpha=1}^N \sum_{l=1}^r \|(\rho_\alpha)^l \circ (\psi_\alpha u) \circ \varphi_\alpha^{-1}\|_{W^{e,q}(\varphi_\alpha(U_\alpha))}$$

It follows from Theorem H.26 that if  $e$  is not a noninteger less than  $-1$  the above characterization of Sobolev spaces is equivalent to the original definition. Also if  $e$  is a noninteger less than  $-1$  and  $\Lambda$  is GL compatible with itself the two characterizations are equivalent.

Now we will focus on proving the equivalence of the original definition and the fifth characterization of Sobolev spaces. In what follows instead of  $\|\cdot\|_{W^{k,q}(M, E; g, \nabla^E)}$  we just write  $|\cdot|_{W^{k,q}(M, E)}$ . Also note that since  $k$  is a nonnegative integer, the choice of the augmented total trivialization atlas in Definition H.1 is immaterial. Our proof follows the argument presented in [21] and is based on the following five facts:

- **Fact 1:** Let  $u \in C^\infty(M, E)$  be such that  $\text{supp } u \subseteq U_\beta$  for some  $1 \leq \beta \leq N$ . Then

$$|u|_{L^q(M, E)}^q = \int_M |u|_E^q dV_g \simeq \sum_l \underbrace{\|\rho_\beta^l \circ u \circ \varphi_\beta^{-1}\|_{L^q(\varphi_\beta(U_\beta))}^q}_u$$

- **Fact 2:** Let  $u \in C^\infty(M, E)$  be such that  $\text{supp } u \subseteq U_\beta$  for some  $1 \leq \beta \leq N$ . Then

$$|u|_{W^{k,q}(M, E)}^q \simeq \sum_{i=0}^k \sum_{a=1}^r \sum_{1 \leq j_1, \dots, j_s \leq n} \|((\nabla^E)^i u)_{j_1 \dots j_s}^a \circ \varphi_\beta^{-1}\|_{L^q(\varphi_\beta(U_\beta))}^q$$

*Proof.*

$$\begin{aligned} |u|_{W^{k,q}(M,E)}^q &\simeq \sum_{i=0}^k |(\nabla^E)^i u|_{L^q(M,(T^*M)^{\otimes i} \otimes E)}^q \\ &\stackrel{\text{Fact 1}}{\simeq} \sum_{i=0}^k \sum_{a=1}^r \sum_{1 \leq j_1, \dots, j_s \leq n} \left\| \underbrace{((\nabla^E)^i u)_{j_1 \dots j_s}^a}_{\text{components w.r.t } (U_\beta, \varphi_\beta, \rho_\beta)} \circ \varphi_\beta^{-1} \right\|_{L^q(\varphi_\beta(U_\beta))}^q \end{aligned}$$

□

- **Fact 3:** Let  $u \in C^\infty(M, E)$  be such that  $\text{supp } u \subseteq U_\beta$  for some  $1 \leq \beta \leq N$ . Then

$$\|u\|_{W^{e,q}(M,E)} \simeq \sum_{l=1}^r \|\rho_\beta^l \circ u \circ \varphi_\beta^{-1}\|_{W^{e,q}(\varphi_\beta(U_\beta))}$$

*Proof.* Let  $\{\psi_\alpha\}$  be a partition of unity such that  $\psi_\beta = 1$  on  $\text{supp } u$  (note that since elements of a partition of unity are nonnegative and their sum is equal to 1, we can conclude that if  $\alpha \neq \beta$  then  $\psi_\alpha = 0$  on  $\text{supp } u$ ). We have

$$\begin{aligned} \|u\|_{W^{e,q}(M,E)} &\simeq \sum_{\alpha=1}^N \sum_{l=1}^r \|\rho_\alpha^l \circ (\psi_\alpha u) \circ \varphi_\alpha^{-1}\|_{W^{e,q}(\varphi_\alpha(U_\alpha))} \\ &= \sum_{l=1}^r \|\rho_\beta^l \circ (\psi_\beta u) \circ \varphi_\beta^{-1}\|_{W^{e,q}(\varphi_\beta(U_\beta))} = \sum_{l=1}^r \|\rho_\beta^l \circ u \circ \varphi_\beta^{-1}\|_{W^{e,q}(\varphi_\beta(U_\beta))} \end{aligned}$$

□

- **Fact 4:** Let  $u \in C^\infty(M, E)$ . Then for any multi-index  $\gamma$  and all  $1 \leq l \leq r$  we have (on any total trivialization triple  $(U, \varphi, \rho)$ ):

$$|\partial^\gamma [\rho^l \circ u \circ \varphi^{-1}]| \preceq \sum_{s \leq |\gamma|} \underbrace{\sum_{a=1}^r \sum_{1 \leq j_1, \dots, j_s \leq n}}_{\text{sum over all components of } (\nabla^E)^s u} |((\nabla^E)^s u)_{j_1 \dots j_s}^a \circ \varphi^{-1}|$$

*Proof.* For any multi-index  $\gamma = (\gamma_1, \dots, \gamma_n)$  we define  $\text{seq } \gamma$  to be the following list of numbers

$$\text{seq } \gamma = \underbrace{1 \cdots 1}_{\gamma_1 \text{ times}} \underbrace{2 \cdots 2}_{\gamma_2 \text{ times}} \cdots \underbrace{n \cdots n}_{\gamma_n \text{ times}}$$

Note that there are exactly  $|\gamma| = \gamma_1 + \dots + \gamma_n$  numbers in  $\text{seq } \gamma$ . By Observation 2 in Section C.5.4 we have

$$((\nabla^E)^{|\gamma|} u)_{\text{seq } \gamma}^l \circ \varphi^{-1} = \partial^\gamma [\rho^l \circ u \circ \varphi^{-1}] + \sum_{a=1}^r \sum_{\alpha: |\alpha| < |\gamma|} C_{\alpha a} \partial^\alpha [\rho^a \circ u \circ \varphi^{-1}]$$

Thus

$$\partial^\gamma [\rho^l \circ u \circ \varphi^{-1}] = ((\nabla^E)^{|\gamma|} u)_{\text{seq } \gamma}^l \circ \varphi^{-1} - \sum_{a=1}^r \sum_{\alpha: |\alpha| < |\gamma|} C_{\alpha a} \partial^\alpha [\rho^a \circ u \circ \varphi^{-1}]$$

$$\partial^\alpha [\rho^a \circ u \circ \varphi^{-1}] = ((\nabla^E)^{|\alpha|} u)_{\text{seq } \alpha}^a \circ \varphi^{-1} - \sum_{b=1}^r \sum_{\beta: |\beta| < |\alpha|} C_{\beta b} \partial^\beta [\rho^b \circ u \circ \varphi^{-1}]$$

⋮

where the coefficients  $C_{\alpha a}$ ,  $C_{\beta b}$ , etc. are polynomials in terms of christoffel symbols and the metric and so they are all bounded on the compact manifold  $M$ . Consequently

$$|\partial^\gamma[\rho^l \circ u \circ \varphi^{-1}]| \preceq \sum_{s \leq |\gamma|} \underbrace{\sum_{a=1}^r \sum_{1 \leq j_1, \dots, j_s \leq n}}_{\text{sum over all components of } (\nabla^E)^s u} |((\nabla^E)^s u)_{j_1 \dots j_s}^a \circ \varphi_\beta^{-1}|$$

□

- **Fact 5:** Let  $f \in C^\infty(M, E)$  and  $u \in W^{k,q}(M, \tilde{E})$  where  $\tilde{E}$  is another vector bundle over  $M$ . Then

$$\|f \otimes u\|_{W^{k,q}(M, E \otimes \tilde{E})} \preceq \|u\|_{W^{k,q}(M, \tilde{E})}$$

where the implicit constant may depend on  $f$  but it does not depend on  $u$ .

*Proof.* Let  $\{(U_\alpha, \varphi_\alpha, \rho_\alpha)\}_{1 \leq \alpha \leq N}$  and  $\{(U_\alpha, \varphi_\alpha, \tilde{\rho}_\alpha)\}_{1 \leq \alpha \leq N}$  be total trivialization atlases for  $E$  and  $\tilde{E}$ , respectively. Let  $\{s_{\alpha,a} = \rho_\alpha^{-1}(e_a)\}_{a=1}^r$  be the corresponding local frame for  $E$  on  $U_\alpha$  and  $\{t_{\alpha,b} = \tilde{\rho}_\alpha^{-1}(e_b)\}_{b=1}^{\tilde{r}}$  be the corresponding local frame for  $\tilde{E}$  on  $U_\alpha$ . Let  $G : \{1, \dots, r\} \times \{1, \dots, \tilde{r}\} \rightarrow \{1, \dots, r\tilde{r}\}$  be an arbitrary but fixed bijective function. Then  $\{(U_\alpha, \varphi_\alpha, \hat{\rho}_\alpha)\}$  is a total trivialization atlas for  $E \otimes \tilde{E}$  where

$$\hat{\rho}_\alpha(s_{\alpha,a} \otimes t_{\alpha,b}) = e_{G(a,b)} \text{ (as an element of } \mathbb{R}^{r\tilde{r}})$$

and it is extended by linearity to the  $E \otimes \tilde{E}|_{U_\alpha}$ . Now we have

$$\begin{aligned} \|f \otimes u\|_{W^{k,q}(M, E \otimes \tilde{E})} &= \sum_{\alpha=1}^N \sum_{a=1}^r \sum_{b=1}^{\tilde{r}} \|\rho_\alpha^{a,b} \circ (\psi_\alpha f \otimes u) \circ \varphi_\alpha^{-1}\|_{W^{k,q}(\varphi_\alpha(U_\alpha))} \\ &= \sum_{\alpha=1}^N \sum_{a=1}^r \sum_{b=1}^{\tilde{r}} \|(\psi_\alpha \circ \varphi_\alpha^{-1})(f_\alpha^a \circ \varphi_\alpha^{-1})(u_\alpha^b \circ \varphi_\alpha^{-1})\|_{W^{k,q}(\varphi_\alpha(U_\alpha))} \end{aligned}$$

where  $f = f_\alpha^a s_a$  and  $u = u_\alpha^b t_b$  on  $U_\alpha$ . Clearly  $f_\alpha^a \circ \varphi_\alpha^{-1} \in C^\infty(\varphi_\alpha(U_\alpha))$ . Therefore

$$\|f \otimes u\|_{W^{k,q}(M, E \otimes \tilde{E})} \preceq \sum_{\alpha=1}^N \sum_{b=1}^{\tilde{r}} \|(\psi_\alpha \circ \varphi_\alpha^{-1})(u_\alpha^b \circ \varphi_\alpha^{-1})\|_{W^{k,q}(\varphi_\alpha(U_\alpha))} \simeq \|u\|_{W^{k,q}(M, \tilde{E})}$$

□

- **Part I:** First we prove that  $\|u\|_{W^{k,q}(M, E)} \preceq |u|_{W^{k,q}(M, E)}$ .

(1) **Case 1:** Suppose there exists  $1 \leq \beta \leq N$  such that  $\text{supp } u \subseteq U_\beta$ . We have

$$\begin{aligned} \|u\|_{W^{k,q}(M, E)}^q &\stackrel{\text{Fact 3}}{\simeq} \sum_{l=1}^r \|\rho_\beta^l \circ u \circ \varphi_\beta^{-1}\|_{W^{k,q}(\varphi_\beta(U_\beta))}^q = \sum_{l=1}^r \sum_{|\gamma| \leq k} \|\partial^\gamma(\rho_\beta^l \circ u \circ \varphi_\beta^{-1})\|_{L^q(\varphi_\beta(U_\beta))}^q \\ &\stackrel{\text{Fact 4}}{\preceq} \sum_{l=1}^r \sum_{|\gamma| \leq k} \sum_{s \leq |\gamma|} \sum_{a=1}^r \sum_{1 \leq j_1, \dots, j_s \leq n} \|((\nabla^E)^s u)_{j_1 \dots j_s}^a \circ \varphi_\beta^{-1}\|_{L^q(\varphi_\beta(U_\beta))}^q \\ &\preceq \sum_{s=0}^k \sum_{a=1}^r \sum_{1 \leq j_1, \dots, j_s \leq n} \|((\nabla^E)^s u)_{j_1 \dots j_s}^a \circ \varphi_\beta^{-1}\|_{L^q(\varphi_\beta(U_\beta))}^q \\ &\stackrel{\text{Fact 2}}{\simeq} |u|_{W^{k,q}(M, E)}^q \end{aligned}$$



(2) **Case 2:** Now let  $u$  be an arbitrary element of  $C^\infty(M, E)$ . We have

$$\begin{aligned} \|u\|_{W^{k,q}(M,E)} &= \left\| \sum_{\alpha=1}^N \psi_\alpha u \right\|_{W^{k,q}(M,E)} \leq \sum_{\alpha=1}^N \|\psi_\alpha u\|_{W^{k,q}(M,E)} \\ &\preceq \sum_{\alpha=1}^N |\psi_\alpha u|_{W^{k,q}(M,E)} \quad (\text{by what was proved in Case 1}) \\ &\stackrel{\text{see the Box}}{\preceq} \sum_{\alpha=1}^N |u|_{W^{k,q}(M,E)} \simeq |u|_{W^{k,q}(M,E)} \end{aligned}$$

$$\begin{aligned} |\psi_\alpha u|_{W^{k,q}(M,E)}^q &= \sum_{i=0}^k \|(\nabla^E)^i(\psi_\alpha u)\|_{L^q(M, (T^*M)^{\otimes i} \otimes E)}^q \\ &= \sum_{i=0}^k \left\| \sum_{j=0}^i \binom{i}{j} \nabla^j \psi_\alpha \otimes (\nabla^E)^{i-j} u \right\|_{L^q(M, (T^*M)^{\otimes i} \otimes E)}^q \\ &\stackrel{\text{Fact 5}}{\preceq} \sum_{i=0}^k \sum_{j=0}^i \|(\nabla^E)^{i-j} u\|_{L^q(M, (T^*M)^{\otimes (i-j)} \otimes E)}^q \\ &\preceq \sum_{s=0}^k \|(\nabla^E)^s u\|_{L^q(M, (T^*M)^{\otimes s} \otimes E)}^q \simeq |u|_{W^{k,q}(M,E)}^q \end{aligned}$$

• **Part II:** Now we show that  $|u|_{W^{k,q}(M,E)} \preceq \|u\|_{W^{k,q}(M,E)}$ .

(1) **Case 1:** Suppose there exists  $1 \leq \beta \leq N$  such that  $\text{supp} u \subseteq U_\beta$ .

$$\begin{aligned} |u|_{W^{k,q}(M,E)}^q &\stackrel{\text{Fact 2}}{\simeq} \sum_{s=0}^k \sum_{a=1}^r \sum_{1 \leq j_1, \dots, j_s \leq n} \|((\nabla^E)^s u)_{j_1 \dots j_s}^a \circ \varphi_\beta^{-1}\|_{L^q(\varphi_\beta(U_\beta))}^q \\ &\stackrel{\text{Observation 1 in C.5.4}}{=} \sum_{s=0}^k \sum_{a=1}^r \sum_{1 \leq j_1, \dots, j_s \leq n} \left\| \sum_{|\eta| \leq s} \sum_{l=1}^r (C_{\eta l})_{j_1 \dots j_s}^a \partial^\eta \underbrace{(u^l \circ \varphi_\beta^{-1})}_{\rho_\beta^l \circ u} \right\|_{L^q(\varphi_\beta(U_\beta))}^q \\ &\preceq \sum_{l=1}^r \sum_{|\eta| \leq k} \|\partial^\eta (u^l \circ \varphi_\beta^{-1})\|_{L^q(\varphi_\beta(U_\beta))}^q = \sum_{l=1}^r \|u^l \circ \varphi_\beta^{-1}\|_{W^{k,q}(\varphi_\beta(U_\beta))}^q \\ &\simeq \|u\|_{W^{k,q}(M,E)}^q \end{aligned}$$

(2) **Case 2:** Now let  $u$  be an arbitrary element of  $C^\infty(M, E)$ .

$$\begin{aligned} |u|_{W^{k,q}(M,E)} &= \left| \sum_{\alpha=1}^N \psi_\alpha u \right|_{W^{k,q}(M,E)} \leq \sum_{\alpha=1}^N |\psi_\alpha u|_{W^{k,q}(M,E)} \\ &\stackrel{\text{Case 1}}{\preceq} \sum_{\alpha=1}^N \|\psi_\alpha u\|_{W^{k,q}(M,E)} \stackrel{\text{Fact 3}}{\simeq} \sum_{\alpha=1}^N \sum_{l=1}^r \|\rho_\alpha^l \circ (\psi_\alpha u) \circ \varphi_\alpha^{-1}\|_{W^{k,q}(\varphi_\alpha(U_\alpha))} \\ &\simeq \|u\|_{W^{k,q}(M,E)} \end{aligned}$$

## APPENDIX I. SOME RESULTS ON DIFFERENTIAL OPERATORS

Let  $M^n$  be a compact smooth manifold. Let  $E$  and  $\tilde{E}$  be two vector bundles over  $M$  of ranks  $r$  and  $\tilde{r}$ , respectively. A **linear** operator  $P : C^\infty(M, E) \rightarrow \Gamma(M, \tilde{E})$  is called **local** if

$$\forall u \in C^\infty(M, E) \quad \text{supp } Pu \subseteq \text{supp } u$$

If  $P$  is a local operator, then it is possible to have a well defined notion of restriction of  $P$  to open sets  $U \subseteq M$ , that is, if  $P : C^\infty(M, E) \rightarrow \Gamma(M, \tilde{E})$  is local and  $U \subseteq M$  is open, then we can define a map

$$P|_U : C^\infty(U, E_U) \rightarrow \Gamma(U, \tilde{E}_U)$$

with the property that

$$\forall u \in C^\infty(M, E) \quad (Pu)|_U = P|_U(u|_U)$$

Indeed suppose  $u, \tilde{u} \in C^\infty(M, E)$  agree on  $U$ , then as a result of  $P$  being local we have

$$\text{supp } (Pu - P\tilde{u}) \subseteq \text{supp } (u - \tilde{u}) \subseteq M \setminus U$$

Therefore if  $u|_U = \tilde{u}|_U$ , then  $(Pu)|_U = (P\tilde{u})|_U$ . Thus, if  $v \in C^\infty(U, E_U)$  and  $x \in U$ , we can define  $(P|_U)(v)(x)$  as follows: choose any  $u \in C^\infty(M, E)$  such that  $u = v$  on a neighborhood of  $x$  and then let  $(P|_U)(v)(x) = (Pu)(x)$ .

Recall that for any nonempty set  $V$ ,  $\text{Func}(V, \mathbb{R}^t)$  denotes the vector space of all functions from  $V$  to  $\mathbb{R}^t$ . By the **local representation of  $P$**  with respect to the total trivialization triples  $(U, \varphi, \rho)$  of  $E$  and  $(U, \varphi, \tilde{\rho})$  of  $\tilde{E}$  we mean the linear transformation  $Q : C^\infty(\varphi(U), \mathbb{R}^r) \rightarrow \text{Func}(\varphi(U), \mathbb{R}^{\tilde{r}})$  defined by

$$Q(f) = \tilde{\rho} \circ P(\rho^{-1} \circ f \circ \varphi) \circ \varphi^{-1}$$

Note that  $\rho^{-1} \circ f \circ \varphi$  is a section of  $E_U \rightarrow U$ . Also note that for all  $u \in C^\infty(M, E)$

$$\tilde{\rho} \circ (P(u|_U)) \circ \varphi^{-1} = Q(\rho \circ (u|_U) \circ \varphi^{-1}) \quad (\text{I.1})$$

Let's denote the components of  $f \in C^\infty(\varphi(U), \mathbb{R}^r)$  by  $(f^1, \dots, f^r)$ . Then we can write  $Q(f^1, \dots, f^r) = (h^1, \dots, h^{\tilde{r}})$  where for all  $1 \leq k \leq \tilde{r}$

$$h^k = \pi_k \circ Q(f^1, \dots, f^r) \stackrel{Q \text{ is linear}}{=} \pi_k \circ Q(f^1, 0, \dots, 0) + \dots + \pi_k \circ Q(0, \dots, 0, f^r)$$

So if for each  $1 \leq k \leq \tilde{r}$  and  $1 \leq i \leq r$  we define  $Q_{ki} : C^\infty(\varphi(U), \mathbb{R}) \rightarrow \text{Func}(\varphi(U), \mathbb{R})$  by

$$Q_{ki}(g) = \pi_k \circ Q(0, \dots, 0, \underbrace{g}_{i^{\text{th}} \text{ position}}, 0, \dots, 0)$$

then we have

$$Q(f^1, \dots, f^r) = \left( \sum_{i=1}^r Q_{1i}(f^i), \dots, \sum_{i=1}^r Q_{\tilde{r}i}(f^i) \right)$$

In particular, note that the  $s^{\text{th}}$  component of  $\tilde{\rho} \circ Pu \circ \varphi^{-1}$ , that is  $\tilde{\rho}^s \circ Pu \circ \varphi^{-1}$ , is equal to the  $s^{\text{th}}$  component of  $Q(\rho^1 \circ u \circ \varphi^{-1}, \dots, \rho^r \circ u \circ \varphi^{-1})$  (see Equation I.1) which is equal to

$$\sum_{i=1}^r Q_{si}(\rho^i \circ u \circ \varphi^{-1})$$

**Theorem I.1.** *Let  $M^n$  be a compact smooth manifold. Let  $P : C^\infty(M, E) \rightarrow \Gamma(M, \tilde{E})$  be a local operator. Let  $\Lambda = \{(U_\alpha, \varphi_\alpha, \rho_\alpha, \psi_\alpha)\}_{1 \leq \alpha \leq N}$  and  $\tilde{\Lambda} = \{(U_\alpha, \varphi_\alpha, \tilde{\rho}_\alpha, \psi_\alpha)\}_{1 \leq \alpha \leq N}$  be two augmented total trivialization atlases for  $E$  and  $\tilde{E}$ , respectively. Suppose the atlas  $\{(U_\alpha, \varphi_\alpha)\}_{1 \leq \alpha \leq N}$  is GL compatible with itself. For each  $1 \leq \alpha \leq N$ , let  $Q^\alpha$  denote the local representation of  $P$  with respect to the total trivialization triples  $(U_\alpha, \varphi_\alpha, \rho_\alpha)$  and  $(U_\alpha, \varphi_\alpha, \tilde{\rho}_\alpha)$  of  $E$  and  $\tilde{E}$ , respectively. Suppose for each  $1 \leq \alpha \leq N$ ,  $1 \leq i \leq \tilde{r}$ , and  $1 \leq j \leq r$ ,*

- (1)  $Q_{ij}^\alpha : (C_c^\infty(\varphi_\alpha(U_\alpha)), \|\cdot\|_{e,q}) \rightarrow W^{e,\sharp}(\varphi_\alpha(U_\alpha))$  is well defined and continuous and does not increase support, and
- (2) if  $\Omega = \varphi_\alpha(U_\alpha)$  or  $\Omega$  is an open bounded subset of  $\varphi_\alpha(U_\alpha)$  with Lipschitz continuous boundary, then for all  $h \in C^\infty(\Omega)$  and  $\eta, \psi \in C_c^\infty(\varphi_\alpha(U_\alpha))$  with  $\eta h \in C_c^\infty(\Omega)$ , we have

$$\|\eta[Q_{ij}^\alpha, \psi]h\|_{W^{\tilde{e},\tilde{q}}(\cdot)} \preceq \|\eta h\|_{W^{e,q}(\cdot)} \quad (\text{I.2})$$

where  $[Q_{ij}^\alpha, \psi]h := Q_{ij}^\alpha(\psi h) - \psi Q_{ij}^\alpha(h)$  (the implicit constant may depend on  $\xi$  and  $\psi$  but it does not depend on  $h$ ). Then

- $P(C^\infty(M, E)) \subseteq W^{e,\sharp}(M, \tilde{E}; \tilde{\Lambda})$
- $P : (C^\infty(M, E), \|\cdot\|_{e,q}) \rightarrow W^{e,\sharp}(M, \tilde{E}; \tilde{\Lambda})$  is continuous and so it can be extended to a continuous linear map  $P : W^{e,q}(M, E; \Lambda) \rightarrow W^{e,\sharp}(M, \tilde{E}; \tilde{\Lambda})$ .

*Proof.* First note that

$$\begin{aligned} \|Pu\|_{W^{\tilde{e},\tilde{q}}(M, \tilde{E}; \tilde{\gamma})} &= \sum_{\alpha=1}^N \sum_{i=1}^{\tilde{r}} \|\tilde{\rho}_\alpha^i \circ (\psi_\alpha(Pu)) \circ \varphi_\alpha^{-1}\|_{W^{\tilde{e},\tilde{q}}(\varphi_\alpha(U_\alpha))} \\ \|u\|_{W^{e,q}(M, E; \gamma)} &= \sum_{\alpha=1}^N \sum_{j=1}^r \|\rho_\alpha^j \circ (\psi_\alpha u) \circ \varphi_\alpha^{-1}\|_{W^{e,q}(\varphi_\alpha(U_\alpha))} \end{aligned}$$

It is enough to show that for all  $1 \leq \alpha \leq N$ ,  $1 \leq i \leq \tilde{r}$

$$\|\tilde{\rho}_\alpha^i \circ (\psi_\alpha(Pu)) \circ \varphi_\alpha^{-1}\|_{W^{\tilde{e},\tilde{q}}(\varphi_\alpha(U_\alpha))} \preceq \sum_{\beta=1}^N \sum_{j=1}^r \|\rho_\beta^j \circ (\psi_\beta u) \circ \varphi_\beta^{-1}\|_{W^{e,q}(\varphi_\beta(U_\beta))}$$

We have

$$\begin{aligned} \|\tilde{\rho}_\alpha^i \circ (\psi_\alpha(Pu)) \circ \varphi_\alpha^{-1}\|_{W^{\tilde{e},\tilde{q}}(\varphi_\alpha(U_\alpha))} &= \|(\psi_\alpha \circ \varphi_\alpha^{-1}) \cdot (\tilde{\rho}_\alpha^i \circ (Pu) \circ \varphi_\alpha^{-1})\|_{W^{\tilde{e},\tilde{q}}(\varphi_\alpha(U_\alpha))} \\ &\leq \sum_{j=1}^r \|(\psi_\alpha \circ \varphi_\alpha^{-1}) \cdot Q_{ij}^\alpha(\rho_\alpha^j \circ (\sum_{\beta=1}^N \psi_\beta u) \circ \varphi_\alpha^{-1})\|_{W^{\tilde{e},\tilde{q}}(\varphi_\alpha(U_\alpha))} \end{aligned}$$

(see the paragraph above Theorem I.1)

$$\leq \sum_{\beta=1}^N \sum_{j=1}^r \|(\psi_\alpha \circ \varphi_\alpha^{-1}) \cdot Q_{ij}^\alpha(\rho_\alpha^j \circ (\psi_\beta u) \circ \varphi_\alpha^{-1})\|_{W^{\tilde{e},\tilde{q}}(\varphi_\alpha(U_\alpha))}$$

$$\begin{aligned}
& \preceq \sum_{\beta=1}^N \sum_{j=1}^r \left( \left\| Q_{ij}^\alpha(\rho_\alpha^j \circ (\psi_\alpha \psi_\beta u) \circ \varphi_\alpha^{-1}) \right\|_{W^{\bar{e}, \bar{q}}(\varphi_\alpha(U_\alpha))} \right. \\
& \quad \left. + \left\| [Q_{ij}^\alpha, \psi_\alpha \circ \varphi_\alpha^{-1}](\rho_\alpha^j \circ (\psi_\beta u) \circ \varphi_\alpha^{-1}) \right\|_{W^{\bar{e}, \bar{q}}(\varphi_\alpha(U_\alpha))} \right) \\
& \preceq \sum_{\beta=1}^N \sum_{j=1}^r \left\| \rho_\alpha^j \circ (\psi_\alpha \psi_\beta u) \circ \varphi_\alpha^{-1} \right\|_{W^{e, q}(\varphi_\alpha(U_\alpha))} \\
& \quad + \sum_{\beta=1}^N \sum_{j=1}^r \left\| [Q_{ij}^\alpha, \psi_\alpha \circ \varphi_\alpha^{-1}](\rho_\alpha^j \circ (\psi_\beta u) \circ \varphi_\alpha^{-1}) \right\|_{W^{\bar{e}, \bar{q}}(\varphi_\alpha(U_\alpha))}
\end{aligned}$$

Note that  $\rho_\alpha^j \circ (\psi_\alpha \psi_\beta u) \circ \varphi_\alpha^{-1} = (\psi_\alpha \psi_\beta \circ \varphi_\alpha^{-1})(\rho_\alpha^j \circ u \circ \varphi_\alpha^{-1})$  and  $[Q_{ij}^\alpha, \psi_\alpha \circ \varphi_\alpha^{-1}](\rho_\alpha^j \circ (\psi_\beta u) \circ \varphi_\alpha^{-1})$  both have compact support in  $\varphi_\alpha(U_\alpha \cap U_\beta)$ . So it follows from Corollary E.44 that

$$\begin{aligned}
& \left\| \rho_\alpha^j \circ (\psi_\alpha \psi_\beta u) \circ \varphi_\alpha^{-1} \right\|_{W^{e, q}(\varphi_\alpha(U_\alpha))} \simeq \left\| \rho_\alpha^j \circ (\psi_\alpha \psi_\beta u) \circ \varphi_\alpha^{-1} \right\|_{W^{e, q}(\varphi_\alpha(U_\alpha \cap U_\beta))} \\
& \left\| [Q_{ij}^\alpha, \psi_\alpha \circ \varphi_\alpha^{-1}](\rho_\alpha^j \circ (\psi_\beta u) \circ \varphi_\alpha^{-1}) \right\|_{W^{\bar{e}, \bar{q}}(\varphi_\alpha(U_\alpha))} \\
& \quad \simeq \left\| [Q_{ij}^\alpha, \psi_\alpha \circ \varphi_\alpha^{-1}](\rho_\alpha^j \circ (\psi_\beta u) \circ \varphi_\alpha^{-1}) \right\|_{W^{\bar{e}, \bar{q}}(\varphi_\alpha(U_\alpha \cap U_\beta))}
\end{aligned}$$

Let  $\xi \in C_c^\infty(U_\alpha)$  be such that  $\xi = 1$  on  $\text{supp } \psi_\alpha$ . Clearly we have

$$\begin{aligned}
& \left\| [Q_{ij}^\alpha, \psi_\alpha \circ \varphi_\alpha^{-1}](\rho_\alpha^j \circ (\psi_\beta u) \circ \varphi_\alpha^{-1}) \right\|_{W^{\bar{e}, \bar{q}}(\varphi_\alpha(U_\alpha \cap U_\beta))} \\
& \quad = \left\| (\xi \circ \varphi_\alpha^{-1})[Q_{ij}^\alpha, \psi_\alpha \circ \varphi_\alpha^{-1}](\rho_\alpha^j \circ (\psi_\beta u) \circ \varphi_\alpha^{-1}) \right\|_{W^{\bar{e}, \bar{q}}(\varphi_\alpha(U_\alpha \cap U_\beta))} \\
& \quad \stackrel{\text{Equation I.2}}{\leq} \left\| \rho_\alpha^j \circ (\xi \psi_\beta u) \circ \varphi_\alpha^{-1} \right\|_{W^{e, q}(\varphi_\alpha(U_\alpha \cap U_\beta))}
\end{aligned}$$

Therefore

$$\begin{aligned}
& \left\| \tilde{\rho}_\alpha^j \circ (\psi_\alpha(Pu)) \circ \varphi_\alpha^{-1} \right\|_{W^{\bar{e}, \bar{q}}(\varphi_\alpha(U_\alpha))} \\
& \preceq \sum_{\beta=1}^N \sum_{j=1}^r \left\| \rho_\alpha^j \circ (\psi_\alpha \psi_\beta u) \circ \varphi_\alpha^{-1} \right\|_{W^{e, q}(\varphi_\alpha(U_\alpha \cap U_\beta))} \\
& \quad + \sum_{\beta=1}^N \sum_{j=1}^r \left\| \rho_\alpha^j \circ (\xi \psi_\beta u) \circ \varphi_\alpha^{-1} \right\|_{W^{e, q}(\varphi_\alpha(U_\alpha \cap U_\beta))} \\
& = \sum_{\beta=1}^N \sum_{j=1}^r \left\| \rho_\alpha^j \circ (\psi_\alpha \psi_\beta u) \circ \varphi_\beta^{-1} \circ \varphi_\beta \circ \varphi_\alpha^{-1} \right\|_{W^{e, q}(\varphi_\alpha(U_\alpha \cap U_\beta))} \\
& \quad + \sum_{\beta=1}^N \sum_{j=1}^r \left\| \rho_\alpha^j \circ (\xi \psi_\beta u) \circ \varphi_\beta^{-1} \circ \varphi_\beta \circ \varphi_\alpha^{-1} \right\|_{W^{e, q}(\varphi_\alpha(U_\alpha \cap U_\beta))} \\
& \stackrel{\text{Theorem E.60}}{\preceq} \sum_{\beta=1}^N \sum_{j=1}^r \left\| \rho_\alpha^j \circ (\psi_\alpha \psi_\beta u) \circ \varphi_\beta^{-1} \right\|_{W^{e, q}(\varphi_\beta(U_\alpha \cap U_\beta))} \\
& \quad + \sum_{\beta=1}^N \sum_{j=1}^r \left\| \rho_\alpha^j \circ (\xi \psi_\beta u) \circ \varphi_\beta^{-1} \right\|_{W^{e, q}(\varphi_\beta(U_\alpha \cap U_\beta))}
\end{aligned}$$

$$\begin{aligned}
 &= \sum_{\beta=1}^N \sum_{j=1}^r \left\| (\psi_\alpha \circ \varphi_\beta^{-1})(\rho_\alpha^j \circ (\psi_\beta u) \circ \varphi_\beta^{-1}) \right\|_{W^{e,q}(\varphi_\beta(U_\alpha \cap U_\beta))} \\
 &\quad + \sum_{\beta=1}^N \sum_{j=1}^r \left\| (\xi \circ \varphi_\beta^{-1})(\rho_\alpha^j \circ (\psi_\beta u) \circ \varphi_\beta^{-1}) \right\|_{W^{e,q}(\varphi_\beta(U_\alpha \cap U_\beta))} \\
 &\preceq \sum_{\beta=1}^N \sum_{j=1}^r \left\| (\psi_\alpha \circ \varphi_\beta^{-1})(\rho_\alpha^j \circ (\psi_\beta u) \circ \varphi_\beta^{-1}) \right\|_{W^{e,q}(\varphi_\beta(U_\beta))} \\
 &\quad + \sum_{\beta=1}^N \sum_{j=1}^r \left\| (\xi \circ \varphi_\beta^{-1})(\rho_\alpha^j \circ (\psi_\beta u) \circ \varphi_\beta^{-1}) \right\|_{W^{e,q}(\varphi_\beta(U_\beta))} \\
 &\preceq \sum_{\beta=1}^N \sum_{j=1}^r \left\| \rho_\alpha^j \circ (\psi_\beta u) \circ \varphi_\beta^{-1} \right\|_{W^{e,q}(\varphi_\beta(U_\beta))} \\
 &= \sum_{\beta=1}^N \sum_{j=1}^r \left\| \pi_j \circ \underbrace{\pi' \circ \Phi_\alpha}_{\rho_\alpha} \circ (\psi_\beta u) \circ \varphi_\beta^{-1} \right\|_{W^{e,q}(\varphi_\beta(U_\beta))} \\
 &= \sum_{\beta=1}^N \sum_{j=1}^r \left\| \pi_j \circ \pi' \circ \Phi_\alpha \circ \Phi_\beta^{-1} \circ \Phi_\beta \circ (\psi_\beta u) \circ \varphi_\beta^{-1} \right\|_{W^{e,q}(\varphi_\beta(U_\beta))}
 \end{aligned}$$

Define  $v_\beta : \varphi_\beta(U_\beta) \rightarrow E$  by  $v_\beta(x) = (\psi_\beta u) \circ \varphi_\beta^{-1}$ . Clearly  $\pi(v_\beta(x)) = \varphi_\beta^{-1}(x)$ . We have

$$\Phi_\beta(v_\beta(x)) = (\pi(v_\beta(x)), \rho_\beta(v_\beta(x))) = (\varphi_\beta^{-1}(x), \rho_\beta(v_\beta(x)))$$

So by Lemma C.24

$$\begin{aligned}
 \pi' \circ \Phi_\alpha \circ \Phi_\beta^{-1}(\Phi_\beta(v_\beta(x))) &= \pi' \circ \Phi_\alpha \circ \Phi_\beta^{-1}(\varphi_\beta^{-1}(x), \rho_\beta(v_\beta(x))) \\
 &= \pi' \circ (\varphi_\beta^{-1}(x), \tau_{\alpha\beta}(\varphi_\beta^{-1}(x))\rho_\beta(v_\beta(x))) \\
 &= \underbrace{\tau_{\alpha\beta}(\varphi_\beta^{-1}(x))}_{\text{an } r \times r \text{ matrix}} \rho_\beta(v_\beta(x))
 \end{aligned}$$

Let  $A_{\alpha\beta} = \tau_{\alpha\beta} \circ \varphi_\beta^{-1}$ . We have

$$\begin{aligned}
 \left\| \tilde{\rho}_\alpha^i \circ (\psi_\alpha(Pu)) \circ \varphi_\alpha^{-1} \right\|_{W^{\tilde{e},\tilde{q}}(\varphi_\alpha(U_\alpha))} &\preceq \sum_{\beta=1}^N \sum_{j=1}^r \left\| \pi_j \circ A_{\alpha\beta}(x) \rho_\beta(v_\beta(x)) \right\|_{W^{e,q}(\varphi_\beta(U_\beta))} \\
 &= \sum_{\beta=1}^N \sum_{j=1}^r \left\| \sum_{l=1}^r (A_{\alpha\beta}(x))_{jl} \rho_\beta^l(v_\beta(x)) \right\|_{W^{e,q}(\varphi_\beta(U_\beta))} \\
 &\leq \sum_{\beta=1}^N \sum_{j=1}^r \sum_{l=1}^r \left\| (A_{\alpha\beta}(x))_{jl} \rho_\beta^l(v_\beta(x)) \right\|_{W^{e,q}(\varphi_\beta(U_\beta))}
 \end{aligned}$$

$\rho_\beta^l(v_\beta(x))$  has support inside the compact set  $\varphi_\beta(\text{supp}\psi_\beta)$  and  $(A_{\alpha\beta}(x))_{jl}$  are smooth functions. Therefore by Theorem E.41 and Corollary E.27

$$\left\| (A_{\alpha\beta}(x))_{jl} \rho_\beta^l(v_\beta(x)) \right\|_{W^{e,q}(\varphi_\beta(U_\beta))} \preceq \left\| \rho_\beta^l(v_\beta(x)) \right\|_{W^{e,q}(\varphi_\beta(U_\beta))}$$

Consequently

$$\begin{aligned}
& \|\tilde{\rho}_\alpha^i \circ (\psi_\alpha(Pu)) \circ \varphi_\alpha^{-1}\|_{W^{\bar{e},\bar{q}}(\varphi_\alpha(U_\alpha))} \preceq \sum_{\beta=1}^N \sum_{j=1}^r \sum_{l=1}^r \|\rho_\beta^l(v_\beta(x))\|_{W^{e,q}(\varphi_\beta(U_\beta))} \\
& \preceq \sum_{\beta=1}^N \sum_{l=1}^r \|\rho_\beta^l(v_\beta(x))\|_{W^{e,q}(\varphi_\beta(U_\beta))} \\
& = \sum_{\beta=1}^N \sum_{l=1}^r \|\rho_\beta^l \circ (\psi_\beta u) \circ \varphi_\beta^{-1}\|_{W^{e,q}(\varphi_\beta(U_\beta))}
\end{aligned}$$

□

In the following examples we assume  $(M^n, g)$  is a compact Riemannian manifold with  $g \in W^{s,p}(M, T^2M)$ ,  $sp > n$ , and  $s \geq 1$ . The local representations are all assumed to be with respect to charts in a super nice total trivialization atlas that is GL compatible with itself.

- **Example 1: Differential** Consider  $d : C^\infty(M) \rightarrow C^\infty(T^*M)$ . The local representation of  $d$  is  $Q : C^\infty(\varphi(U)) \rightarrow C^\infty(\varphi(U), \mathbb{R}^n)$  which is defined by

$$\begin{aligned}
Q(f)(a) &= \tilde{\rho} \circ d(\rho^{-1} \circ f \circ \varphi) \circ \varphi^{-1}(a) \\
&= \tilde{\rho} \circ \left( \frac{\partial f}{\partial x^i} \Big|_{\varphi(\varphi^{-1}(a))} dx^i \Big|_{\varphi^{-1}(a)} \right) \\
&= \left( \frac{\partial f}{\partial x^1} \Big|_a, \dots, \frac{\partial f}{\partial x^n} \Big|_a \right)
\end{aligned}$$

Here we used  $\rho = Id$  and the fact that if  $g : M \rightarrow \mathbb{R}$  is smooth, then

$$(dg)(p) = \frac{\partial(g \circ \varphi^{-1})}{\partial x^i} \Big|_{\varphi(p)} dx^i \Big|_p$$

Clearly each component of  $Q$  is a continuous operator from  $(C_c^\infty(\varphi(U)), \|\cdot\|_{e,q})$  to  $W^{e-1,q}(\varphi(U))$  (see Theorem E.63; note that  $\varphi(U) = \mathbb{R}^n$ ). Also considering that

$$\forall 1 \leq i \leq n \quad Q_{i1}(h) = \frac{\partial h}{\partial x^i}, \quad [Q_{i1}, \psi]h = \frac{\partial \psi}{\partial x^i} h$$

the required property for  $[Q_{i1}, \psi]$  holds true.

Hence  $d$  can be viewed as a continuous operator from  $W^{e,q}(M)$  to  $W^{e-1,q}(T^*M)$ .

- **Example 2: Gradient** Suppose  $e$  and  $q$  are such that for balls  $\Omega \subseteq \mathbb{R}^n$  or for  $\Omega = \mathbb{R}^n$

$$W^{s,p}(\Omega) \times W^{e,q}(\Omega) \hookrightarrow W^{e,q}(\Omega)$$

In section 4 we proved that  $\text{sharp}_g : W^{e,q}(T^*M) \rightarrow W^{e,q}(TM)$  is well defined and continuous. Also in the previous example we showed that for all  $e$  and  $q$ ,  $d : W^{e+1,q}(M) \rightarrow W^{e,q}(T^*M)$  is well defined and continuous. Consequently  $\text{grad}_g : W^{e+1,q}(M) \rightarrow W^{e,q}(TM)$  defined by

$$\text{grad}_g = \text{sharp}_g \circ d$$

is also continuous.

- **Example 3: Divergence** Consider  $\text{div} : C^\infty(TM) \rightarrow \text{Func}(M, \mathbb{R})$ . Here we will show that if  $e$  and  $q$  are such that

$$W^{s,p}(\mathbb{R}^n) \times W^{e,q}(\mathbb{R}^n) \hookrightarrow W^{e,q}(\mathbb{R}^n) \tag{I.3}$$

$$W^{s,p}(\mathbb{R}^n) \times W^{e-1,q}(\mathbb{R}^n) \hookrightarrow W^{e-1,q}(\mathbb{R}^n) \tag{I.4}$$

then  $\text{div}$  can be considered as a continuous operator from  $W^{e,q}(TM)$  to  $W^{e-1,q}(M)$ . The local representation of divergence with respect to the coordinate chart  $(U, \varphi)$  is  $Q : C^\infty(\varphi(U), \mathbb{R}^n) \rightarrow \text{Func}(\varphi(U), \mathbb{R})$  defined by

$$\begin{aligned} Q(Y) &= \tilde{\rho} \circ \text{div}(\rho^{-1} \circ Y \circ \varphi) \circ \varphi^{-1} \quad (Y : \varphi(U) \rightarrow \mathbb{R}^n, \quad Y = (Y^1, \dots, Y^n)) \\ &= \text{div}((Y^1 \circ \varphi)\partial_1 + \dots + (Y^n \circ \varphi)\partial_n) \circ \varphi^{-1} \\ &= \sum_{j=1}^n \frac{1}{\sqrt{\det g} \circ \varphi^{-1}} \frac{\partial}{\partial x^j} [(\sqrt{\det g} \circ \varphi^{-1})(Y^j)] \end{aligned}$$

Note that in the above,  $\tilde{\rho} = Id$  and

$$\rho^{-1}(Y \circ \varphi) = \rho^{-1}(Y^1 \circ \varphi, \dots, Y^n \circ \varphi) = (Y^1 \circ \varphi)\partial_1 + \dots + (Y^n \circ \varphi)\partial_n$$

Moreover, we used the fact that for any vector field  $X$  defined on  $U$

$$(\text{div} X) \circ \varphi^{-1} = \sum_{j=1}^n \frac{1}{\sqrt{\det g} \circ \varphi^{-1}} \frac{\partial}{\partial x^j} [(\sqrt{\det g} \circ \varphi^{-1})(X^j \circ \varphi^{-1})]$$

Also note that  $Q(Y) = \sum_{j=1}^n Q_{1j}(Y^j)$  where  $Q_{1j} : C^\infty(\varphi(U), \mathbb{R}) \rightarrow \text{Func}(\varphi(U), \mathbb{R})$  and for all  $f \in C^\infty(\varphi(U), \mathbb{R})$ ,  $Q_{1j}(f)$  is the first (the only) component of

$$Q(0, \dots, 0, \underbrace{f}_{j^{\text{th}} \text{ position}}, 0, \dots, 0)$$

That is,

$$\forall 1 \leq j \leq n \quad Q_{1j}(f) = \frac{1}{\sqrt{\det g} \circ \varphi^{-1}} \frac{\partial}{\partial x^j} [(\sqrt{\det g} \circ \varphi^{-1})(f)]$$

Now suppose  $f \in C_c^\infty(\varphi(U))$ . In particular,  $f \in W_{\text{comp}}^{e,q}(\varphi(U))$ . It follows from the hypotheses on  $e$  and  $q$  that (see Lemma F.9)

$$\begin{aligned} W_{\text{loc}}^{s,p}(\varphi(U)) \times W_{\text{comp}}^{e,q}(\varphi(U)) &\hookrightarrow W^{e,q}(\varphi(U)) \\ W_{\text{loc}}^{s,p}(\varphi(U)) \times W_{\text{comp}}^{e-1,q}(\varphi(U)) &\hookrightarrow W^{e-1,q}(\varphi(U)) \end{aligned}$$

Also by Theorem H.20 we know that  $\sqrt{\det g} \circ \varphi^{-1}$  and  $\frac{1}{\sqrt{\det g} \circ \varphi^{-1}}$  are in  $W_{\text{loc}}^{s,p}(\varphi(U))$ . Hence we have the following chain of continuous maps

$$W^{e,q} \rightarrow W^{e,q} \rightarrow W^{e-1,q} \rightarrow W^{e-1,q}$$

$$f \mapsto (\sqrt{\det g} \circ \varphi^{-1})f \mapsto \frac{\partial}{\partial x^j} ((\sqrt{\det g} \circ \varphi^{-1})f) \mapsto \frac{1}{\sqrt{\det g} \circ \varphi^{-1}} \frac{\partial}{\partial x^j} ((\sqrt{\det g} \circ \varphi^{-1})f)$$

which proves the continuity of  $Q_{1j} : (C_c^\infty(\varphi(U)), \|\cdot\|_{e,q}) \rightarrow W^{e-1,q}(\varphi(U))$ . Finally considering that

$$\forall 1 \leq j \leq n \quad [Q_{1j}, \psi]h = \frac{\partial \psi}{\partial x^j} h$$

the required property for  $[Q_{1j}, \psi]$  obviously holds true.

**Remark I.2.** Instead of I.3 and I.4, we may alternatively assume that for all balls  $\Omega \subseteq \mathbb{R}^n$

$$\begin{aligned} W^{s,p}(\Omega) \times W^{e,q}(\Omega) &\hookrightarrow W^{e,q}(\Omega) \\ W^{s,p}(\Omega) \times W^{e-1,q}(\Omega) &\hookrightarrow W^{e-1,q}(\Omega) \end{aligned}$$

and work with nice charts instead of super nice charts. However, if we do so, then we need to additionally assume that  $e$  and  $q$  are such that  $\frac{\partial}{\partial x^j} : W^{e,q}(\Omega) \rightarrow W^{e-1,q}(\Omega)$  ( $1 \leq j \leq n$ ) is continuous (see Theorem E.63).

- **Example 4: Lie Derivative** Let  $X \in W^{s,p}(TM)$ . Consider  $L_X : C^\infty(T^k M) \rightarrow \Gamma(T^k M)$ . Here we will show that if  $e$  and  $q$  are such that

$$W^{s,p}(\mathbb{R}^n) \times W^{e-1,q}(\mathbb{R}^n) \hookrightarrow W^{e-1,q}(\mathbb{R}^n) \quad (\text{I.5})$$

$$W^{s-1,p}(\mathbb{R}^n) \times W^{e,q}(\mathbb{R}^n) \hookrightarrow W^{e-1,q}(\mathbb{R}^n) \quad (\text{I.6})$$

then  $L_X$  can be considered as a continuous operator from  $W^{e,q}(T^k M)$  to  $W^{e-1,q}(T^k M)$ . The local representation of  $L_X$  with respect to the coordinate chart  $(U, \varphi)$  is  $Q : C^\infty(\varphi(U), \mathbb{R}^{(n^k)}) \rightarrow \text{Func}(\varphi(U), \mathbb{R}^{(n^k)})$  defined by

$$Q(F) = \rho \circ L_X(\rho^{-1} \circ F \circ \varphi) \circ \varphi^{-1} \quad (F : \varphi(U) \rightarrow \mathbb{R}^{(n^k)}, \quad F = (F_{i_1 \dots i_k}))$$

In components

$$(Q(F))_{i_1 \dots i_k} = \rho_{i_1 \dots i_k} \circ L_X(\rho^{-1} \circ F \circ \varphi) \circ \varphi^{-1} = (L_X(\rho^{-1} \circ F \circ \varphi))_{i_1 \dots i_k} \circ \varphi^{-1}$$

Recall that if  $T$  is any  $k$ -covariant tensor field on  $U$  then

$$\begin{aligned} (L_X T)_{i_1 \dots i_k} \circ \varphi^{-1} &= \sum_p (X^p \circ \varphi^{-1}) \frac{\partial (T_{i_1 \dots i_k} \circ \varphi^{-1})}{\partial x^p} + \\ &\frac{\partial (X^p \circ \varphi^{-1})}{\partial x^{i_1}} (T_{p i_2 \dots i_k} \circ \varphi^{-1}) + \dots + \frac{\partial (X^p \circ \varphi^{-1})}{\partial x^{i_k}} (T_{i_1 \dots i_{k-1} p} \circ \varphi^{-1}) \end{aligned}$$

Therefore

$$\begin{aligned} (Q(F))_{i_1 \dots i_k} &= \sum_p (X^p \circ \varphi^{-1}) \frac{\partial F_{i_1 \dots i_k}}{\partial x^p} + \\ &\frac{\partial (X^p \circ \varphi^{-1})}{\partial x^{i_1}} F_{p i_2 \dots i_k} + \dots + \frac{\partial (X^p \circ \varphi^{-1})}{\partial x^{i_k}} F_{i_1 \dots i_{k-1} p} \end{aligned}$$

Now note that

$$(Q(F))_{i_1 \dots i_k} = \sum_{j_1 \dots j_k} Q_{(i_1 \dots i_k)(j_1 \dots j_k)}(F_{j_1 \dots j_k})$$

where

$$Q_{(i_1 \dots i_k)(j_1 \dots j_k)} : C^\infty(\varphi(U), \mathbb{R}) \rightarrow \text{Func}(\varphi(U), \mathbb{R})$$

and for all  $f \in C^\infty(\varphi(U), \mathbb{R})$ ,  $Q_{(i_1 \dots i_k)(j_1 \dots j_k)}(f)$  is the  $(i_1 \dots i_k)$ -component of  $Q(F)$  with

$$F_{i_1 \dots i_k} = \begin{cases} f & \text{if } i_1 = j_1, \dots, i_k = j_k \\ 0 & \text{otherwise} \end{cases}$$

Hence

$$\begin{aligned} Q_{(i_1 \dots i_k)(j_1 \dots j_k)}(f) &= \sum_p \delta_{j_1}^{i_1} \dots \delta_{j_k}^{i_k} (X^p \circ \varphi^{-1}) \frac{\partial f}{\partial x^p} + \\ &\delta_{j_2}^{i_2} \dots \delta_{j_k}^{i_k} \frac{\partial (X^{j_1} \circ \varphi^{-1})}{\partial x^{i_1}} f + \dots + \delta_{j_1}^{i_1} \dots \delta_{j_{k-1}}^{i_{k-1}} \frac{\partial (X^{j_k} \circ \varphi^{-1})}{\partial x^{i_k}} f \end{aligned}$$

Now suppose  $f \in C_c^\infty(\varphi(U))$ . In particular,  $f \in W_{comp}^{e,q}(\varphi(U))$ . It follows from the hypotheses on  $e$  and  $q$  that (see Lemma F.9)

$$W_{loc}^{s,p}(\varphi(U)) \times W_{comp}^{e-1,q}(\varphi(U)) \hookrightarrow W^{e-1,q}(\varphi(U))$$

$$W_{loc}^{s-1,p}(\varphi(U)) \times W_{comp}^{e,q}(\varphi(U)) \hookrightarrow W^{e-1,q}(\varphi(U))$$



Also by Corollary H.18 and Theorem F.6 we know that for all  $p$  and  $q$ ,  $X^p \circ \varphi^{-1}$  is in  $W_{loc}^{s, \mathcal{P}}$  and  $\frac{\partial(X^p \circ \varphi^{-1})}{\partial x^q}$  is in  $W_{loc}^{s-1, \mathcal{P}}$ . Hence

$$Q_{(i_1 \dots i_k)(j_1 \dots j_k)} : (C_c^\infty(\varphi(U)), \|\cdot\|_{e,q}) \rightarrow W^{e-1,q}(\varphi(U))$$

is continuous. Moreover,

$$[Q_{(i_1 \dots i_k)(j_1 \dots j_k)}, \psi]h = \sum_p \delta_{j_1}^{i_1} \dots \delta_{j_k}^{i_k} (X^p \circ \varphi^{-1}) \frac{\partial \psi}{\partial x^p} h$$

and so, as an immediate consequence, the required property for  $[Q_{(i_1 \dots i_k)(j_1 \dots j_k)}, \psi]$  holds true.

**Remark I.3.** *Instead of I.5 and I.6, we may alternatively assume that for all balls  $\Omega \subseteq \mathbb{R}^n$*

$$\begin{aligned} W^{s, \mathcal{P}}(\Omega) \times W^{e-1,q}(\Omega) &\hookrightarrow W^{e-1,q}(\Omega) \\ W^{s-1, \mathcal{P}}(\Omega) \times W^{e,q}(\Omega) &\hookrightarrow W^{e-1,q}(\Omega) \end{aligned}$$

and work with nice charts instead of super nice charts. However, if we do so, then we need to additionally assume that (see Theorem E.63)

- $\tilde{s}$  and  $\tilde{p}$  are such that  $\frac{\partial}{\partial x^j} : W^{s, \mathcal{P}}(\Omega) \rightarrow W^{s-1, \mathcal{P}}(\Omega)$  ( $1 \leq j \leq n$ ) is continuous.
  - $e$  and  $q$  are such that  $\frac{\partial}{\partial x^j} : W^{e,q}(\Omega) \rightarrow W^{e-1,q}(\Omega)$  ( $1 \leq j \leq n$ ) is continuous.
- **Example 5: Covariant Derivative** Consider  $\nabla : C^\infty(T_l^k M) \rightarrow \Gamma(T_l^{k+1} M)$ . Here we will show that if  $e$  and  $q$  are such that

$$W^{s-1, \mathcal{P}}(\mathbb{R}^n) \times W^{e,q}(\mathbb{R}^n) \hookrightarrow W^{e-1,q}(\mathbb{R}^n) \quad (\text{I.7})$$

then  $\nabla$  can be considered as a continuous operator from  $W^{e,q}(T_l^k M)$  to  $W^{e-1,q}(T_l^{k+1} M)$ . The local representation of covariant derivative with respect to the coordinate chart  $(U, \varphi)$  is  $Q : C^\infty(\varphi(U), \mathbb{R}^{n^{k+l}}) \rightarrow \text{Func}(\varphi(U), \mathbb{R}^{n^{k+l+1}})$  defined by

$$Q(F) = \tilde{\rho} \circ \nabla(\rho^{-1} \circ F \circ \varphi) \circ \varphi^{-1} \quad (F : \varphi(U) \rightarrow \mathbb{R}^{n^{k+l}}, \quad F = (F_{i_1 \dots i_k}^{j_1 \dots j_l}))$$

In components

$$(Q(F))_{i_1 \dots i_k r}^{j_1 \dots j_l} = \tilde{\rho}_{i_1 \dots i_k r}^{j_1 \dots j_l} \circ \nabla(\rho^{-1} \circ F \circ \varphi) \circ \varphi^{-1} = (\nabla(\rho^{-1} \circ F \circ \varphi))_{i_1 \dots i_k r}^{j_1 \dots j_l} \circ \varphi^{-1}$$

Recall that if  $T$  is any  $\binom{k}{l}$ -covariant tensor field on  $U$  then

$$\begin{aligned} (\nabla T)_{i_1 \dots i_k r}^{j_1 \dots j_l} \circ \varphi^{-1} &= (\nabla_r T)_{i_1 \dots i_k}^{j_1 \dots j_l} \circ \varphi^{-1} \\ &= \frac{\partial}{\partial x^r} (T_{i_1 \dots i_k}^{j_1 \dots j_l} \circ \varphi^{-1}) + \sum_p (T_{i_1 \dots i_k}^{p j_2 \dots j_l} \circ \varphi^{-1}) (\Gamma_{rp}^{j_1} \circ \varphi^{-1}) + \dots + (T_{i_1 \dots i_k}^{j_1 \dots j_{l-1} p} \circ \varphi^{-1}) (\Gamma_{rp}^{j_l} \circ \varphi^{-1}) \\ &\quad - \sum_p (T_{p i_2 \dots i_k}^{j_1 \dots j_l} \circ \varphi^{-1}) (\Gamma_{r i_1}^p \circ \varphi^{-1}) + \dots + (T_{i_1 \dots i_{k-1} p}^{j_1 \dots j_l} \circ \varphi^{-1}) (\Gamma_{r i_k}^p \circ \varphi^{-1}) \end{aligned}$$

Therefore

$$\begin{aligned} (Q(F))_{i_1 \dots i_k r}^{j_1 \dots j_l} &= \frac{\partial}{\partial x^r} F_{i_1 \dots i_k}^{j_1 \dots j_l} \\ &\quad + \sum_p (F_{i_1 \dots i_k}^{p j_2 \dots j_l}) (\Gamma_{rp}^{j_1} \circ \varphi^{-1}) + \dots + (F_{i_1 \dots i_k}^{j_1 \dots j_{l-1} p}) (\Gamma_{rp}^{j_l} \circ \varphi^{-1}) \\ &\quad - \sum_p (F_{p i_2 \dots i_k}^{j_1 \dots j_l}) (\Gamma_{r i_1}^p \circ \varphi^{-1}) + \dots + (F_{i_1 \dots i_{k-1} p}^{j_1 \dots j_l}) (\Gamma_{r i_k}^p \circ \varphi^{-1}) \end{aligned}$$

Now note that

$$(Q(F))_{i_1 \dots i_k r}^{j_1 \dots j_l} = \sum_{\hat{j}_s, \hat{i}_s} Q_{(i_1 \dots i_k r)(\hat{i}_1 \dots \hat{i}_k)}^{(j_1 \dots j_l)(\hat{j}_1 \dots \hat{j}_l)} (F_{\hat{i}_1 \dots \hat{i}_k}^{\hat{j}_1 \dots \hat{j}_l})$$

where

$$Q_{(i_1 \dots i_k r)(\hat{i}_1 \dots \hat{i}_k)}^{(j_1 \dots j_l)(\hat{j}_1 \dots \hat{j}_l)} : C^\infty(\varphi(U), \mathbb{R}) \rightarrow \text{Func}(\varphi(U), \mathbb{R})$$

and for all  $f \in C^\infty(\varphi(U), \mathbb{R})$ ,  $Q_{(i_1 \dots i_k r)(\hat{i}_1 \dots \hat{i}_k)}^{(j_1 \dots j_l)(\hat{j}_1 \dots \hat{j}_l)}(f)$  is the  $(i_1 \dots i_k r)^{(j_1 \dots j_l)}$ -component of  $Q(F)$  with

$$F_{i_1 \dots i_k}^{j_1 \dots j_l} = \begin{cases} f & \text{if } i_1 = \hat{i}_1, \dots, i_k = \hat{i}_k, j_1 = \hat{j}_1, \dots, j_l = \hat{j}_l \\ 0 & \text{otherwise} \end{cases}$$

Hence

$$\begin{aligned} Q_{(i_1 \dots i_k r)(\hat{i}_1 \dots \hat{i}_k)}^{(j_1 \dots j_l)(\hat{j}_1 \dots \hat{j}_l)}(f) &= \delta_{\hat{i}_1}^{i_1} \dots \delta_{\hat{i}_k}^{i_k} \delta_{\hat{j}_1}^{j_1} \dots \delta_{\hat{j}_l}^{j_l} \frac{\partial}{\partial x^r} f \\ &+ \delta_{\hat{i}_1}^{i_1} \dots \delta_{\hat{i}_k}^{i_k} \delta_{\hat{j}_2}^{j_2} \dots \delta_{\hat{j}_l}^{j_l} (f)(\Gamma_{r \hat{j}_1}^{j_1} \circ \varphi^{-1}) + \dots + \delta_{\hat{i}_1}^{i_1} \dots \delta_{\hat{i}_k}^{i_k} \delta_{\hat{j}_1}^{j_1} \dots \delta_{\hat{j}_{l-1}}^{j_{l-1}} (f)(\Gamma_{r \hat{j}_l}^{j_l} \circ \varphi^{-1}) \\ &- \delta_{\hat{i}_2}^{i_2} \dots \delta_{\hat{i}_k}^{i_k} \delta_{\hat{j}_1}^{j_1} \dots \delta_{\hat{j}_l}^{j_l} (f)(\Gamma_{r \hat{i}_1}^{\hat{i}_1} \circ \varphi^{-1}) + \dots + \delta_{\hat{i}_1}^{i_1} \dots \delta_{\hat{i}_{k-1}}^{i_{k-1}} \delta_{\hat{j}_1}^{j_1} \dots \delta_{\hat{j}_l}^{j_l} (f)(\Gamma_{r \hat{i}_k}^{\hat{i}_k} \circ \varphi^{-1}) \end{aligned}$$

Now suppose  $f \in C_c^\infty(\varphi(U))$ . In particular,  $f \in W_{comp}^{e,q}(\varphi(U))$ . It follows from the hypotheses on  $e$  and  $q$  that (see Lemma F.9)

$$W_{loc}^{s-1,p}(\varphi(U)) \times W_{comp}^{e,q}(\varphi(U)) \hookrightarrow W^{e-1,q}(\varphi(U))$$

Also we know that for all  $a, b$ , and  $c$ ,  $\Gamma_{bc}^a \circ \varphi^{-1}$  is in  $W_{loc}^{s-1,p}$ . Hence

$$Q_{(i_1 \dots i_k r)(\hat{i}_1 \dots \hat{i}_k)}^{(j_1 \dots j_l)(\hat{j}_1 \dots \hat{j}_l)} : (C_c^\infty(\varphi(U)), \|\cdot\|_{e,q}) \rightarrow W^{e-1,q}(\varphi(U))$$

is continuous. Finally, considering that

$$[Q_{(i_1 \dots i_k r)(\hat{i}_1 \dots \hat{i}_k)}^{(j_1 \dots j_l)(\hat{j}_1 \dots \hat{j}_l)}, \psi]h = \delta_{\hat{i}_1}^{i_1} \dots \delta_{\hat{i}_k}^{i_k} \delta_{\hat{j}_1}^{j_1} \dots \delta_{\hat{j}_l}^{j_l} \frac{\partial \psi}{\partial x^r} h$$

the required property for  $[Q_{(i_1 \dots i_k r)(\hat{i}_1 \dots \hat{i}_k)}^{(j_1 \dots j_l)(\hat{j}_1 \dots \hat{j}_l)}, \psi]$  clearly holds.

**Remark I.4.** *Instead of I.7, we may alternatively assume that for all balls  $\Omega \subseteq \mathbb{R}^n$*

$$W^{s-1,p}(\Omega) \times W^{e,q}(\Omega) \hookrightarrow W^{e-1,q}(\Omega)$$

*and work with nice charts instead of super nice charts. However, if we do so, then we need to additionally assume that  $e$  and  $q$  are such that  $\frac{\partial}{\partial x^j} : W^{e,q}(\Omega) \rightarrow W^{e-1,q}(\Omega)$  ( $1 \leq j \leq n$ ) is continuous (see Theorem E.63).*

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