Analysis on singular spaces: Lie manifolds and operator algebras
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ANALYSIS ON SINGULAR SPACES: LIE MANIFOLDS AND OPERATOR ALGEBRAS

VICTOR NISTOR

Abstract. We discuss and develop some connections between analysis on singular spaces and operator algebras, as presented in my sequence of four lectures at the conference Noncommutative geometry and applications, Frascati, Italy, June 16-21, 2014. Therefore this paper is mostly a survey paper, but the presentation is new, and there are included some new results as well. In particular, Sections 3 and 4 provide a complete short introduction to analysis on noncompact manifolds that is geared towards a class of manifolds—called “Lie manifolds”—that often appears in practice. Our interest in Lie manifolds is due to the fact that they provide the link between analysis on singular spaces and operator algebras. The groupoids integrating Lie manifolds play an important background role in establishing this link because they provide operator algebras whose structure is often well understood. The initial motivation for the work surveyed here—work that spans over close to two decades—was to develop the index theory of stratified singular spaces. Meanwhile, several other applications have emerged as well, including applications to Partial Differential Equations and Numerical Methods. These will be mentioned only briefly, however, due to the lack of space. Instead, we shall concentrate on the applications to Index theory.

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Introduction

We survey some connections between analysis on singular spaces and operator algebras, concentrating on applications to Index theory. The paper follows rather closely my sequence of four lectures at the conference Noncommutative geometry and applications, Frascati, Italy, June 16-21, 2014. From a technical point of view, the paper mostly sets up the analysis tools needed for developing a certain approach to the Index theory of singular and non-compact spaces. These results were developed by many people over several years. In addition to these older contributions, we include here also several new results tying various older results together. In particular, for the benefit of the reader, we have written the paper in such a way that the third and fourth sections are to a large extend self-contained. They include most of the needed proofs, and thus can be regarded as a very short introduction to analysis on non-compact manifolds that focuses on applications to Lie manifolds. Lie manifolds are a class of non-compact manifolds that arise naturally in many applications involving non-compact and singular spaces.

The main story told by this paper is, briefly, as follows. Some of the classical Analysis and Index theory results deal with the index of Fredholm operators. This is rather well understood in the case of smooth, compact manifolds and in the case of smooth, bounded domains. By contrast, the non-smooth and non-compact cases are much less well understood. Moreover, it has become clear that the index theorems in these frameworks require non-local invariants and (hence) cyclic homology. The full implementation of this program requires, however, further algebraic and analytic developments. More specifically, one important auxiliary question that needs to be answered is: “Which operators on a given non-smooth or non-compact space are Fredholm.” A convenient answer to this question involves Lie manifolds and the Lie groupoids that integrate them. The techniques that were developed for this purpose have then proved to be useful also in other mathematical areas, such as Spectral theory and the Finite Element Method.

Fredholm operators play a central role in this paper for the following reasons. First of all, the (Fredholm) index is defined only for Fredholm operators, thus, in order to state an index theorem for the Fredholm index, one needs to have examples of Fredholm operators. In fact, the data that is needed to decide whether a given operator is Fredholm (principal symbol, boundary–or indicial–symbols) is also the
data that is used for the actual computation of the index of that operator. Moreover, many interesting quantities (such as the signature of a compact manifold) are, in fact, the indices of certain operators. Second, Fredholm operators have been widely used in Partial Differential Equations (PDEs). For instance, non-linear maps whose linearization is Fredholm play a central role in the study of non-linear PDEs. Also, Fredholm operators are useful in determining the essential spectra of Hamiltonians. Finally, the Fredholm index is the first obstruction for an operator to be invertible. As an illustration, this simple last observation is exploited in our approach to the Neumann problem on polygonal domains (Theorem 5.14). The proof of that theorem relies first on the calculation of the index of an auxiliary operator, this auxiliary operator is then shown to be injective, and the final step is to augment its domain so that it becomes an isomorphism [87].

A certain point on the analysis on singular and non-compact spaces is worth insisting upon. A typical approach to analysis on singular spaces—employed also in this paper—is that the analysis on a singular space happens on the smooth part of the space, with the singularities playing the important role of providing the behavior “at infinity.” Thus, from this point of view, the analysis on non-compact spaces is more general than the analysis on singular spaces. However, for the simplicity of the presentation, we shall usually discuss only singular spaces, with the understanding that the results also extend to non-compact manifolds.

Here are the contents of the paper. The first section is devoted to describing the Index theory motivation for the results presented in this paper. The approach to Index theory used in this paper is based on exact sequences of operator algebras. Thus, in the first section, we discuss the exact sequences appearing in the Atiyah-Singer index theorem, in Connes’ index theorem for foliations, and in the Atiyah-Patodi-Singer (APS) index theorem. The second section is devoted to explaining the motivation for the results presented in this paper coming from degenerate (or singular) elliptic partial differential equations. In that section, we just present some typical examples of degenerate elliptic operators that suggest how ubiquitous they are and point out some common structures that have lead to Lie manifolds, a class of manifolds that is discussed in the third section. In this third section, we include the definition of Lie manifolds, a discussion of manifolds with cylindrical ends (the simplest non-trivial example of a Lie manifold, the one that leads to the APS framework), a discussion of Lie algebroids and of their relation to Lie manifolds, and a discussion of the natural metric and connection on a Lie manifold. The fourth section is a basic introduction to analysis on Lie manifolds. It begins with discussions of the needed functions spaces, of “comparison algebras,” and of Fredholm conditions. The last section is devoted to applications, including the formulation of an index problem for Lie manifolds in periodic cyclic cohomology, an application to essential spectra, an index theorem for Callias-type operators, and the Hadamard well posedness for the Poisson problem with Dirichlet boundary conditions on polyhedral domains.

The four lectures of my presentation at the above mentioned conference were devoted, each, to one of the following subjects: I. Index theory, II. Lie manifolds, III. Pseudodifferential operators on groupoids, and IV. Applications, and are based mostly on my joint works with Bernd Ammann (Regensburg), Catarina Carvalho (Lisbon), Alexandru Ionescu (Princeton), Robert Lauter (Mainz), Anna Mazzucato (Penn State) and Bertrand Monthubert (Toulouse). Nevertheless, I made an effort
to put the results in context by quoting and explaining other relevant results. I have also included significant background results and definitions to make the paper easier to read for non-specialists. I have also tried to summarize some of the more recent developments. Unfortunately, the growing size of the paper has finally prevented me from including more information. Moreover, it was unpractical to provide all the related references, and I apologize to the authors whose work has not been mentioned enough.

I would like to thank the Max Planck Institute for Mathematics in Bonn, where part of this work was completed. Also, I would like to thank Bernd Ammann, Ingrid and Daniel Beltiță, Karsten Bohlen, Claire Debord, Vladimir Georgescu, Marius Mântoiu, Jean Renault, Elmar Schrohe, and Georges Skandalis for useful comments.

1. Motivation: Index Theory

This paper is devoted in large part to explaining some applications of Lie manifolds and of their associated operator algebras to analysis on singular and non-compact spaces. The initial motivation of this author for studying analysis on singular and non-compact spaces (and hence also for studying Lie manifolds) comes from Index theory. In this section, I will describe this initial motivation, while in the next section, I will provide further motivation coming from degenerate partial differential equations. Thus, I will not attempt here to provide a comprehensive introduction to Index Theory, but rather to motivate the results and constructions introduced in this paper using it. In particular, I will stress the important role that Fredholm conditions play for index theorems. In fact, in our approach, both the index theorem studied and the associated Fredholm conditions rely on the same exact sequence discussed in general in the next subsection. No results in this section are new.

1.1. An abstract index theorem. An approach to Index theory is based on exact sequences of algebras of operators. We shall thus consider an abstract exact sequence

\[ 0 \to I \to A \to \text{Symb} \to 0, \]

in which the algebras involved will be specified in each particular application. The same exact sequence will be used to establish the corresponding Fredholm conditions. Typically, \( A \) will be a suitable algebra of operators that describes the analysis on a given (class of) singular space(s). In our presentation, the algebra \( A \) will be constructed using Lie algebroids and Lie groupoids. The choice of the ideal \( I \) also depends on the particular application at hand and is not necessarily determined by \( A \). In fact, the analysis on singular spaces distinguishes itself from the analysis on compact, smooth manifolds in that there will be several reasonable choices for the ideal \( I \).

Often, in problems related to classical analysis—such as the ones that involve the Fredholm index of operators—the ideal \( I \) will be contained in the ideal of compact operators \( \mathcal{K} \) (on some separable Hilbert space). In fact, in most applications in this presentation, we will have \( I := A \cap \mathcal{K} \). We insist, however, that this is not the only legitimate choice, even if it is the most frequently used one. An important other example is provided by taking \( I \) to be the kernel of the principal symbol map. As we will see below, in the case of singular and non-compact spaces, the kernel of the
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principal symbol map does not consist generally of compact operators. This is the case in the analysis on covering spaces and on foliations, which also lead naturally to von Neumann algebras [29, 70, 76, 156].

If \( I := A \cap K \) and \( P \in A \) has an invertible image in \( A/I \) (that is, it is invertible modulo \( I \)), then the principal symbol map, does not consist generally of compact operators. This is the case in the analysis on covering spaces and on foliations, which also lead naturally to von Neumann algebras [29, 70, 76, 156].

If \( I := A \cap K \) and \( P \in A \) has an invertible image in \( A/I \) (that is, it is invertible modulo \( I \)), then the operator \( P \) is Fredholm and a natural and far reaching question to ask then is to compute \( \text{ind}(P) := \dim \ker(P) - \dim \text{coker}(P) \), the Fredholm index of \( P \), defined as the difference of the dimensions of the kernel and cokernel of \( P \). In any case, we see that in order to formulate an index problem, we need criteria for the relevant operators to be Fredholm, because it is the condition that \( P \) be Fredholm that guarantees that \( \ker(P) \), the kernel of \( P \), and \( \text{coker}(P) \), the cokernel of \( P \), are finite dimensional. This is also related to the structure of the exact sequence (1).

When the algebra \( A \) of the exact sequence (1) is defined using groupoids—as is the case in this presentation—then the structure of the quotient algebra \( \text{Symb} := A/I \) is related to the representation theory of the underlying groupoid. Unfortunately, we will not have time to treat this important subject in detail, but we will provide several references in the appropriate places.

The exact sequence (1) provides us with a boundary (or index) map

\[
\partial : K^\text{alg}_1(\text{Symb}) \to K^\text{alg}_0(I),
\]

between algebraic \( K \)-theory groups, whose calculation will be regarded as an index formula for the reasons explained in the following subsections (see, for instance, Remark 1.4). Thus, in general, the index of an operator is an element of a \( K_0 \) group, which explains why the usual index, which is an integer, is called the Fredholm index in this paper. In case \( A \) and \( I \) are \( C^* \)-algebras, the boundary map \( \partial \) descends to a map between the corresponding topological \( K \)-theory groups. Moreover, we obtain also a map \( \partial' : K_0(\text{Symb}) \to K_1(I) \), acting also between topological \( K \)-theory groups. The maps \( \partial \) and \( \partial' \) and the maps obtained from the functoriality of (topological) \( K \)-groups, give rises to a six-term exact sequence of \( K \)-groups [139, 157]. Unfortunately, often the \( K \)-groups are difficult to compute, so we need to consider suitable dense subalgebras of \( C^* \)-algebras and their cyclic homology (see, for instance, Subsection 1.5).

We begin with a quick introduction to differential and pseudodifferential operators needed to fix the notation and to introduce some basic concepts. It is written to be accessible to graduate students. We then discuss three basic index theorems and their associated analysis (or exact sequences). These three index theorems are: the Atiyah-Singer (AS) index theorem, Connes’ index theorem for foliations, and the Atiyah-Patodi-Singer (APS) index theorem. We will see that, at least from the point of view adopted in this presentation, Connes’ and APS’ frameworks extend the Atiyah-Singer’s framework in complementary directions.

1.2. Differential and pseudodifferential operators. We now fix some notation and recall a few basic concepts. On \( \mathbb{R}^n \), we consider the derivations (or, which is the same thing, vector fields) \( \partial_j = \frac{\partial}{\partial x_j}, j = 1, \ldots, n \), and form the differential monomials \( \partial^n := \partial_1^{\alpha_1} \partial_2^{\alpha_2} \cdots \partial_n^{\alpha_n}, \alpha \in \mathbb{Z}_+^n \). We let \( |\alpha| := \alpha_1 + \alpha_2 + \cdots + \alpha_n \in \mathbb{Z}_+ \).

A differential operator of order \( m \) on \( \mathbb{R}^n \) is then an operator \( P : C^\infty_c(\mathbb{R}^n) \to C^\infty_c(\mathbb{R}^n) \) of the form

\[
Pu = \sum_{|\alpha| \leq m} a_\alpha \partial^n u,
\]
with $m$ minimal with this property. Sometimes $P : C^\infty_c(\mathbb{R}^n) \to L^2(\mathbb{R}^n)$, but in this paper we consider only operators $P$ having smooth coefficients $a_\alpha$.

It is easy, but important, to extend the above constructions to systems of differential operators, in order to account for important operators such as: vector Laplacians, elasticity, signature, Maxwell, and many others. We then take $u = (u_1, \ldots, u_k) \in C^\infty_c(\mathbb{R}^n)^k = C^\infty_c(\mathbb{R}^n; \mathbb{R}^k)$ to be a smooth, compactly supported section of the trivial vector bundle $\mathbb{R}^k = \mathbb{R}^k \times \mathbb{R}^n \to \mathbb{R}^n$ and we take $a_\alpha \in C^\infty(\mathbb{R}^n; M_k(\mathbb{R}))$ to be a matrix valued function. Each coefficient $a_\alpha$ is hence an endomorphism of the trivial vector bundle $\mathbb{R}^k$. Then $P$ maps $C^\infty_c(\mathbb{R}^n; \mathbb{R}^k)$ to $C^\infty(\mathbb{R}^n; \mathbb{R}^k)$. Let $\Delta = -\partial_1^2 - \ldots - \partial_n^2 \geq 0$ and $s \in \mathbb{Z}_+$. We denote as usual

$$H^s(\mathbb{R}^n) := \{ u : \mathbb{R}^n \to \mathbb{C}, \partial^s u \in L^2(\mathbb{R}^n), |\alpha| \leq s \} = D(\Delta^{s/2}).$$

As we will see below, both definitions above of Sobolev spaces extend to the case of “Lie manifolds.” These definitions of Sobolev spaces also extend immediately to vector valued functions and, if the coefficients $a_\alpha$ of $P$ are bounded (together with enough derivatives, more precisely, if $P \in W^{s, \infty}(\mathbb{R}^n)$), then we obtain that $P$ maps $H^s(\mathbb{R}^n)$ to $H^{s-n}(\mathbb{R}^n)$.

For $P$ a differential operator of order $\leq m$ as in Equation (3), we let

$$\sigma_m(P)(x, \xi) = \sum_{|\alpha| = m} a_\alpha(x)(\xi)^\alpha \in C^\infty(\mathbb{R}^n \times \mathbb{R}^n; M_k),$$

and call it the principal symbol of $P$. In particular, we have $\sigma_{m+1}(P) = 0$. Here $x \in \mathbb{R}^n$ and $\xi \in \mathbb{R}^n$ is the dual variable.

The fact that $\xi$ is a dual variable to $x \in \mathbb{R}^n$ is confirmed by the formula for transformations of coordinates. The principal symbol is thus seen to be a function on $T^*\mathbb{R}^n \simeq \mathbb{R}^n \times \mathbb{R}^n$. It turns out that the principal symbol $\sigma_m(P)$ of $P$ has a much simpler transformation formula than the (full) symbol $\sigma(P)$ of $P$ defined by

$$\sigma(P)(x, \xi) = \sum_{|\alpha| \leq m} a_\alpha(x)(\xi)^\alpha \in C^\infty(\mathbb{R}^n \times \mathbb{R}^n; M_k).$$

The full symbol $p(x, \xi) := \sigma(P)(x, \xi)$ of $P$ defined as above in Equation (5) is nevertheless important because $P = p(x, D)$, where

$$p(x, D)u(x) := (2\pi)^{-n} \int_{\mathbb{R}^n} e^{ix \cdot \xi} p(x, \xi) \hat{u}(\xi) d\xi.$$

There exist more general classes of functions (or symbols) $p$ for which $p(x, D)$ can still be defined by the above formula (6). The resulting operator will be a pseudodifferential operator with symbol $p$. Let us recall the definition of the two most basic classes of symbols for which the formula (6) defining $p(x, D)$ still makes sense [68, 143, 112]. For simplicity, we shall consider in the beginning only scalar symbols, although matrix valued symbols can be handled in a completely similar way. The first class of symbols $p$ for which the formula (6) still makes sense is the class $S^m_{1,0}(\mathbb{R}^k \times \mathbb{R}^N)$, $m \in \mathbb{R}$. It is defined as the space of functions $a : \mathbb{R}^{k+N} \to \mathbb{C}$ that satisfy, for any $i, j \in \mathbb{Z}_+$, the estimate

$$|\partial^i_x \partial^j_\xi a(x, \xi)| \leq C_{ij} (1 + |\xi|)^{m-j},$$

for a constant $C_{ij} > 0$ independent of $x$ and $\xi$. Of course, in (6), we take $N = n$.

Let us now introduce classical symbols. A function $a : \mathbb{R}^k \times \mathbb{R}^N \to \mathbb{C}$ is called eventually homogeneous of order $s$ if there exists $M > 0$ such that $a(x, t\xi) = t^s a(x, \xi)$
for $|\xi| \geq M$ and $t \geq 1$. A very useful class of symbols is $S^m_{cl}(\mathbb{R}^{2n})$, defined as the subspace of symbols $a \in S^m_{1,0}(\mathbb{R}^{2n})$ that can be written as asymptotic series $a \sim \sum_{j=0}^{N} a_{m-j}$, meaning
\[
a - \sum_{j=0}^{N} a_{m-j} \in S^{m-N-1}_{1,0}(\mathbb{R}^{2n}),
\]
with $a_k \in S^k_{1,0}(\mathbb{R}^{2n})$ eventually homogeneous of order $k$. If $a \in S^m_{cl}(\mathbb{R}^{2n})$, the pseudodifferential operator $a(x, D)$ is called a classical pseudodifferential operator and its principal symbol is defined by
\[
\sigma_m(a(x, D)) := a_m
\]
and is regarded as a smooth, order $m$ homogeneous function on
\[
T^*\mathbb{R}^n \setminus \text{“zero section”} = \mathbb{R}^{2n} \setminus (\mathbb{R}^n \times \{0\}).
\]
For Index theory, it is generally enough to consider classical pseudodifferential operators. The reason is that the inverses and parametrices of classical pseudodifferential operators are again classical and, if $P$ is a classical pseudodifferential operator of order $m$, then $P$ is a classical pseudodifferential operator of order $m$.

The definition of a (pseudo) differential operator $P$ (of order $\leq m$) and of its principal symbol $\sigma_m(P)$ then extend to manifolds and vector bundles by using local coordinate charts. To fix notation, if $E \to M$ is a smooth vector bundle over a manifold $M$, we shall denote by $\Gamma(M; E)$ the space of its smooth sections:
\[
\Gamma(M; E) := \{ s : M \to E, s(x) \in E_x \}.
\]
Similarly, we shall denote by $\Gamma_c(M; E) \subset \Gamma(M; E)$ the subspace of smooth, compactly supported sections of $E$ over $M$. Sometimes, when no confusion can arise, we denote $\Gamma(E) = \Gamma(M; E)$ and, similarly, $\Gamma_c(E) = \Gamma_c(M; E)$. Getting back to our extension of pseudodifferential operators to manifolds, we obtain this extension by replacing as follows:
\[
\mathbb{R}^n \leftrightarrow M = \text{a smooth manifold}
\]
\[
C_c^\infty(\mathbb{R}^n)^k \leftrightarrow \text{sections of a vector bundle},
\]
which gives for an order $m$ operator $P$ acting between smooth, compactly supported sections of $E$ and $F$:
\[
P : \Gamma_c(M; E) \to \Gamma_c(M; F)
\]
\[
\sigma_m(P) \in \Gamma(T^*M \setminus \{0\}; \text{Hom}(E, F)).
\]
Of course, $\sigma_m(P)$ is homogeneous of order $m$. Thus, if $m = 0$ and if we denote by $S^0* := (T^*M \setminus \{0\})/\mathbb{R}^*_+$ the (unit) cosphere bundle, then $\sigma_0(P)$ identifies with a smooth function on $S^0* M$. (The name “cosphere bundle” is due to the fact that, if we choose a metric on $M$, then the cosphere bundle identifies with the set of vectors of length one in $T^*M$.)

The main property of the principal symbol is the multiplicative property
\[
\sigma_{m+m'}(PP') = \sigma_m(P)\sigma_{m'}(P'),
\]
a property that is enjoyed by its extension to pseudodifferential operators (which are allowed to have negative and non-integer orders as well).
Definition 1.1. A (classical, pseudo)differential operator $P$ is called elliptic if its principal symbol is invertible away from the zero section of $T^*M$.

See [68, 128, 112, 148] for a more complete discussion of various classes of symbols and of pseudodifferential operators. See also [8, 57, 84, 99, 120, 143].

As a last ingredient before discussing the Fredholm index, we need to extend the definition of Sobolev spaces to manifolds. To that end, we consider also a metric $g$ on our manifold $M$ (or a Lipschitz equivalence class of such metrics) [12, 63]. Then, for a complete manifold $M$, the Sobolev spaces are given by the domains of the powers of the (positive) Laplacian. In general, this will depend on the choice of the metric $g$.

1.3. The Fredholm index. Let now $M$ be a compact, smooth manifold, so the Sobolev spaces $H^s(M)$ are uniquely defined. Let also $P$ be a (classical, pseudo) differential operator of order $\leq m$ acting between the smooth sections of the hermitian vector bundles $E$ and $F$. We denote by $H^s(M; E)$ and $H^s(M; F)$ the corresponding Sobolev spaces of sections of these bundles.

Recall that a continuous, linear operator $T : X \to Y$ acting between topological vector spaces is Fredholm, if and only if, the vector spaces $\ker(P) := \{ u \in X, Tu = 0 \}$ and $\ker(P) := Y/TX$ are finite dimensional. One of our model results is then the following classical theorem [36, 144, 145].

Theorem 1.2. Let $P$ be an order $m$ pseudodifferential operator acting between the smooth sections of the bundles $E$ and $F$ on the smooth, compact manifold $M$ and $s \in \mathbb{R}$. Then

$$P : H^s(M; E) \to H^{s-m}(M; F)$$

is Fredholm $\iff$ $P$ is elliptic.

Fredholm operators appear all the time in applications (because elliptic operators are so fundamental). For instance, the theorem mentioned above is one of the crucial ingredients in the “Hodge theory” for smooth compact manifolds, which is quite useful in Gauge theory.

By the Open Mapping theorem, the invertibility of a continuous, linear operator $P : X_1 \to X_2$ acting between two Banach spaces is equivalent to the condition $\dim \ker(P) = \dim \ker(P) = 0$. It is important then to calculate the Fredholm index $\text{ind}(P)$ of $P$, defined by

$$\text{ind}(P) := \dim \ker(P) - \dim \ker(P).$$

The reason for looking at the Fredholm index rather than looking simply at the numbers $\dim \ker(P)$ and $\dim \ker(P)$ is that $\text{ind}(P)$ has better stability properties than these numbers. For instance, the Fredholm index is homotopy invariant and depends only on the principal symbol of $P$.

1.4. The Atiyah-Singer index formula. The index of elliptic operators on smooth, compact manifolds is computed by the Atiyah-Singer index formula [11]:

Theorem 1.3 (Atiyah-Singer). Let $M$ be a compact, smooth manifold and let $P$ be elliptic, classical (pseudo)differential operator acting on sections of smooth vector bundles on $M$. Then

$$\text{ind}(P) = \langle \sigma_m(P), [T^*M] \rangle.$$
A suitable orientation has to be, of course, chosen on $T^*M$. There are many accounts of this theorem, and we refer the reader for instance to [57, 119, 145, 151] for more details. See [31, 76] for an approach using non-commutative geometry. Let us nevertheless mention some of the main ingredients appearing in the statement of this theorem, because they are being generalized (or need to be generalized) to the non-smooth case. This generalization is in part achieved by non-commutative geometry and by analysis on singular spaces. Thus, returning to Theorem 1.3, the meanings of the undefined terms in Theorem 1.3 are as follows:

(i) The principal symbol $\sigma_m(P)$ of $P$ defines a $K$-theory class in $K^0(T^*M)$ (with compact supports) by the ellipticity of $P$ [11] and $\text{ch}(\sigma_m(P)) \in H^\text{even}_c(T^*M)$ is the Chern character of this class.

(ii) $\mathcal{T}(M) \in H^\text{even}(M) \simeq H^\text{even}(T^*M)$ is the Todd class of $M$, so the product $\text{ch}(\sigma_m(P))\mathcal{T}(M)$ is well-defined in $H^\text{even}_c(T^*M)$.

(iii) $[T^*M] \in H^\text{even}_c(T^*M)^\ast$ is the fundamental class of $T^*M$ and is chosen such that no sign appears in the index formula.

The AS index formula was much studied and has found a number of applications. It is based on earlier work of Grothendieck and Hirzebruch and answers to a question of Gelfand. One of the main motivations for the work presented here is the desire to extend the index formula for compact manifolds (the AS index formula) to the noncompact and singular cases. To this end, it will be convenient to use the exact sequence formalism described in Subsection 1.1. Namely, the exact sequence (1) corresponding to the AS index formula is

\begin{equation}
0 \to \Psi^{-1}(M) \to \Psi^0(M) \to C^\infty(S^*M) \to 0,
\end{equation}

where $S^*M$ is the cosphere bundle of $M$, as before, (that is, the set of vectors of length one of the cotangent space $T^*M$ of $M$). That is, in the exact sequence (1), we have $I = \Psi^{-1}(M)$, $A = \Psi^0(M)$, and $\text{Symb} := A/I \simeq C^\infty(S^*M)$.

It is interesting to point out that both the AS index formula and the Fredholm condition of Theorem 1.2 are based on the exact sequence (10). Of course, to actually determine the index, one has to do additional work, but the information needed is contained in the exact sequence. This remains true for most of the other index theorems. We continue with some remarks.

**Remark 1.4.** Let us see now how the exact sequence (10) and Theorem 1.3 are related. Recall the boundary map $\partial : K^\text{alg}_1(\text{Symb}) \to K^\text{alg}_0(I)$ in *algebraic* $K$-theory associated to the exact sequence (1), see Equation (2), and let us assume that the ideal $I$ of that exact sequence consists of compact operators (i.e. $I \subset \mathbb{K}$). We first consider the natural map

\begin{equation}
\text{Tr}_* : K^\text{alg}_0(I) \to \mathbb{Z},
\end{equation}

where the trace refers to the trace (or dimension) of a projection. We have, of course, that $\text{Tr}_* : K^\text{alg}_0(K) = K^\text{alg}_0(\mathbb{K}) \to \mathbb{Z}$ is the usual isomorphism. Then $\text{Tr}_* \circ \partial$ computes the usual (Fredholm) index, that is, we have the equality of the morphisms

\begin{equation}
\text{ind} = \text{Tr}_* \circ \partial : K^\text{alg}_1(\text{Symb}) \xrightarrow{\partial} K^\text{alg}_0(I) \xrightarrow{\text{Tr}_*} \mathbb{C}.
\end{equation}

Indeed, if $P \in A$ is invertible in $A/I = \text{Symb}$, then, on the one hand, $P$ defines a class $[P] \in K_1(\text{Symb})$, and, on the other hand, $P$ is *Fredholm* and its Fredholm index is given by

\begin{equation}
\text{ind}(P) = \text{Tr}_* \circ \partial[P].
\end{equation}
We thus see that computing the index of a Fredholm (pseudo)differential operator on $M$ is equivalent to computing the composite map $Tr_\gamma \circ \partial : K_1(\text{Symb}) \to \mathbb{C}$. This observation due to Connes is the starting point of the approach to index theorems described in this paper.

**Remark 1.5.** Let us discuss now shortly the role of the Chern character in the AS index formula. First, let us recall that the Chern character establishes an isomorphism $ch : K^*(M_1) \otimes \mathbb{C} \to H^*(M_1) \otimes \mathbb{C}$ for any compact, smooth manifold $M_1$. Moreover, in the case of the commutative algebra $\mathcal{C}^\infty(M_1)$, we have that $K_*(\mathcal{C}^\infty(M_1)) \simeq K^*(M_1)$ and hence any group morphism $K_*(\mathcal{C}^\infty(M_1)) \to \mathbb{C}$ factors through the Chern character $ch : K^*(M_1) \to H^*(M_1) \otimes \mathbb{C}$. Returning to the AS index formula, we have that $\text{Symb} = \mathcal{C}^\infty(S^*M)$ and hence the index map $\text{ind} = Tr_\gamma \circ \partial : K_1(\text{Symb}) \simeq K^1(S^*M) \to \mathbb{C}$ can be expressed solely in terms of the Chern character. It is therefore possible to express the AS Index Formula purely in classical terms (vector bundles and cohomology) because the quotient $A/I := \text{Symb} \simeq \mathcal{C}^\infty(S^*M)$ is commutative.

**Remark 1.6.** Technically, one may have to replace the algebra $A$ with $M_n(A)$ and take $P \in M_n(A)$, but this is not an issue since the $K$-groups (both topological and algebraic) are invariant for the replacement of $A$ with its matrix algebras. However, the approach to the index of elliptic (pseudo)differential operators using exact sequences can be used to deal with operators $P$ acting between sections of isomorphic bundles. For non-compact manifolds (and hence also for singular spaces), this is enough. For the AS index formula, however, one may have to replace first $M$ with $M \times S^1$. For this reason, in the case of the AS index formula, Connes’ approach using the tangent groupoid may be more convenient.

**Remark 1.7.** Elliptic operators on a smooth, compact manifolds $M$ have certain properties that are similar to the properties to $\Gamma$-invariant elliptic operators on a covering space $\Gamma \to \hat{M} \to M$ (so here $\Gamma$ is the group of deck transformations of $\hat{M}$ and hence $\hat{M}/\Gamma \simeq M$). The reason is that they correspond the the same Lie algebroid on $M$, namely $TM \to M$. The two frameworks correspond however to different Lie groupoids, and their analysis is consequently also quite different. In particular, if $\Gamma$ is non-trivial, one is lead to consider von Neumann algebras [29, 70, 156]. This is related to the example of foliations discussed in the next subsection.

### 1.5. Cyclic homology and Connes’ index formula for foliations.

The map $Tr_\gamma$ of the basic equation $\text{ind}(P) = Tr_\gamma \circ \partial[P]$ (recall Equation (12), which is valid when $I \subset K$), is a particular instance of the pairing between cyclic cohomology and $K$-theory [31]. See also [30, 71, 90, 93, 152]. This pairing is even more important when $I \not\subset K$. Let us explain this. Let us denote by $HP^*(B)$ the periodic cyclic cohomology groups of an algebra $B$ (for topological algebras, suitable topological versions of these groups have to be considered).

Let us look again at the general exact sequence of Equation (1) and let $\phi$ be a cyclic cocycle on $I$, that is, $\phi \in HP^0(I)$. A more general (higher) index theorem is then to compute

$$\phi_* \circ \partial : K_1(\text{Symb}) \to \mathbb{C}.$$  

It is known that $\phi_* \circ \partial = (\partial \phi)_*$, and hence the map $\phi_* \circ \partial$ is also given by a cyclic cocycle [114].
The map $\phi_*$ and, in general, the approach to Index theory using cyclic homology is especially useful for foliations for the reasons that we are explaining now. We regard a foliation $(M, \mathcal{F})$ of a smooth, compact manifold $M$ as a sub-bundle $\mathcal{F} \subset TM$ that is integrable (that is, its space of smooth sections, denoted $\Gamma(\mathcal{F})$, is closed under the Lie bracket). Connes’ construction of pseudodifferential operators along the leaves of a foliation [29] then yields the exact sequence of algebras

$$0 \to \Psi^{-1}_\mathcal{F}(M) \to \Psi^0_\mathcal{F}(M) \xrightarrow{\sigma_0} \mathcal{C}^\infty(S^*\mathcal{F}) \to 0,$$

where $\sigma_0$ is again the principal symbol, defined essentially in the same manner as for the case of smooth manifolds. In fact, for $\mathcal{F} = TM$, with $M$ a smooth, compact manifold, this exact sequence reduces to the earlier exact sequence (10). It also yields a boundary (or index) map

$$\partial : K_1(\mathcal{C}^\infty(S^*\mathcal{F})) = K^1(S^*\mathcal{F}) \to K_0(\Psi^{-1}_\mathcal{F}(M)) \simeq K_0(\mathcal{C}^\infty_c(\mathcal{F})).$$

Unlike its $K$-theory, the cyclic homology of $\Psi^{-1}_\mathcal{F}(M)$ is much better understood, in particular, it contains as a direct summand the twisted cohomology of the classifying space of the groupoid (graph) of the foliation [20]. We thus have a large set of linearly independent cyclic cocycles and hence many linear maps $\phi_* : K_0(\mathcal{C}^\infty_c(\mathcal{F})) \to \mathbb{C}$, each of which defines an index map $\phi_* \circ \partial : K_0(\mathcal{C}^\infty(S^*\mathcal{F})) \to \mathbb{C}$.

We will not pursue further the determination of $\phi_* \circ \partial$, but we note Connes’ results in [31, 29, 76], the results of Benameur–Heitsch for Haeffliger homology [16], the results of Connes–Skandalis [33], and of myself for foliated bundles [113]. We also stress that in the case of foliations, it is the ideal $I$ that causes difficulties, whereas the quotient $\text{Symb} := A/I$ is commutative and, hence, relatively easy to deal with. The opposite will be the case in the following subsection.

1.6. The Atiyah-Patodi-Singer index formula. A related but different type of example is provided by the Atiyah-Patodi-Singer (APS) index formulas [10]. Let $\overline{M}$ be an $n$-dimensional compact manifold with smooth boundary $\partial\overline{M}$. By definition, this means that $\overline{M}$ is locally diffeomorphic to an open subset of $[0, 1) \times \mathbb{R}^{n-1}$. The transition functions for a manifold with boundary will be assumed to be smooth. To $\overline{M}$ we attach the semi-infinite cylinder

$$\partial\overline{M} \times (-\infty, 0],$$

yielding a manifold with cylindrical ends. The metric is taken to be a product metric $g = g_{\partial\overline{M}} + dt^2$ far on the end. Kondratiev’s transform $r = e^t$ then maps the cylindrical end to a tubular neighborhood of the boundary, such that the cylindrical end metric becomes $g = g_{\partial\overline{M}} + (r^{-1}dr)^2$ near the boundary, since $r^{-1}dr = e^{-t}d(e^t) = dt$.

Thus, on $\overline{M}$, we consider two metrics: first, the initial, everywhere smooth metric (including up to the boundary) and, second, the modified, singular metric $g$.
that corresponds to the compactification of the cylindrical end manifold. This is illustrated in the following pictures:

We have thus obtained the simplest examples of a non-compact manifold, that of a manifold with cylindrical ends. We will consider on this non-compact manifold only differential operators with coefficients that extend to smooth functions up to infinity (so, in particular, they have limits at infinity). Because of this, it will be more convenient to work on $\overline{M}$ than on $\overline{M} \cup \partial M \times (-\infty, 0]$. This is achieved by the Kondratiev transform $r = e^t$. The Kondratiev transform is such that $\partial_t$ becomes $r \partial_r$. On $\overline{M}$, we then take the coefficients to be smooth functions up to the boundary. Therefore, in local coordinates $(r, x') \in [0, \epsilon) \times \partial M$ on the distinguished tubular neighborhood of $\partial \overline{M}$, we obtain the following form for our differential operators (here $n = \dim(M)$):

\begin{equation}
P = \sum_{|\alpha| \leq m} a_\alpha(r, x') (r \partial_r)^{\alpha_1} \partial_{x_2}^{\alpha_2} \ldots \partial_{x_n}^{\alpha_n} = \sum_{|\alpha| \leq m} a_\alpha(r \partial_r)^{\alpha_1} \partial_{x'}^{\alpha}.
\end{equation}

Operators of this form are called totally characteristic differential operators.

Away from the boundary, the definition of the principal symbol for a totally characteristic differential operator is unchanged. However, in the same local coordinates near the boundary as in Equation (15), the principal symbol for the totally characteristic differential operator of Equation (15) is

\begin{equation}
\sigma_m(P) := \sum_{|\alpha|=m} a_\alpha \xi^\alpha.
\end{equation}

Thus the principal symbols is not $\sum_{|\alpha|=m} a_\alpha r^{\alpha_1} \xi^\alpha$ as one might first think! Other than the fact that this definition of the principal symbol gives the “right results,” it can be motivated by considering the original coordinates $(t, x') \in (-\infty, 0] \times \partial \overline{M}$ on the cylindrical end.

The principal symbol is something that was encountered in the classical case of the AS-index formula as well as in the case of foliations, so it is not something significantly new in the case of manifolds with cylindrical ends—even if in that case the definition is slightly different. However, in the case of manifolds with cylindrical
ends, there is another significant new ingredient, which will turn out to be both crucial and typical in the analysis on singular spaces. This significant new ingredient is the indicial family of a totally characteristic differential operator. To define and discuss the indicial family of a totally characteristic differential operator, let $P$ be as in Equation (15) and consider the same local coordinates near the boundary as in that equation. The definition of the indicial family $\hat{P}$ of $P$ is then as follows (we underline the most significant new ingredients of the definition):

$$\hat{P}(\tau) := \sum_{|\alpha| \leq m} a_\alpha(0, x')(\tau)^{\alpha_1} \partial^{\alpha'}.$$  

Note that $\hat{P}(\tau)$ is a family of differential operators on $\partial M$ that depends on the coefficients of $P$ only through their restrictions to the boundary. Moreover, we see that the indicial family $\hat{P}(\tau)$ of $P$ is the Fourier transform of the operator

$$I(P) := \sum_{|\alpha| \leq m} a_\alpha(0, x')\partial_{\alpha_1}^{\alpha_1} \partial^{\alpha'},$$

which is a translation invariant operator on $\partial M \times \mathbb{R}$. The operator $\mathcal{I}(P)$ is called the indicial operator of $P$ [85, 110]. Note that we have denoted $\partial^{\alpha'} = \partial_{\alpha_1}^{\alpha_1} \partial^{\alpha'}$.

We are interested in Fredholm conditions for totally characteristic differential operators, so let us introduce the last ingredient for the Fredholm conditions. Let us endow $M := \overline{M} \setminus \partial M$ with a cylindrical end metric. Since the cylindrical end metric is complete, the Laplacian $\Delta$ is self-adjoint, and hence we can define the Sobolev space $H^s(M)$ as the domain of $\Delta^{s/2}$, that is, $H^s(M) := \mathcal{D}(\Delta^{s/2})$, which turns out to be independent of the choice of the cylindrical end metric. (We consider all differential operators to be defined on their minimal domain, unless otherwise mentioned, and thus, in particular, they give rise to closed, densely defined operators.) We then have a characterization of Fredholm totally characteristic differential operators similar to the compact case (the differences to the compact case are underlined).

**Theorem 1.8.** Assume $M$ has cylindrical ends and $P$ is a totally characteristic differential operator of order $m$ acting between the sections of the bundles $E$ and $F$. Then, for any fixed $s \in \mathbb{R}$, we have that

$$P : H^s(M; E) \to H^{s-m}(M; F)$$

is Fredholm if, and only if, $P$ is elliptic and $\hat{P}(\tau)$ is invertible for all $\tau \in \mathbb{R}$.

This result has a long history and related theorems are due to many people, too many to mention them all here. Nevertheless, one has to mention the pioneering work of Lockhart-Owen on differential operators [89] and the work of Melrose-Mendoza for totally characteristic pseudodifferential operators [100]. A closely related theorem for differential operators and domains with conical points has appeared in a landmark paper by Kondratiev in 1967 [73]. Other important results in this direction were obtained by Mazya [77] and Schrohe–Schultze [141, 142]. See the books of Schulze [143], Lesch [85], and Plamenevski˘ı [128] for introductions and more information on the topics and results of this subsection.

One can easily show that $\mathcal{I}(P)$ is invertible if, and only if, $\hat{P}(\tau)$ is invertible for all $\tau \in \mathbb{R}$. Thus the Fredholmness criterion of Theorem 1.8 can also be given the following formulation that is closer to our more general result of Theorem 4.14.
Theorem 1.9. Let $M$ and $P$ be as in Theorem 1.8 and $s \in \mathbb{R}$. Then

$$P : H^s(M; E) \rightarrow H^{s-m}(M; F)$$

is Fredholm if and only if $P$ is elliptic and $\mathcal{I}(P)$ is invertible.

Let us consider now a totally characteristic, twisted Dirac operator $P$. In case $P$ is Fredholm, its Fredholm index is given by the Atiyah-Patodi-Singer (APS) formula [10], which expresses $\text{ind}(P)$ as the sum of two terms:

(i) the integral over $\overline{M}$ of an explicit form, which is a local term that depends only on the principal symbol of the operator $P$, as in the case of the AS formula, and

(ii) a boundary contribution that depends only on the indicial family $\hat{P}(\tau)$, namely the $\eta$-invariant, which is this time a non-local invariant. It can be expressed in terms of $\mathcal{I}(P)$ [101].

We thus see that even to be able to formulate the APS-index formula, we need to know which totally characteristic operators will be Fredholm. Moreover, the ingredients needed to compute the index of such an operator $P$ (that is, its principal symbol $\sigma_m(P)$ and the indicial operator $\mathcal{I}(P)$) are exactly the ingredients needed to decide that the given operator $P$ is Fredholm. See [17, 81, 101, 140] for further results.

Let us now introduce the exact sequence of the APS index formula. First of all, $A := \Psi^0_b(M)$ is the algebra of totally characteristic pseudodifferential operators on $M$. One of its main properties is that the differential operators in $A$ are exactly the totally characteristic differential operators. See [85, 143] for a definition of $\Psi^\infty_b(M)$. A definition using groupoids (of a slightly different algebra) will be given in Subsection 4.5 in a more general setting. Let $r$ be a defining function of the boundary $\partial M$ of $M$, as before. Next, the ideal is $I := r \Psi^{-1}_b(M) = \Psi^0_b(M) \cap \mathcal{K}$.

Then the symbol algebra $\text{Symb} := A/I$ is the fibered product

$$\text{Symb} = C^\infty(S^*\overline{M}) \oplus_\partial \Psi^0(\partial \overline{M} \times \mathbb{R})^R,$$

more precisely, Symb consists of pairs $(f, Q)$ such that the principal symbol of the $\mathbb{R}$ invariant pseudodifferential operator $Q$ matches the restriction of $f \in C^\infty(S^*\overline{M})$ to the boundary. Recalling the definition of $\mathcal{I}$ in Equation (18) (and extending it to totally characteristic pseudodifferential operators), we obtain the exact sequence

$$0 \rightarrow r\Psi_b^{-1}(M) \rightarrow \Psi^0_b(M) \xrightarrow{\sigma_0 \oplus \mathcal{I}} C^\infty(S^*\overline{M}) \oplus_\partial \Psi^0(\partial \overline{M} \times \mathbb{R})^R \rightarrow 0. \quad (20)$$

(The exact sequence $0 \rightarrow \Psi_b^{-1}(M) \rightarrow \Psi^0_b(M) \xrightarrow{\sigma_0} C^\infty(S^*\overline{M}) \rightarrow 0$ is, by contrast, less interesting.)

The exact sequence (20) in particular gives that $P$ is Fredholm if, and only if, the pair $(\sigma_0(P), \mathcal{I}(P)) \in \text{Symb} := C^\infty(S^*\overline{M}) \oplus_\partial \Psi^0(\partial \overline{M} \times \mathbb{R})^R$ is invertible, which, in turn, is true if, and only if, $P$ is elliptic and $\mathcal{I}(P)$ is invertible. Thus the exact sequence (20) implies Theorem 1.9.

As before, composing $\partial : K_1(\text{Symb}) \rightarrow K_0(I), I = r\Psi^{-1}(\overline{M})$, with the trace map $Tr_*$ gives us the Fredholm index

$$\text{ind} = Tr_* \circ \partial : K_1(\text{Symb}) \rightarrow \mathbb{C}.$$
Since $\text{Tr}_* \circ \partial = (\partial \text{Tr})_*$ [30] (see [114] for the case when $\text{Tr}$ is replaced by a general cyclic cocycle), we see that the APS index formula is also equivalent to the calculation of the class of the cyclic cocycle $\partial \text{Tr} \in \text{HP}^1(\text{Symb})$. This was the approach undertaken in [101, 108].

Remark 1.10. It is important to stress here first the role of cyclic homology, which is to define natural morphisms $K_1(\text{Symb}) \to \mathbb{C}$, morphisms that are otherwise difficult to come by. Also, it is important to stress that it is the noncommutativity of the algebra of symbols $\text{Symb}$ that explains the fact that the APS index formula is non-local.

We need to insist of the fact that in the case of the APS framework, it is the symbol algebra $\text{Symb} := A/I$ that causes difficulties, in large part because it is noncommutative (so the classical Chern character is not defined), whereas the ideal $I \subset \mathcal{K}$ is easy to deal with. This is an opposite situation to the one encountered for foliations. It is for this reason that the foliation framework and the APS framework extend the AS framework in different directions.

The approach to Index theory explained in this last subsection extends to more complicated singular spaces, and this has provided the author of this presentation the motivation to study analysis on singular spaces.

2. Motivation: Degeneration and singularity

The totally characteristic differential operators studied in the previous subsection appear not only in index problems, but actually arise in many practical applications. We shall now examine how the totally characteristic differential operators and other related operators appear in practice. In a nut-shell, these operators can be used to model degenerations and singularities. In this section, we introduce several examples. We begin with the ones related to the APS index theorem (the totally characteristic ones, called “rank one” by analogy with locally symmetric spaces) and then we continue with other examples. Again, no results in this section are new.

2.1. APS-type examples: rank one. Let us denote by $\rho$ the distance to the origin in $\mathbb{R}^d$. Here is a list of examples of totally characteristic operators.

Example 2.1. In our three examples below, the first one is a true totally characteristic operator, whereas the other two require us to remove the factor $\rho^{-2}$ first.

1. The elliptic generator $L$ of the Black-Scholes PDE $\partial_t - L$ [146]

$Lu := \frac{\sigma^2}{2} x^2 \partial_x^2 u + rx \partial_x u - ru$.

2. The Laplacian in polar coordinates $(\rho, \theta)$

$\Delta u = \rho^{-2} (\rho^2 \partial_\rho^2 u + \rho \partial_\rho u + \partial_\theta^2 u)$.

3. The Schrödinger operator in spherical coordinates $(\rho, x')$, $x' \in S^2$,

$-(\Delta + \frac{Z}{\rho}) u = -\rho^{-2} (\rho^2 \partial_\rho^2 u + 2\rho \partial_\rho u + \Delta_{S^2} u + Z \rho u)$.

A similar expansion is valid for elliptic operators in generalized spherical coordinates in arbitrary dimensions and was used by Kondratiev in [73] to study domains with conical points. Kondratiev’s paper is widely used since it provides
the needed analysis facts to deal with polygonal domains, the main testing ground for numerical methods.

2.2. Manifolds with corners. For more complicated examples we will need manifolds with corners. Recall that $\mathcal{M}$ is a manifold with corners if, and only if, $\mathcal{M}$ is locally diffeomorphic to an open subset of $[0,1)^n$. The transition functions of $\mathcal{M}$ are supposed to be smooth, as in the case of manifolds with smooth boundary. A manifold with boundary is a particular case of a manifold with corners, but we agree in this paper that a smooth manifold does not have boundary (or corners), since we regard the corners (or boundary) as some sort of singularity.

A point $p \in \mathcal{M}$ is called of depth $k$ if it has a neighborhood $V_p$ diffeomorphic to $[0,1)^k \times (-1,1)^{n-k}$ by a diffeomorphism $\phi_p : V_p \to [0,1)^k \times (-1,1)^{n-k}$ mapping $p$ to the origin: $\phi_p(p) = 0$. A connected component $F$ of the set of points of depth $k$ will be called an open face (of codimension $k$) of $\mathcal{M}$. The set of points of depth 0 of $\mathcal{M}$ is called the interior of $\mathcal{M}$, is denoted $\mathcal{M}$, and its connected components are also considered to be an open faces of $\mathcal{M}$. The closure in $\mathcal{M}$ of an open face $F$ of $\mathcal{M}$ will be called a closed face of $\mathcal{M}$. A closed face of $\mathcal{M}$ may not be a manifold with corners in its own. The union of the proper faces of $\mathcal{M}$ is denoted by $\partial \mathcal{M}$ and is called the boundary of $\mathcal{M}$. Thus $\mathcal{M} := \mathcal{M} \setminus \partial \mathcal{M}$.

The following set of vector fields will be useful when defining Lie manifolds:

\[ \mathcal{V}_b := \{ X \in \Gamma(\mathcal{M} ; T \mathcal{M}) , \ X \text{ is tangent to all boundary faces of } \mathcal{M} \} . \]

Let us notice that in the case of manifolds with boundary, the totally characteristic differential operators on $\mathcal{M}$, see Equation (15), are generated by $C^\infty(\mathcal{M})$ and the vector fields $X \in \mathcal{V}_b$.

2.3. Higher rank examples. We now continue with more complicated examples, which we call “higher rank” examples, again by analogy with locally symmetric spaces. In general, the natural domains for these higher rank examples will be manifolds with corners.

Example 2.2. There are no “higher rank” example in dimension one, so we begin with an example in dimension two.

1. The simplest non-trivial example is the Laplacian

\[ \Delta_\mathbb{H} = y^2(\partial_x^2 + \partial_y^2) \]

on the hyperbolic plane $\mathbb{H} = \mathbb{R} \times [0, \infty)$, whose metric is $y^{-2}(dx^2 + dy^2)$.

2. The Laplacian on the hyperbolic plane is closely related to the SABR Partial Differential Equation (PDE) due to Lesniewsky and collaborators [62].

\[ 2L := y^2(x^2\partial_x^2 + y^2\partial_y^2 + \rho \nu x \partial_x \partial_y + \nu^2 \partial_y^2) , \]

with $\rho$ and $\nu$ real parameters. Stochastic differential equations provide many interesting and non-trivial examples of degenerate parabolic PDEs that can be treated using Lie manifolds.

3. A related example is that of the Laplacian in cylindrical coordinates $(\rho, \theta, z)$ in three dimensions:

\[ \Delta u = \rho^{-2}((\rho \partial_\rho)^2 u + \partial_\theta^2 u + (\rho \partial_z)^2) . \]
Ignoring the factor $\rho^{-2}$, which amounts to a conformal change of metric, we see that our differential operator (that is, $\rho^2 \Delta$) is generated by the vector fields

$$\rho \partial_\rho, \partial_\theta, \text{ and } \rho \partial_z,$$

and that the linear span of these vector fields is a Lie algebra. The resulting partial differential operators are usually called edge differential operators. This example can be used to treat the behavior near edges of polyhedral domains of elliptic PDEs. This behavior is more difficult to treat than the behavior near vertices. For a boundary value problems in a three dimensions wedge of dihedral angle $\alpha$, the natural domain is $[0, \alpha] \times [0, \infty) \times \mathbb{R}$, a manifold with corners of codimension two.

We thus again see that Lie algebras of vector fields are one of the main ingredients in the definition of the differential operators that we are interested in. More related examples will be provided below as examples of Lie manifolds.

Degenerate elliptic equations have many applications in Numerical Analysis, see [14, 38, 41, 88, 87], for example.

3. Lie manifolds: definition and geometry

Motivated by the previous two sections, we now give the definition of a Lie manifold largely following [7]. We also introduce a slightly more general class of manifolds than in [7] by allowing the manifold with corners appearing in the definition to be noncompact. We also slightly simplify the definition of a Lie manifold based on a comment of Skandalis. We thus define our Lie manifolds using Lie algebroids and then we recover the usual definition in terms of Lie algebras of vector fields. I have tried to make this section as self-contained as possible, thus including most of the proofs, some of which are new.

3.1. Lie algebroids and Lie manifolds. We have found it convenient to introduce Lie manifolds and “open manifolds with a Lie structure at infinity” in terms of Lie algebroids, which we will recall shortly. First, recall that we use the following notation, if $E \to X$ is a smooth vector bundle, we denote by $\Gamma(X; E)$ (respectively, by $\Gamma_c(X; E)$) the space of smooth (respectively, smooth, compactly supported) sections of $E$. Sometimes, when no confusion can arise, we simply write $\Gamma(E)$, or, respectively, $\Gamma_c(E)$. We now introduce Lie algebroids. Lie algebroids were introduced by Pradines [129]. See also [65, 66] for some basic results on Lie algebroids and Lie groupoids. We refer to [92, 103] for further material and references to Lie algebroids and groupoids.

**Definition 3.1.** A Lie algebroid $A \to \overline{M}$ is a real vector bundle over a manifold with corners $\overline{M}$ together with a Lie algebra structure on $\Gamma(\overline{M}; A)$ (with bracket $[\cdot, \cdot]$) and a vector bundle map $\varrho : A \to T\overline{M}$, called anchor, such that the induced map $\varrho_* : \Gamma(\overline{M}; A) \to \Gamma(\overline{M}; T\overline{M})$ satisfies the following two conditions:

(i) $\varrho_*([X, Y]) = [\varrho_*(X), \varrho_*(Y)]$ and

(ii) $[X, fY] = f[X, Y] + (\varrho_*(X)f)Y$, for all $X, Y \in \Gamma(\overline{M}; A)$ and $f \in C^\infty(\overline{M})$.

For further reference, let us recall here the isotropy of a Lie algebroid.

**Definition 3.2.** Let $\varrho : A \to T\overline{M}$ be a Lie algebroid on $\overline{M}$ with anchor $\varrho$. Then the kernel $\ker(\varrho_* : A_x \to T_x \overline{M})$ of the anchor is the isotropy of $A$ at $x \in \overline{M}$.
The isotropy at any point can be shown to be a Lie algebra. See [9] for generalizations. Recall that we denote by $\partial\overline{M}$ the boundary $\overline{M}$, that is, the union of its proper faces, and by $M := \overline{M} \setminus \partial\overline{M}$ its interior.

**Definition 3.3.** A pair $(\overline{M}, A)$ consisting of a manifold with corners $\overline{M}$ and a Lie algebroid $A \to \overline{M}$ is called an open manifold with a Lie structure at infinity if its anchor $\varrho : A \to TM$ satisfies the following properties:

(i) $\varrho : A_x \to T_x\overline{M}$ is an isomorphism for all $x \in M := \overline{M} \setminus \partial M$ and 
(ii) $\mathcal{V} := \varrho_* (\Gamma (\overline{M}; A)) \subset \mathcal{V}_b$.

If $\overline{M}$ is compact, then the pair $(\overline{M}, A)$ will be called a Lie manifold.

Condition (ii) means that the Lie algebra of vector fields $\mathcal{V} := \varrho_* (\Gamma (A))$ consists of vector fields tangent to all faces of $\overline{M}$. One of the main reasons for introducing open manifolds with a Lie structure at infinity is in order to be able to localize Lie manifolds. Thus, if $(\overline{M}, A)$ is a Lie manifold and $V \subset \overline{M}$ is an open subset, then $(V, A|_V)$ will not be a Lie manifold, in general, but will be an open manifold with a Lie structure at infinity. Thus the Lie manifolds are exactly the compact open manifold with a Lie structure at infinity. Lie manifolds were introduced in [7].

By extension, $\overline{M}$ and $M := \overline{M} \setminus \partial\overline{M}$ in Definition 3.3 will also be called open manifolds with a Lie structure at infinity. We shall write $\Gamma (A)$ instead of $\Gamma (\overline{M}; A)$ when no confusion can arise, also, we shall usually write $\Gamma (A)$ instead of $\varrho_* (\Gamma (A))$. We have the following “trivial” example.

**Example 3.4.** The “example zero” of a Lie manifold is that of a smooth, compact manifold $M = \overline{M}$ (no boundary or corners) and is obtained by taking $A = TM$, thus $\mathcal{V} = \Gamma (TM) = \Gamma (M; TM) = \mathcal{V}_b$. Then $(M, A)$ is a (trivial) example of a Lie manifold. This example of a Lie manifold provides the framework for the AS Index Theorem. Similarly, every smooth manifold $M$ is an open manifold with a Lie structure at infinity by taking $\overline{M} = M$ and $A = TM$.

**Example 3.5.** Let $\overline{M}$ be a manifold with corners such that its interior $M := \overline{M} \setminus \partial\overline{M}$ identifies with the quotient of a Lie group $G$ by a discrete subgroup $\Gamma$ and the action of $G$ on $G/\Gamma$ by left multiplication extends to an action of $G$ on $\overline{M}$. Let $\mathfrak{g}$ be the Lie algebra of $G$. Then $A := \overline{M} \times \mathfrak{g}$ with anchor given by the infinitesimal action of $G$ is naturally a Lie algebroid. Note that the action of the Lie algebra $\mathfrak{g}$ preserves the structure of faces of $\overline{M}$ and hence $\varrho_* (\Gamma (A)) \subset \mathcal{V}_b$. We call the corresponding manifold with a Lie structure at infinity a group enlargement. The simplest example is that of $G = M = R^*_+ \subset [0, \infty]$. Many interesting Lie manifolds arising in practice are, locally, group enlargements, see for instance [54, 55] for some examples coming from quantum mechanics.

Let $(\overline{M}, A)$ be an open manifold with a Lie structure at infinity. In applications, it is easier to work with the vector fields $\mathcal{V} := \varrho_* (\Gamma (A))$, associated to a Lie manifold $(M, A)$, than with the Lie algebroid $A \to M$. We shall then use the following alternative definition of Lie manifolds.

**Proposition 3.6.** Let us consider a pair $(\overline{M}, \mathcal{V})$ consisting of a compact manifold with corners $\overline{M}$ and a subspace $\mathcal{V} \subset \Gamma (\overline{M}; TM)$ of vector fields on $\overline{M}$ that satisfy:

(i) $\mathcal{V}$ is closed under the Lie bracket $[\cdot, \cdot]$;
(ii) $\Gamma_v(M; TM) \subset \mathcal{V} \subset \mathcal{V}_b$;
(iii) $C^\infty (\overline{M})\mathcal{V} = \mathcal{V}$ and $\mathcal{V}$ is a finitely-generated $C^\infty (\overline{M})$–module;
(iv) \( \mathcal{V} \) is projective (as a \( C^\infty(\overline{M}) \)-module).

Then there exists a Lie manifold \((\overline{M}, A)\) with anchor \( \varrho \) such that \( \varrho_*(\Gamma(\overline{M}; A)) = \mathcal{V} \).

Conversely, if \((\overline{M}, A)\) is a Lie manifold, then \( \mathcal{V} := \varrho_*(\Gamma(\overline{M}; A)) \) satisfies the conditions (i)–(iv) above.

**Proof.** Let \((\overline{M}, \mathcal{V})\) be as in the statement. Since \( \mathcal{V} \) is a finitely generated, projective \( C^\infty(\overline{M}) \)-module, the Serre–Swan Theorem implies then that there exists a finite dimensional vector bundle \( A_\mathcal{V} \to \overline{M} \), uniquely defined up to isomorphism, such that

\[
\mathcal{V} \simeq \Gamma(\overline{M}; A_\mathcal{V}),
\]

as \( C^\infty(\overline{M}) \)-modules. Let \( I_x := \{ \phi \in C^\infty(\overline{M}), \phi(x) = 0 \} \) be the maximal ideal corresponding to \( x \in \overline{M} \). The fibers \( (A_\mathcal{V})_x, x \in \overline{M} \), of the vector bundle \( A_\mathcal{V} \to \overline{M} \) are given by \( (A_\mathcal{V})_x = \mathcal{V}/I_x\mathcal{V} \). Since \( \Gamma(\overline{M}; A_\mathcal{V}) \simeq \mathcal{V} \subset \Gamma(\overline{M}; \mathcal{T}\overline{M}) \), we automatically obtain for each \( x \in \overline{M} \) a map

\[
(A_\mathcal{V})_x := \mathcal{V}/I_x\mathcal{V} \to \Gamma(\overline{M}; \mathcal{T}\overline{M})/I_x\Gamma(\overline{M}; \mathcal{T}\overline{M}) = T_x\overline{M}.
\]

These maps piece together to yield a bundle map (anchor) \( \varrho : A_\mathcal{V} \to T\overline{M} \) that makes \( A_\mathcal{V} \to \overline{M} \) a Lie algebroid. The anchor map \( \varrho \) is an isomorphism over the interior \( M \) of \( \overline{M} \) since \( \Gamma_c(M; \mathcal{T}M) \subset \mathcal{V} \), which is part of Assumption (ii). Since \( \mathcal{V} \subset \mathcal{V}_o \), again by Assumption (ii), we obtain that \((\overline{M}, A_\mathcal{V})\) is indeed a Lie manifold.

Conversely, let \((\overline{M}, A)\) be a Lie manifold with anchor \( \varrho : A \to T\overline{M} \). We need to check that \( \mathcal{V} := \varrho_*(\Gamma(\overline{M}; A)) \) satisfies conditions (i)–(iv) of the statement. Indeed, \( \mathcal{V} := \varrho_*(\Gamma(\overline{M}; A)) \) is a Lie algebra because \( \Gamma(\overline{M}; A) \) is a Lie algebra and \( \varrho_* : \Gamma(\overline{M}; A) \to \Gamma(\overline{M}; T\overline{M}) \) is an injective Lie algebra morphism. So Condition (i) is satisfied. To check the second conditions, we notice that Definition 3.3(i) (isomorphism over the interior) gives that \( \Gamma_c(M; T\overline{M}) \subset \mathcal{V} \). Since we have by assumption \( \mathcal{V} \subset \mathcal{V}_o \), we see that Condition (ii) is also satisfied. Finally, Conditions (iii) and (iv) are satisfied since the space of smooth sections of a finite dimensional vector bundle defines a projective module over the algebra of smooth functions on the base, again by the Serre-Swan theorem. \( \square \)

Let \((\overline{M}, \mathcal{V})\) as in the statement of the above proposition, Proposition 3.6. We call \( \mathcal{V} \) its *structural Lie algebra of vector fields* and we call the Lie algebroid \( A_\mathcal{V} \to \overline{M} \) introduced in Equation (23) the *Lie algebroid associated to \((\overline{M}, \mathcal{V})\)*. The alternative characterization of Lie manifolds in Proposition 3.6 is the one that will be used in our examples.

**Remark 3.7.** It is worthwhile pointing out that the condition that \( \mathcal{V} \) be a finitely generated, projective \( C^\infty(\overline{M}) \)-module in Proposition 3.6 together with the fact that the anchor \( \varrho \) is an isomorphism over the interior of \( \overline{M} \) are equivalent to the following condition, where \( n = \dim(\overline{M}) \):

For every point \( p \in \overline{M} \), there exist a neighborhood \( V_p \) of \( p \) in \( \overline{M} \) and \( n \)-vector fields \( X_1, X_2, \ldots, X_n \in \mathcal{V} \) such that, for any vector field \( Y \in \mathcal{V} \), there exist smooth functions \( \phi_1, \phi_2, \ldots, \phi_n \in C^\infty(\overline{M}) \) such that

\[
Y = \phi_1 X_1 + \phi_2 X_2 + \ldots + \phi_n X_n \quad \text{on} \quad V_p, \quad \text{with} \quad \phi_i|_{V_p} \text{ uniquely determined.}
\]
The vector fields $X_1, X_2, \ldots, X_n$ are then called a *local basis* of $\mathcal{V}$ on $V_p$. (This is the analog in our case of the well known fact from commutative algebra that a module is projective if, and only if, it is locally free.)

In the next example, we shall need the defining functions of a “hyperface.” A hyperface is a proper face $H \subset \overline{M}$ of maximal dimension (dimension $\dim(H) = \dim(M) - 1$). Recall that a defining function of a hyperface $H$ of $\overline{M}$ is a function $x$ such that $H = \{ x = 0 \}$ and $dx \neq 0$ on $H$. The hyperface $H \subset \overline{M}$ is called embedded if it has a defining function. The existence of a defining function is a global property, because locally one can always find defining functions, a fact that will be needed in the example below.

The following pictures show some examples of manifolds with corners $\overline{M}$ with embedded and non-embedded faces. In the example with a non-embedded face (the “tear drop” domain), the vertex point that creates the problem will have a neighborhood $V$ such $V \cap \overline{M}$ has *two* hyperfaces and each of them has a defining function. By contrast, the tear drop domain has only *one* hyperface, and that hyperface is not embedded.

The simplest example of a non-compact Lie manifold is that of a manifold with cylindrical ends. The following example generalizes this example to the higher rank case. It is a basic example to which we will come back later.

**Example 3.8.** Let $\overline{M}$ a compact manifold with corners and $\mathcal{V} = \mathcal{V}_b$. Let us check that $(\overline{M}, \mathcal{V}_b)$ is a Lie manifold. We shall use Proposition 3.6. Condition (i) is easily verified since the Lie bracket of two vector fields tangent to a submanifold is again tangent to that submanifold. Condition (ii) in the Proposition 3.6 is even easier since, by definition, vector fields that are zero near the boundary $\partial \overline{M}$ are contained in $\mathcal{V}_b$. Clearly, $\mathcal{V}$ is a $C^\infty(\overline{M})$ module. The only non-trivial fact to check is that $\mathcal{V}$ is finitely generated and projective as an $C^\infty(\overline{M})$ module. This is actually the only fact that we still need to check. To verify it, let us fix a corner point $p$ of codimension $k$ (that is, $p$ belongs to an open face $F$ of codimension $k$). Then, in a neighborhood of $p$, we can find $k$ defining functions $r_1, r_2, \ldots, r_k$ of the hyperfaces.
now on, \((\text{Lie structure at infinity})\) this extension is straightforward, but needed. Thus, from results in this direction following \([7]\) and we extend them to open manifolds with a cylindrical ends, Lie manifolds have an intrinsic geometry. We now discuss some

3.2. The metric on Lie manifolds. As seen from the example of manifolds with cylindrical ends, Lie manifolds have an intrinsic geometry. We now discuss some results in this direction following \([7]\) and we extend them to open manifolds with a Lie structure at infinity (this extension is straightforward, but needed). Thus, from now on, \((\overline{M}, A)\) will be an open manifold with a Lie structure at infinity. (Thus we will not assume \((\overline{M}, A)\) to be a Lie manifold, unless explicitly stated.)

**Definition 3.9.** Let \((\overline{M}, A)\) be an open manifold with a Lie structure at infinity. A metric on \(TM\) is called compatible (with the structure at infinity) if it extends to a metric on \(A \to \overline{M}\).

We shall need the following lemma.

**Lemma 3.10.** Let \((\overline{M}, A)\) be an open manifold with a Lie structure at infinity with compatible metric \(g\). Assume \(\overline{M}\) to be paracompact. Then there exists a smooth metric \(h\) on \(T\overline{M}\) such that \(h \leq g\).

**Proof.** Let us choose an arbitrary metric \(h_0\) on \(\overline{M}\) (or, more precisely, on \(T\overline{M}\)). For each \(p \in \overline{M}\), let \(U_p \subset V_p\) be open neighborhoods of \(p\) in \(\overline{M}\) such that \(V_p\) has compact closure and contains the closure of \(U_p\). Since \(V_p\) has compact closure and the anchor map \(\rho\) is continuous, we obtain that there exists \(M_p > 0\) such that \(h_0(\xi) \leq M_p g(\xi)\) for every \(\xi \in A|_{V_p}\). Let us choose \(I \subset \partial \overline{M}\) such that \(\{U_p, p \in I\}\) is a locally finite covering of the boundary \(\partial \overline{M}\). Let \(V_0\) be the complement of \(\cup_{p \in I} \overline{U_p}\) and let \((\phi_p)_{p \in I \cup \{0\}}\) be a smooth, locally finite partition of unity on \(\overline{M}\) subordinated to the covering \((V_p)_{p \in I \cup \{0\}}\). Then, if we define

\[
    h = \sum_{p \in I} \phi_p M_p^{-1} h_0 + \phi_0 g ,
\]

the metric \(h\) will satisfy \(h \leq g\) everywhere, as desired. \(\square\)

Let us fix from now on a metric \(g\) on \(A\), which restricts to a compatible Riemannian metric on \(M\). The inner product of two vectors (or vector fields) \(X, Y \in \Gamma(M; TM)\) containing \(p\) such that a local basis of \(V\) around \(p\) (see Remark 3.7) is given by

\[
    r_1 \partial_{r_1}, r_2 \partial_{r_2}, \ldots, r_k \partial_{r_k}, \partial_{y_{k+1}}, \ldots, \partial_{y_n} ,
\]

where \(y_{k+1}, \ldots, y_n\) are local coordinates on the open face \(F\) of dimension \(k\) containing \(p\), so that \((r_1, r_2, \ldots, r_k, y_{k+1}, \ldots, y_n)\) provide a local coordinate system in a neighborhood of \(p\) in \(\overline{M}\). If \(\overline{M}\) has a smooth boundary, then \(V\) generates the totally characteristic differential operators, which were introduced in Equation (15), and hence this example corresponds to a manifold with cylindrical ends. In fact, we will see that the natural Riemannian metric of a manifold with (asymptotically) cylindrical ends. This example was studied also by Debord and Lescure [44, 45], Melrose and Piazza [102], Monthubert [105], Schulze [143], and many others.

By [7], every vector field \(X \in V\) that has compact support in \(\overline{M}\) gives rise to a one parameter group of diffeomorphisms \(\exp(tX) : \overline{M} \to \overline{M}, t \in \mathbb{R}\). We denote by \(\exp(V)\) the subgroup of diffeomorphisms generated by all \(\exp(X)\) with \(X \in V\) and compact support in \(\overline{M}\). The results in [9] show that \(\exp(V)\) acts by Lie automorphisms of \(V\) (the condition (iv) of Proposition 3.6 that \(V\) be a projective module is not necessary). Also, it would be interesting to see how the groups \(\exp(V)\) fit into the general theory of infinite dimensional Lie groups [111].
in this metric will be denoted \((X,Y) \in C^\infty(M)\) and the associated volume form \(d\text{vol}_g\). Of course, if \(X,Y \in V := \varrho_*(\Gamma(M;A))\), then \((X,Y) \in C^\infty(\overline{M})\). We now want to investigate some properties of the metric \(g\). For simplicity, we write \(\Gamma(TM) = \Gamma(M;TM)\) and \(\varrho_*(\Gamma(A)) = \Gamma(M;A)\). Let us consider the Levi-Civita connection

\[ \nabla^g : \Gamma(TM) \to \Gamma(TM \otimes T^*M) \]

associated to the metric \(g\). Recall that an \(A\)-connection on a vector bundle \(E \to M\) (see [7] and the references therein) is given by a differential operator \(\nabla\) such that

\[ \nabla f X (f_1 \xi) = f_1 \nabla_X (f \xi) + f \nabla_X (f_1 \xi) \]

for all \(f, f_1 \in C^\infty(M)\) and \(\xi \in \Gamma(M;E)\). The following proposition from [7] gives that the Levi-Civita connection extends to an “\(A\)-connection.”

**Proposition 3.11.** Let \((\overline{M}, A)\) be an open manifold with a Lie structure at infinity and \(g\) be a compatible metric on \(M\). The Levi-Civita connection associated to the compatible metric \(g\) extends to a linear differential operator \(\nabla = \nabla^g : \varrho_*(\Gamma(A)) \to \Gamma(A \otimes A^*)\), satisfying

(i) \(\nabla_X (fY) = X(fY) + f \nabla_X (Y)\),

(ii) \(X(Y,Z) = (\nabla_X Y, Z) + (Y, \nabla_X Z)\), and

(iii) \(\nabla_X Y - \nabla_Y X = [X,Y]\),

for all \(X,Y,Z \in V = \varrho_*(\Gamma(A))\).

**Proof.** We recall the proof for the benefit of the reader. Since the metric \(g\) actually comes from an metric on \(A\) by restriction to \(TM \subset A\), we see that

\[ \phi(Z) := ([X,Y],Z) - ([Y,Z],X) + ([Z,X],Y) + X(Y,Z) + Y(Z,X) - Z(X,Y) \]

defines a smooth function on \(\overline{M}\) for any \(Z \in V\) and that this smooth function depends linearly on \(Z\). Hence there exists a smooth section \(V \in V\) such that \(\phi(Z) = (V,Z)\) for all \(Z \in V\). We then define \(\nabla_X Y := V\). By the definition of \(\nabla\) and by the classical definition of the Levi-Civita connection, \(\nabla\) extends the Levi-Civita connection. Since the Levi-Civita connection satisfies the properties that we need to prove (on \(M\)), by the density of \(M\) in \(\overline{M}\), we obtain that \(\nabla\) satisfies the same properties. \(\square\)

We continue with some remarks

**Remark 3.12.** An important consequence of the above proposition is that each of the covariant derivatives \(\nabla^k R\) of the curvature \(R\) extends to a tensor defined on the whole of \(\overline{M}\). If \(\overline{M}\) is compact (that is, if \((\overline{M}, A)\) is a Lie manifold), it follows that the curvature and all its covariant derivatives are bounded. It turns out also that the radius of injectivity of \(M\) is positive [6, 42], and hence \(M\) has bounded geometry.

We next discuss the divergence of a vector field, which is needed to define adjoints.

**Remark 3.13.** Another important consequence of the existence of an extension of the Levi-Civita connection to \(\overline{M}\) is the definition of the divergence of a vector field. Indeed, let us fix a point \(p \in \overline{M}\) and a local orthonormal basis \(X_1, \ldots, X_n\)
We then write \( \nabla_{X_i} X = \sum_{j=1}^{n} c_{ij}(X) X_j \) and define

\[
\text{div}(X) := -\sum_{j=1}^{n} c_{jj}(X),
\]

which is a smooth function on the given neighborhood of \( p \) that does not depend on the choice of the local orthonormal basis \( (X_i) \) used to define it. Consequently, this formula defines a global function \( \text{div}(X) \in C^\infty(M) \).

We now introduce differential operators on open manifolds with a Lie structure at infinity. The desire to study these operators is the main reason why we are interested in Lie manifolds.

**Definition 3.14.** Let \((\overline{M}, A)\) be an open manifold with a Lie structure at infinity and \( \mathcal{V} := \Gamma(\overline{M}; A) \). The algebra \( \text{Diff}(\mathcal{V}) \) is the algebra of differential operators on \( \overline{M} \) generated by the operators of multiplication with functions in \( C^\infty(\overline{M}) \) and by the directional derivatives with respect to vector fields \( X \in \mathcal{V} \).

In [9], the definition of \( \text{Diff}(\mathcal{V}) \) was extended to the case of not necessarily projective \( C^\infty(\overline{M}) \)-modules \( \mathcal{V} \).

Clearly, in our first example, Example 3.8, the resulting algebra of differential operators \( \text{Diff}(\mathcal{V}) = \text{Diff}(\mathcal{V}_b) \) for \( M \) a manifold with boundary is the algebra of totally characteristic differential operators. We shall see several other examples in this paper. The differential operators in \( \text{Diff}(\mathcal{V}) \) can be regarded as acting either on functions on \( \overline{M} \) or on functions on \( M := \overline{M} \setminus \partial \overline{M} \). When it comes to classes of measurable functions—say Sobolev spaces—this makes no difference. However, the fact that \( \text{Diff}(\mathcal{V}) \) maps \( C^\infty(\overline{M}) \) to \( C^\infty_c(\overline{M}) \) is a non-trivial property that does not follow from the \( L^2 \)-mapping properties of \( \text{Diff}(\mathcal{V}) \) on \( M \). We have the following simple remark on the local structure of operators in \( \text{Diff}(\mathcal{V}) \).

**Remark 3.15.** Every \( P \in \text{Diff}(\mathcal{V}) \) of order at most \( m \) can be written as a sum of differential monomials of the form \( X_1^{\alpha_1} X_2^{\alpha_2} \ldots X_k^{\alpha_k} \), where \( X_i \in \mathcal{V} \), \( k \leq m \), and \( \alpha \) is a multi-index. If \( Y_1, Y_2, \ldots, Y_n \) are vector fields in \( \mathcal{V} \) forming a local basis around \( p \in \overline{M} \) (so \( \dim(M) = n \)), then every \( P \in \text{Diff}(\mathcal{V}) \) of order at most \( m \) can be written in a neighborhood of \( p \) in \( \overline{M} \) uniquely as

\[
P = \sum_{|\alpha| \leq m} a_\alpha Y_1^{\alpha_1} Y_2^{\alpha_2} \ldots Y_n^{\alpha_n}, \quad a_\alpha \in C^\infty_c(\overline{M}).
\]

This follows from the Poincaré-Birkhoff-Witt theorem of [118].

The next remark states that the algebra \( \text{Diff}(\mathcal{V}) \) is closed under adjoints.

**Remark 3.16.** We shall denote the inner product on \( L^2(M; \text{vol}_g) \) by \( \langle , \rangle_{L^2} \). Let \( P \in \text{Diff}(\mathcal{V}) \). The formal adjoint \( P^* \) of \( P \) is then defined by

\[
(P f_1, f_2)_{L^2} = (f_1, P^* f_2)_{L^2}, \quad f_1, f_2 \in C^\infty_c(M).
\]

Let \( X \in \mathcal{V} := \mathfrak{a}_*(\Gamma(A)) \). Since \( \text{div}(X) \in C^\infty(\overline{M}) \) of Equation (29) extends the classical definition on \( M \), we have that

\[
\int_M X(f) \ d\text{vol}_g = \int_M f \text{div}(X) \ d\text{vol}_g .
\]
In particular, the formal adjoint of $X$ is

$$X^\ast = -X + \text{div}(X) \in \text{Diff}(V),$$

and hence $\text{Diff}(V)$ is closed under formal adjoints.

We can consider matrices of operators in $\text{Diff}(V)$ and operators acting on bundles.

**Remark 3.17.** We can extend the definition of $\text{Diff}(V)$ by considering the space $\text{Diff}(V; E, F)$ of operators acting between smooth sections of the vector bundles $E, F \to \mathcal{M}$. This can be done either by embedding the vector bundles $E$ and $F$ into trivial bundles or by looking at a local basis. The formal adjoint of $P \in \text{Diff}(V; E, F)$ is then an operator $P^\ast \in \text{Diff}(V; F^\ast, E^\ast)$. We shall write $\text{Diff}(V; E) := \text{Diff}(V; E, E)$.

Typically $E$ and $F$ will have hermitian metrics and then we identify $E^\ast$ with $E$ and $F^\ast$ with $F$. In particular, if $E$ is a Hermitian bundle, then $\text{Diff}(V; E)$ is an algebra closed under formal adjoints.

We are ready now to prove that all geometric operators on $M$ that are associated to a compatible metric $g$ are generated by $V := g_\ast(\Gamma(A))$ [7]. (Recall that a compatible metric on $M$ is a metric coming from a metric on the Lie algebroid $A$ of our Lie manifold $(\mathcal{M}, A)$ by restriction to $TM$.) In particular, we have the following result [7].

**Proposition 3.18.** We have that the de Rham differential $d$ on $M$ extends to a differential operator $d \in \text{Diff}(V; \Lambda^q A^\ast, \Lambda^{q+1} A^\ast)$. Similarly, the extension $\nabla$ of the Levi-Civita connection to an $A$-valued connection defines a differential operator $\nabla \in \text{Diff}(V; A, A \otimes A^\ast)$.

**Proof.** The proof of this theorem is to see that the classical formulas for these geometric operators extend to $\mathcal{M}$, provided that $TM$ is replaced by $A$. For instance, for the de Rham differential, let $\omega \in \Gamma(\mathcal{M}; \Lambda^k A^\ast)$ and $X_0, \ldots, X_k \in V$, and use the formula

$$(d\omega)(X_0, \ldots, X_k) = \sum_{j=0}^q (-1)^j X_j(\omega(X_0, \ldots, \hat{X}_j, \ldots, X_k)) + \sum_{0 \leq i < j \leq q} (-1)^{i+j} \omega([X_i, X_j], X_0, \ldots, \hat{X}_i, \ldots, \hat{X}_j, \ldots, X_k) \in C^\infty(\mathcal{M}).$$

By choosing $X_0, \ldots, X_k$ among a local basis of $V := \Gamma(\mathcal{M}; A)$ and using the fact that $V$ is closed under the Lie bracket, we obtain that $d \in \text{Diff}(V; \Lambda^q A^\ast, \Lambda^{q+1} A^\ast)$, as claimed.

For the Levi-Civita connection, it suffices to show that $\nabla_X \in \text{Diff}(V; A)$ for all $X \in V$ (we could even restrict $X$ to a local basis, but this is not really necessary). We will show that, in a local basis of $A$, the differential operator $\nabla_X$ is given by an operator involving only derivatives in $V$. To this end, we shall use the formula (28) defining $\nabla_X$, but choose $Y = fY_0$ for $f \in C^\infty(\mathcal{M})$ and $Y_0$ and $Z$ in a local basis in some neighborhood $V$ of an arbitrary point $p \in \mathcal{M}$. Then we see from formula (28), using also the linearity of $f$ in $Z$, that $(\nabla_X(Y), Z) = f z_0 + X(f) z_1$, with $z_0$ and $z_1$ smooth functions on the given neighborhood $V$. Since the only derivative in this formula is $X$ and $X \in V$, this proves the desired statement for $\nabla$. $\square$
Let us consider a vector bundle $E \to \overline{M}$. If $E$ has a metric, then an $A$-connection $\nabla \in \text{Diff}(\mathcal{V}; E, E \otimes A^*)$ is said to preserve the metric if
\begin{equation}
(\nabla_X(\xi), \zeta)_E + (\xi, \nabla_X(\zeta))_E = X(\xi, \zeta)_E
\end{equation}
for all $X \in \mathcal{V}$ and $\xi, \zeta \in \Gamma(\overline{M}; E)$. In particular, it follows from Proposition 3.11 that the extension of the Levi-Civita connection to an $A$-connection on $A$ preserves the metric used to define it. We then have the following theorem.

**Theorem 3.19.** We continue to consider the fixed metric on $A$ and its associated compatible metric $g$ on $M$. Let $E \to \overline{M}$ be a hermitian bundle with a metric preserving $A$-connection. Then $\Delta_E := \nabla^* \nabla \in \text{Diff}(\mathcal{V}; E)$. Similarly,
\[
\Delta_g := d^* d \in \text{Diff}(\mathcal{V}).
\]

**Proof.** This follows from the fact that $\text{Diff}(\mathcal{V})$ and its vector bundle analogues are closed under formal adjoints and from Proposition 3.18. \hfill \Box

Thus, in order to study geometric operators on a Lie manifold, it is enough to study the properties of differential operators generated by $\mathcal{V}$. It should be noted, however, that a Riemannian manifold may have different compactifications to a Lie manifold. An example is $\mathbb{R}^n$, which can either be compactified to $([-1, 1]^n, V_b)$ (a product of manifolds with cylindrical ends) or it can be radially compactified to yield an asymptotically euclidean manifold. (See Example 5.3.)

Theorem 3.19 also gives the following.

**Remark 3.20.** Similarly, since $d \in \text{Diff}(\mathcal{V}; E, F)$, we get that the Hodge operator $d + d^* \in \text{Diff}(\mathcal{V}; \Lambda^* A^*)$, the same is true for the signature operator. More generally, let $W \to \overline{M}$ be a Clifford bundle with admissible connection in $\text{Diff}(\mathcal{V}; W, W \otimes A^*)$. Then the associated Dirac operators are also generated by $\mathcal{V}$. If $W$ is the Clifford bundle associated to a Spin$^c$-structure on $A$, then the Levi-Civita connection on $W$ is in $\text{Diff}(\mathcal{V}; W, W \otimes A^*)$. All these statements seem to be more difficult to prove directly in local coordinates. See [7, 82] for proofs.

### 3.3. Anisotropic structures

It is very important in applications to extend the previous frameworks to include anisotropic structures [14]. We introduce them now for the purpose of later use.

**Definition 3.21.** An anisotropic structure on an open manifold $(\overline{M}, A)$ with a Lie structure at infinity is an open manifold manifold with a Lie structure at infinity $(\overline{M}, B)$ (same $\overline{M}$) together with a vector bundle map $A \to B$ that is the identity over $M$ and makes $\Gamma(A) = \Gamma(\overline{M}; A)$ an ideal (in Lie algebra sense) of $\Gamma(B) = \Gamma(\overline{M}; B)$.

We shall denote $\mathcal{W} := g_*(\Gamma(B))$, so $\mathcal{V} := g_*(\Gamma(A))$ satisfies $[X, Y] \subset \mathcal{V}$ for all $X \in \mathcal{W}$ and $Y \in \mathcal{V}$. Recall the groups $\exp(\mathcal{V})$ and $\exp(\mathcal{W})$ introduced at the end of Subsection 3.1 (and recall that they are generated by compactly supported vector fields), then we have the following.

**Remark 3.22.** The group $\exp(\mathcal{W})$ acts on $\overline{M}$ by Lipschitz diffeomorphisms, it acts on $A$ by Lie algebroid morphism, it acts on $\mathcal{V} := g_*(\Gamma(A))$ by Lie algebra morphisms, and it acts on on $\text{Diff}(\mathcal{V})$ by algebra morphisms. Moreover,
\[
\exp(\mathcal{V}) \subset \exp(\mathcal{W})
\]
is a normal subgroup.
4. Analysis on Lie manifolds

Our main interest is in the analytic properties of the differential operators in $\text{Diff}(V)$. In this section, we introduce our function spaces following [6] and discuss Fredholm conditions. Throughout this section, $(\mathcal{M}, A)$ will denote an open manifold with a Lie structure at infinity and Lie algebroid $A$ with anchor $\varrho : A \to T\mathcal{M}$. Also, by $V := \varrho^*(\Gamma(A))$ we shall denote the structural Lie algebra of vector fields on $\mathcal{M}$.

4.1. Function spaces. We review in this subsection the needed definitions of function spaces. Let $(\mathcal{M}, A)$ be our given open manifold with a Lie structure at infinity and let $g$ be a compatible metric on the interior $M$ of $\mathcal{M}$ (that is, coming from a metric on $A$ denoted with the same letter, see Definition 3.9). Let $\nabla$ be the Levi-Civita connection acting on the tensor powers of the bundles $A$ and $A^*$. We then define, for $m \in \mathbb{Z}_+$, the Sobolev spaces as in [4, 6, 59, 63]:

$$H^m(M) = \{ u : M \to \mathbb{C}, \nabla^k u \in L^2(M; A^*\otimes k), \ 0 \leq k \leq m \}.$$  

Remark 4.1. In general, the Sobolev spaces $H^m(M)$ will depend on the choice of the metric $g$, but if $\mathcal{M}$ is compact (that is, if $(\mathcal{M}, A)$ is a Lie manifold), then they are independent of the choice of the metric, as we shall see below. It is interesting to notice that if denote by $d\text{vol}_g$ the volume form (1-density) associated to $g$. If $h$ is another such compatible metric, then $d\text{vol}_g / d\text{vol}_h$ extend to smooth, bounded functions on $\mathcal{M}$. Hence the space $L^2(M) := L^2(M; \text{vol}_g)$ is independent of the choice of the compatible metric $g$.

The spaces $H^m(M)$ behave well with respect to anisotropic structures.

Proposition 4.2. Let $(\mathcal{M}, A)$ be an open manifold with a Lie structure at infinity and with an anisotropic structure $(\mathcal{M}, B)$, such that $W := \Gamma(B) \supset \Gamma(A)$. Then $\exp(W)$ acts by bounded operators on $H^m(M)$.

Proof. This follows from the fact that $\exp(W)$ is generated by vector fields with compact support in $\mathcal{M}$. □

We now consider some alternative definitions of these Sobolev spaces in particular cases. We first consider the case of complete manifolds [4, 6, 59, 63, 64].

Remark 4.3. Let us assume that $(\mathcal{M}, A)$ and the compatible metric $g$ are such that $M$ is complete and let $\Delta_g$ be (positive) Laplacian associated to the metric $g$. Then $H^s(M)$ coincides with the domain of $(1 + \Delta_g)^{s/2}$ (we use the geometer’s Laplacian, which is positive).

In the bounded geometry case we can consider partitions of unity.

Remark 4.4. Let us assume that $(\mathcal{M}, A)$ and the compatible metric $g$ are such that $M := \mathcal{M} \setminus \partial \mathcal{M}$ is of bounded geometry. Then the definition of the Sobolev spaces on $M$ can be given using a choice of partition of unity with bounded derivatives as in [6], for example, to patch the locally defined classical Sobolev spaces. See also [4, 6, 49, 59, 74, 75, 147].

Finally, if $\mathcal{M}$ is an open subset of a Lie manifold, we have yet the following definition.
Remark 4.5. Let \( U \subset \overline{M} \) be an open subset of a Lie manifold \((\overline{M}, A)\) (so \(\overline{M}\) is compact) and let, as usual, \( \mathcal{V} \) denote the structural Lie algebra of vector fields \( \Gamma(\overline{M}, A) \), then [7]

\[
H^m(U) := \{ u : U \to \mathbb{C}, X_1X_2\ldots X_ku \in L^2(U), k \leq m, X_j \in \mathcal{V} \},
\]

so the Sobolev spaces \( H^m(U) \) will be independent of the chosen compatible metric on the Lie manifold.

Each of these definitions of the Sobolev spaces has its own advantages and disadvantages. For instance, the definition (34) has the advantage that it immediately gives the boundedness of operators \( P \in \text{Diff}(\mathcal{V}) \), see Lemma 4.6. Let \( H^{-s}(M) := (H^s(M))^* \) and extend the definition of Sobolev space to \( s \) non-integer by interpolation.

**Lemma 4.6.** Let us assume that \( A \) is endowed with a metric such that the resulting metric \( g \) on \( TM \subset A \) is of bounded geometry. Let \( P \in \text{Diff}(\mathcal{V}) \) of order \( \text{ord}(P) \leq m \) and with coefficients that are compactly supported in \( \overline{M} \). Then the map \( P : H^s(M) \to H^{s-m}(M) \) is bounded for all \( s \in \mathbb{R} \).

Note that if \( \overline{M} \) is compact (i.e. \((\overline{M}, A)\) is a Lie manifold), then all \( P \in \text{Diff}(\mathcal{V}) \) have compactly supported coefficients. Let us denote by \((E)_r\), the set of vectors of length \( < r \), where \( E \) is a real or complex vector bundle endowed with a metric.

**Proof.** Let \( K \subset \overline{M} \) be a compact subset such that the coefficients of \( P \) are zero outside \( K \). Let us choose a compact neighborhood \( L \) of \( K \) in \( \overline{M} \) and let \( r_0 \) be the distance from \( K \) to the complement of \( L \) in a metric \( h \) on \( \overline{M} \) such that \( h \leq g \), which exists by Lemma 3.10. Then \( r_0 > 0 \), because \( K \) is compact. Moreover, the distance from \( K \) to the complement of \( L \) in the metric \( g \) is \( \geq r_0 \) since \( h \leq g \). Let us fix \( r \) less than the injectivity radius of \( M \) and with \( r_0 > r > 0 \). For every \( p \in M \), we then consider the exponential map \( \exp : T_pM \to M \), which is a diffeomorphism from (the open ball of radius \( r \)) \((T_pM)_r\) onto its image. Thus \( P \) gives rise to a differential operator \( P_p \) on each of the open balls \((T_pM)_r\). Using the results of [147], it suffices to show that the coefficients of \( P \) in any of these balls of radius \( r \) are uniformly bounded. Indeed, this is a consequence of the following lemma, where the support of the resulting map is contained in \( L \).

The following lemma (see [8]) underscores the additional properties that the Lie manifolds enjoy among the class of all manifolds with bounded geometry.

**Lemma 4.7.** Let us use the notation of the proof of the previous lemma and denote for any \( p \in M \) by \( P_p \) the differential operator on \((T_pM)_r\) induced by the exponential map. Then the map \( M \ni p \to P_p \) extends to a compactly supported smooth function defined on \( \overline{M} \) such that \( P_p \) is a differential operator on \((A_p)_r\).

We define the anisotropic Sobolev spaces in a similar way.

**Remark 4.8.** Let \((\overline{M}, A)\) be a Lie manifold with an anisotropic structure \((\overline{M}, B)\), and let \( \mathcal{W} := \Gamma(B) \supset \Gamma(A) \). Then we define

\[
H^{m+q}_\mathcal{W}(M) := \{ u : M \to \mathbb{C}, X_1X_2\ldots X_kY_1, Y_2\ldots Y_lu \in L^2(M), \quad \text{for all } X_j \in \mathcal{W}, 0 \leq j \leq k \leq m, \text{ and for all } Y_i \in \mathcal{V}, 0 \leq i \leq l \leq q \}.
\]

The spaces \( H^{m+q}_\mathcal{W}(M) \) are again independent of the chosen compatible metric on the Lie manifold.
4.2. Pseudodifferential operators on Lie manifolds. Let us begin by recalling the definition of a tame submanifold with corners from [7] (we changed slightly the terminology).

**Definition 4.9.** Let $\overline{M}$ be a manifold with corners and $L \subset \overline{M}$ be a submanifold. We shall say that $L$ is a tame submanifold with corners if $L$ is a manifold with corners (in its own) that intersects transversely all faces of $\overline{M}$ and such that each open face $F_0$ of $L$ is the open component of a set of the form $F \cap L$, where $F$ is an open face of $\overline{M}$ (of the same codimension as $F_0$).

The closed faces of a manifold with corners $\overline{M}$ are thus *not* tame submanifolds with corners of $\overline{M}$ even if they happen to be manifolds with corners. Also, the diagonal of the $n$-dimensional cube $[-1,1]^n$ is *not* a tame submanifold with corners. However, $\{0\} \times [-1,1]^{n-1}$ is a tame submanifold with corners of $[-1,1]^n$. In fact, all tame submanifolds with corners $L \subset \overline{M}$ have a tubular neighborhood [6, 8].

This tubular neighborhood allows us then to define the space $\mathcal{I}_m(\overline{M}, L)$ of classical conormal distributions as in [68] or as in [118] for manifolds with corners as follows. Let $V \to X$ be a real vector bundle. A distribution on $V$ is (classically) conormal to $X$ if its fiberwise Fourier transform is a classical symbol on $V^* \to M$. We shall denote the set of these distributions corresponding to a symbol of order $\leq m$ by $\mathcal{I}_m(V, M)$. We shall denote by $\mathcal{I}_c^m(V, M) \subset \mathcal{I}_m(V, M)$ the subset of conormal distributions with compact support. We extend the definition of $\mathcal{I}_c^m(V, M)$ to the case of a tame submanifold $M \subset V$ by localization.

Let us fix a compatible metric on $M$, the interior of our open manifold with a Lie structure at infinity $(\overline{M}, A)$. Also, let us fix $r > 0$ less than the injectivity radius of $M$. As in the proof of Lemma 4.6, the exponential map then defines a diffeomorphism from the set $(TM)_r$ of vectors of length $< r$ to $(M \times M)_r$, which is an open neighborhood of the diagonal in $M \times M$. This allows us to define a natural bijection

$$\Phi : \mathcal{I}_c^m((TM)_r, M) \to \mathcal{I}_c^m((M \times M)_r, M),$$

Similarly, we obtain by restriction an inclusion

$$\mathcal{I}_c^m((A)_r, \overline{M}) \to \mathcal{I}_c^m((TM)_r, M).$$

Recall the group of diffeomorphisms $\exp(V)$ defined at the end of Subsection 3.1. Then we define as in [8]

$$\Psi_V^m(M) := \Phi(\mathcal{I}_c^m((A)_r, \overline{M})) + \Phi(\mathcal{I}_c^{-\infty}((A)_r, \overline{M})) \exp(V).$$

Then $\Psi_V^m(M)$ is independent of the parameter $r > 0$ or the compatible metric $g$ used to define it and we have the following result [8].

**Theorem 4.10.** Let $(\overline{M}, A)$ be a Lie manifold, $M := \overline{M} \setminus \partial \overline{M}$ and $V := g_*(\Gamma(A))$. We have $\Psi_V^m(M) \Psi_V^m(M) \subset \Psi_V^{m+m'}(M)$. The subspace $\Psi_V^m(M)$ is closed under adjoints and the principal symbol $\sigma_m : \Psi_V^m(M) \to S_{cl}^m(A^*)/S_{cl}^{m-1}(A^*)$ is surjective with kernel $\Psi_V^{m-1}(M)$. Moreover, any $P \in \Psi_V^m(M)$ defines a bounded operator $H^s(M) \to H^{s-m}(M)$. If an anisotropic structure with structural vector fields $\mathcal{W}$ is given, then the group $\exp(\mathcal{W})$ acts by degree preserving automorphisms on $\Psi_V^m(M)$.

The group $\exp(\mathcal{W})$ is seen to act on $\Psi_V^m(M)$ since it acts by Lipschitz diffeomorphisms of $\overline{M}$. The proof of the above theorem is too long to include here. See [8] for details. Let us just say that it is obtained by realizing $\Psi_V^m(M)$ as the image of a
groupoid pseudodifferential operator algebra [8, 105, 107, 118] for any Lie groupoid integrating the Lie algebroid $A$ defining the Lie manifold $(\overline{M}, A)$ [42, 43, 115].

The algebra $\Psi^*_v(M)$ has the property that its subset of differential operators coincides with $\text{Diff}(\mathcal{V})$. It also has the good symbolic properties that answer to a question of Melrose [8, 99].

4.3. Comparison algebras. We continue to denote by $(\overline{M}, A)$ an open manifold with a Lie structure at infinity and by $\mathcal{V} := \varphi_*(\Gamma(A))$. For simplicity, we shall assume that $\overline{M}$ is connected. We now recall from [106] the comparison $C^*$-algebra $\mathfrak{A}(U, \mathcal{V})$ associated to an open subset $U \subset \overline{M}$. Its definition extends to open manifolds with a Lie structure at infinity by Lemma 4.6 that justifies the following definition.

Definition 4.11. Let us assume that $A$ has a metric $g$ such that the induced metric on $U$ is of bounded geometry and let $U \subset \overline{M}$ be an open subset. Then $\mathfrak{A}(U; \mathcal{V})$ is the norm closed subalgebra of the algebra $\mathcal{B}(L^2(M; \text{vol}_g))$ of bounded operators on $L^2(M; \text{vol}_g)$ generated by all the operators of the form $\phi_1 P (1 + \Delta_g)^{-k} \phi_2$, where $\phi_1 \in C^\infty_c(U)$, $P \in \text{Diff}(\mathcal{V})$ is a differential operator of order $\leq 2k$, and $\Delta_g$ is the Laplacian on $M$ (not on $U$) associated to the metric $g$.

In case an anisotropic structure is given, the group $\exp(\mathcal{W})$ acts by automorphisms on the comparison algebra $\mathfrak{A}(\overline{M}; \mathcal{V})$. We shall need the following lemma that follows right away from the results in [7] and [82]. By a pseudodifferential operator on a manifold, we shall mean one that is obtained by the usual quantization procedure on a manifold, we shall mean one that is obtained by the usual quantization formula in any coordinate system.

Lemma 4.12. Let us use the notation and the assumptions of Definition 4.11 and let $T := \phi_1 P (1 + \Delta_g)^{-k} \phi_2$. Then $T$ is contained in the norm closure of $\Psi^*_v(M)$ and is a pseudodifferential operator of order $\leq 0$ with principal symbol

$$\sigma_0(T) = \phi_1 \sigma_2k(P)(1 + |\xi|^2)^{-k} \phi_2.$$ 

Moreover, the principal symbol depends continuously on $T$, and hence extends to a continuous, surjective morphism $\sigma_0 : \mathfrak{A}(U; \mathcal{V}) \to C_0(S^* A| U)$.

As in [106], we obtain the following result.

Theorem 4.13. Let $(\overline{M}, A)$ be a connected open manifold with a Lie structure at infinity with a compatible metric of bounded geometry. Then $\mathfrak{A}(M; \mathcal{V})$ contains the algebra $\mathcal{K}(L^2(M))$ of all compact operators on $L^2(M)$ and is contained in the norm closure of $\Psi^*_v(M)$.

Proof. We recall the proof for the benefit of the reader. The inclusion of $\mathfrak{A}(\overline{M}; \mathcal{V})$ in the norm closure of $\Psi^*_v(M)$ follows from Lemma 4.12.

Let $\phi_1, \phi_2 \in C^\infty_c(M)$ and $P \in \text{Diff}(\mathcal{V})$ be a differential operator of order at most $2k - 1$, then the composition operator $\phi_1 P (1 + \Delta)^{-k} \phi_2$ is a non-zero compact operator and belongs to $\mathfrak{A}(\overline{M}; \mathcal{V})$, by the definition. The role of the cut-off functions is to decrease the support of the distribution kernel of $P (1 + \Delta)^{-k}$. Since $\phi_1 P (1 + \Delta)^{-k} \phi_2$ is compact, we thus obtain that $\mathfrak{A}(\overline{M}; \mathcal{V})$ contains non-zero compact operators. Let $\xi_1, \xi_2 \in L^2(M)$ be non-zero. Then we can find $\phi_1, \phi_2$, and $P$ as above such that $T := \phi_1 P (1 + \Delta)^{-k} \phi_2$ satisfies $(T \xi_1, \xi_2) \neq 0$. Hence $\mathfrak{A}(\overline{M}; \mathcal{V})$ has no non-trivial invariant subspace. Hence $\mathfrak{A}(\overline{M}; \mathcal{V})$ contains all compact operators because any proper subalgebra of the algebra of compact operators has an invariant subspace. \qed
4.4. Fredholm conditions. Theorem 4.13 allows us, in principle, to study the Fredholm property of operators in $\mathfrak{A}(\overline{M}; \mathcal{V})$. Let us denote by $\mathcal{K} = \mathcal{K}(L^2(M))$ the ideal of compact operators in $\mathfrak{A}(\overline{M}; \mathcal{V})$. Recall then Atkinson’s classical result [50] that states that $T \in \mathfrak{A}(\overline{M}; \mathcal{V})$ is Fredholm if, and only if, its image $T + \mathcal{K}$ in $\mathfrak{A}(\overline{M}; \mathcal{V})/\mathcal{K}$ is invertible.

Usually it is difficult to check directly that $T + \mathcal{K}$ is invertible in $\mathfrak{A}(\overline{M}; \mathcal{V})/\mathcal{K}$, and, instead, one checks the invertibility of operators of the form $\pi(T)$, where $\pi$ ranges through a suitable family of representations of $\mathfrak{A}(\overline{M}; \mathcal{V})/\mathcal{K}$. Exactly what are the needed properties of the family of representations of $\mathfrak{A}(\overline{M}; \mathcal{V})/\mathcal{K}$ was studied in [117, 135]. Let us recall the main conclusions of that paper. Let us consider a family $F_1, F_2, \ldots$ exhausting $\mathcal{K}$ of representations $\pi$. Let us denote by $F_1$ the family of representations of $\mathfrak{A}(\overline{M}; \mathcal{V})$ such that for any $\pi \in F_1$ we have $\pi(T)$ invertible for $T \in \mathfrak{A}(\overline{M}; \mathcal{V})$. An equivalent condition (in the separable case) is that the family $F_1$ be exhausting, in the sense that every irreducible representation of $\mathfrak{A}(\overline{M}; \mathcal{V})/\mathcal{K}$ is weakly contained in one of the representations $\pi \in F_1$.

This approach was used (more or less explicitly) in [40, 46, 53, 54, 55, 79, 82, 94, 104, 131, 135, 136, 141], and in many other papers. However, in order for this approach to be effective, we need to have a good understanding of the representation theory of the quotient $\mathfrak{A}(\overline{M}; \mathcal{V})/\mathcal{K}$. This seems to be difficult in general, at least without using groupoids. Thus we shall replace the comparison algebra $\mathfrak{A}(\overline{M}; \mathcal{V})$ with the norm closure of the algebra $\Psi_0^1(M)$. The algebra $\Psi_0^1(M)$ is defined in the next section.

There are many general results that yield Fredholm conditions for operators. We formulate now one such result that is sufficient in most applications. We shall make some the following assumptions on the Lie manifold $(\overline{M}, A)$

(a) We assume that there exists a filtration

$$\emptyset =: U_{-1} \subset U_0 \subset \ldots \subset U_k \subset U_{k+1} \subset \ldots \subset U_N := \overline{M}$$

of $\overline{M}$ with open sets such that each $S_k := U_k \setminus U_{k-1}$ is a manifold (possibly with corners) and that there exists submersions $p_k : S_k \to B_k$ of manifolds (possibly with corners) whose fibers are orbits of $\exp(\mathcal{V})$.

(b) We assume that, for each $k = 0, \ldots, N$, there exists a Lie algebroid $A_k \to B_k$ with zero anchor map such that $A|_{S_k} \simeq p_k^{-1}(A_k)$, the pull-back of $A_k$ by the submersion $p_k$ [66]. In particular, we have the isomorphism of vector bundles

$$A|_{S_k} \simeq \ker(p_k) \oplus p_k^*(A_k).$$

(c) Let us denote by $(Z_\alpha)_{\alpha \in J}$ the family of orbits $Z_\alpha = \exp(\mathcal{V})p$ of $\mathcal{V}$ and by $G_\alpha$ the simply-connected Lie group that integrates the Lie algebra $(A_k)_{p_k(p)} \simeq \ker(\varrho_p)$, for any $p \in Z_\alpha \subset S_k$. Also, let us denote by $\mathcal{G}$ the disjoint union

$$\mathcal{G} := \cup_{\alpha \in J} Z_\alpha \times Z_\alpha \times G_\alpha$$

with the induced groupoid structure. We assume that the groupoid exponential map makes $\mathcal{G}$ a Hausdorff Lie groupoid [115]. In particular, $\mathcal{G}$ is a manifold (possibly with corners).

Under the above assumptions, the results in [72, 79, 82, 117, 132, 134] give the following theorem.
Theorem 4.14. Let $I$ be an index parametrizing the set of orbits of $V$ on $\partial M$. (So $J = I \cup \{0\}$.) We can associate to each $P \in \Diff(V; E, F)$ a family $(P_\alpha)_\alpha$, of $G_\alpha$-invariant operators $P_\alpha$ on $Z_\alpha \times G_\alpha$. If all the groups $G_\alpha$, $\alpha \in I$ are amenable, then the following Fredholm condition holds.

$$P : H^s(M) \to H^{s-m}(M) \text{ is Fredholm } \iff \text{ P is elliptic and all } P_\alpha : H^s(Z_\alpha \times G_\alpha) \to H^{s-m}(Z_\alpha \times G_\alpha), \alpha \in I, \text{ are invertible.}$$

Proof. (Sketch) The exact sequence of (full) $C^*$-algebras associated to an open subset of the set of units of a groupoid [132] tells us that $\text{Prim}(C^*(\mathcal{G}))$ is the disjoint union of the sets $\text{Prim}(C^*(\mathcal{G}_{S_\alpha}))$. We have that $C^*(\mathcal{G}) \simeq C^*_r(\mathcal{G})$, because $C^*(\mathcal{G}_{S_\alpha}) \simeq C^*_r(\mathcal{G}_{S_\alpha})$ for each $k$, by the amenability of the groups $G_\alpha$. This shows that the set $\{\text{Ind}(\lambda_\alpha)\}$ of representations of $C^*(\mathcal{G})$ induced from the regular representations $\lambda_\alpha$ of $G_\alpha$ is an exhausting set of representations of $C^*(\mathcal{G}) \simeq C^*_r(\mathcal{G})$. Each $\pi_\alpha := \text{Ind}(\lambda_\alpha)$ is the regular representation of $C^*_r(\mathcal{G})$ associated to (any unit in) the orbit $Z_\alpha$, with $\pi_0$ being the vector representation on $L^2(M)$.

The assumptions imply that $S_0 = U_0 = M$ and that $G_0 = \{e\}$. Hence $\mathcal{G}_{S_0}$ is the pair groupoid $S_0 \times S_0$ and $C^*(\mathcal{G}_{S_0}) \simeq \mathcal{K}$, the algebra of compact operators on $L^2(M)$. We obtain that $C^*(\mathcal{G})/\mathcal{K} \simeq C^*(\mathcal{G}_{S_0}) \simeq C^*_r(\mathcal{G}_{S_0})$ and the regular representations of $C^*(\mathcal{G}_{S_0})$ form an invertibility sufficient set of representations of $C^*(\mathcal{G}_{S_0})$. This gives that $a \in C^*(\mathcal{G}) \simeq C^*_r(\mathcal{G})$ is Fredholm if, and only if, $\pi_\alpha(a)$ is invertible for all $\alpha$ corresponding to orbits in $\partial M$.

We shall apply these observations to the algebra $\Psi^\infty(\mathcal{G})$ of pseudodifferential operators on groupoids, which is recalled in the next subsection. The fact that $\mathcal{G}$ is Hausdorff implies that the vector representation of $C^*(\mathcal{G})$ (associated to the orbit $M \subset \overline{M}$) is injective, by [72]. We shall use then the vector representation to identify $\Psi^\infty(\mathcal{G})$ and $C^*_r(\mathcal{G})$ with their images under the vector representation. In particular, $P$ is given by a family of operators $(P_\alpha)_\alpha$, with operators corresponding to units in the same orbit unitarily equivalent. We then let $P_\alpha := P_\alpha$, for some $\alpha$ in the orbit corresponding to $\alpha$.

Let $a := (1 + \Delta)^{(s-m)/2}P(1 + \Delta)^{-s/2} \in \Psi^0(\mathcal{G})$ [79, 82]. We then have that $P$ is Fredholm if, and only if, $a$ is Fredholm on $L^2(M)$, which, in turn, is true, if, and only if, $\pi_\alpha(a)$ is invertible for all $Z_\alpha \subset \partial M$. Since

$$\pi_\alpha(a) := (1 + \pi_\alpha(\Delta))^{(s-m)/2}P_\alpha(1 + \pi_\alpha(\Delta))^{-s/2},$$

acting on $Z_\alpha \times G_\alpha$, the result follows from the fact that the set of arrows of $\mathcal{G}$ with domain $x \in Z_\alpha$ is $Z_\alpha \times G_\alpha$. \hfill $\Box$

This theorem is closely related to the representations of Lie groupoids, see [21, 27, 28, 51, 52, 69, 133, 154]. For our result, we need Hausdorff groupoids, see however also [72, 153] for some results on non-Hausdorff groupoids. More general Fredholm conditions can be obtained along the same lines, but the result mentioned here, although having a rather long list of assumptions, is easy to prove and to use. More references to earlier results will be given in the next section when discussing examples.

Remarks 4.15. We continue with a few remarks.

(1) If $\overline{M}$ is compact and smooth (so without corners), then $I = \emptyset$, and we recover Theorem 1.2. As we will explain below, we also recover Theorem 1.9. Each operator $P_\alpha$ is “of the same kind” as $P$ (Laplace, Dirac, ... )
and can be recovered by "freezing the coefficients" at the orbit $Z_\alpha$. The theorem allows us to reduce some questions on $M$ to questions on $P_\alpha$ and $G_\alpha$. Because of the $G_\alpha$-invariance of our operators, we can use results on harmonic analysis on $G_\alpha$ to obtain an inductive procedure to study geometric operators on $M$ [91, 121].

(2) Each open face $F_0$ of $\overline{M}$ is invariant for $\exp(\mathcal{V})$, and hence, if an orbit $Z_\alpha$ intersects $F_0$, then it is completely contained in $F_0$. In particular, the set of orbits $I$ identifies with the disjoint union of the sets $B_k$ for $k = 1, 2, \ldots, N$.

(3) The sections of $\ker(p_k)_*$ act by derivation on the sections of $p_k^*(\mathcal{A})$. Also, it follows that for any $p \in F_0$, the isotropy Lie algebra $\ker(g_p)$ is canonically isomorphic to the Lie algebra $(A_k)_{p_k(p)}$, see Definition 3.2.

(4) We note that our assumptions on $(\overline{M}, \mathcal{A})$ imply that the groupoid $\mathcal{G}$ considered in our assumptions must coincide with the one introduced by Claire Debord [42, 43].

4.5. Pseudodifferential operators on groupoids. Let us briefly recall, for the benefit of the reader, the definition of pseudodifferential operators on a Lie groupoid $\mathcal{G}$. Let $d : \mathcal{G} \to \overline{M}$ be the domain map and $\mathcal{G}_x = d^{-1}(x)$. Then $\Psi^m(\mathcal{G}), m \in \mathbb{R}$, consists of smooth families $(P_x)_{x \in \overline{M}}$ of classical, order $m$ pseudodifferential operators $(P_x \in \Psi^m(\mathcal{G}_x))$ that are right invariant with respect to multiplication by elements of $\mathcal{G}$ and are "uniformly supported." To define what uniformly supported means, let us observe that the right invariance of the operators $P_x$ implies that their distribution kernels $K_{P_x}$ descend to a distribution $k_P \in I^m(\mathcal{G}, \overline{M})$ [104, 118].

The family $P = (P_x)$ is called uniformly supported if, by definition, $k_P$ has compact support in $\mathcal{G}$.

Groupoids simplify the study of pseudodifferential operators on singular and non-compact spaces. For instance, one obtains a straightforward definition of the "generalized indicial operators" as restrictions to invariant subsets [79]. More precisely, let $N \subset \overline{M}$ be an invariant subset for $\mathcal{G}$, that is, $d^{-1}(N) = r^{-1}(N)$, and let $\mathcal{G}_N := d^{-1}(N)$. Let us now assume that $P \in \Psi^m(\mathcal{G})$ is given by the family $(P_x)_{x \in \overline{M}}$, then the $N$–indicial family $I_N(P) := (P_x)_{x \in N}$ is defined simply as the restriction of $P$ to $N$ and is in $\Psi^m(\mathcal{G}_N)$. See [47] for an extension of these results in relation to the adiabatic groupoid. See also [1, 19, 18, 98] for results on the Boutet-de-Montvel calculus in the framework of groupoids.

In order to be able to use the machinery of Lie groupoids in analysis, one has to sometimes first integrate the Lie algebroid that naturally arises in the analysis problem at hand. That is, given a Lie algebroid $A \to \overline{M}$, one wants to find a Lie groupoid $\mathcal{G}$ such that $A(\mathcal{G}) \simeq A$. Such a groupoid $\mathcal{A}$ does not always exist, and when it exists, it is not unique. Moreover, the choice of the groupoid $\mathcal{G}$ depends on the analysis problem one is interested to solve. For example, the Lie algebroid $TM \to M$ for a smooth, compact manifold $M$ has the pair groupoid $M \times M$ as a minimal integrating groupoid and has $\mathcal{P}(M)$, the path groupoid of $M$ as the maximal integrating groupoid [42, 43, 115]. The first groupoid leads to the usual analysis on compact, smooth manifolds (the AS-framework), whereas the second one leads to the analysis of invariant operators on $\overline{M}$, the universal covering space of $M$ (with group of deck transformation $\pi_1(M)$). Both these examples are examples of $d$-connected integrating groupoids (i.e. the fibers of the domain map $d$ are connected). There are analysis problems, however, when one is lead to non-$d$-connected groupoids [25].
There are many works dealing with pseudodifferential operators on groupoids, on singular spaces, or with the related $C^*$-algebras, see for example [3, 15, 26, 37, 46, 58, 86, 95, 96, 109, 122, 130, 135, 136, 149, 150, 155].

5. Examples and applications

We now discuss some applications. They are included just to give an idea of the many possible applications of Lie manifolds, so we will be short, but we refer to the existing literature for more details. We begin with some examples.

5.1. Examples of Lie manifolds and Fredholm conditions. We now include examples of Lie manifolds and show how to use Theorem 4.14. The following examples cover many of the examples appearing in practice.

Example 5.1. We now review our first, basic example, Example 3.8, in view of the new results. Recall that $\mathcal{V} = \mathcal{V}_b :=$ the space of vector fields on $\overline{M}$ that are tangent to $\partial \overline{M}$. Near the boundary, a local basis is given by Equation (25) of Example 3.8, and hence $\text{Diff}(\mathcal{V}_b)$ is the algebra of totally characteristic differential operators. If $\overline{M}$ has a smooth boundary and we denote by $r$ the distance to the boundary (in some everywhere smooth metric—including the boundary), then a typical compatible metric on $M$ is given near the boundary by $(r^{-1} dr)^2 + h$, where $h$ is a metric smooth up to the boundary. Hence the geometry is that of a manifold with cylindrical ends.

We have that the orbits $Z_\alpha$ are the open faces of $\overline{M}$, except $M$ itself. The groups are $G_\alpha \simeq \mathbb{R}^k$, where $k$ is the codimension of the corresponding face (so all are commutative Lie groups). In the case of a smooth boundary, the $Z_\alpha$’s are the connected components of the boundary, $G_\alpha = \mathbb{R}$, and $P_\alpha$ is the restriction of $\mathcal{I}(P)$ to a translation invariant operator on $Z_\alpha \times \mathbb{R}$. See also [85, 102, 100, 105, 107, 142] for just a sample of the many papers on this particular class of manifolds.

In the following examples, $\overline{M}$ will be a compact manifold with smooth boundary $\partial \overline{M}$. The following example is that of an asymptotically hyperbolic space and has the feature that it leads to non-commutative groups $G_\alpha$.

Example 5.2. Let $\overline{M}$ be a compact manifold with smooth boundary $\partial \overline{M}$ and defining function $r$. We proceed as in Example (3.8). The structural Lie algebra of vector fields is $\mathcal{V} = r \Gamma(T \overline{M}) =$ the space of vector fields on $\overline{M}$ that vanish on the boundary. Near a point of the boundary $\partial \overline{M} = \{ r = 0 \}$, a local basis is given by

$$r \partial_r, r \partial_{y_1}, \ldots, r \partial_{y_n},$$

so $\mathcal{V}$ is a finitely generated, projective $C^\infty(\overline{M})$–module. Since $\mathcal{V}$ is also closed under the Lie bracket and $\Gamma_c(M; TM) \subset \mathcal{V} \subset \mathcal{V}_b$, we have that $(\overline{M}, \mathcal{V})$ defines indeed a Lie manifold.

The orbits $Z_\alpha \subset \partial \overline{M}$ are reduced to points, so we can take $I := \partial \overline{M}$, and $G_\alpha = T_\alpha \partial \overline{M} \rtimes \mathbb{R}$ is the semi-direct product with $\mathbb{R}$ acting by dilations on the vector space $T_\alpha \partial \overline{M}$, $\alpha \in I$. The pseudodifferential calculus $\Psi^*_V(M)$ for this example was defined also by [78], Lauter-Moroianu [80], Mazzeo [97], and Schulze [143]. The metric is asymptotically hyperbolic. See also [2, 56, 61].

The following example covers, in particular, $\mathbb{R}^n$ with the usual Euclidean metric and with the radial compactification.
Example 5.3. As in the previous example, $\overline{M}$ is a compact manifold with smooth boundary $\partial \overline{M} = \{ r = 0 \}$. We shall take now $\mathcal{V} = r \mathcal{V}_b$ = the space of vector fields on $\overline{M}$ that vanish on the boundary $\partial \overline{M}$ and whose normal covariant derivative to the boundary also vanishes. Using the same notation as in the previous two examples, at the boundary $\partial \overline{M}$, a local basis is given by

$$(42) \quad r^2 \partial_r, r \partial_{y_2}, \ldots, r \partial_{y_n}.$$ 

Again the orbits $Z_\alpha$ are reduced to points, so $\alpha \in I := \partial \overline{M}$, but this time $G_\alpha = T_\alpha \overline{M} = T_\alpha \partial \overline{M} \times \mathbb{R}$ is commutative. See also [22, 99, 120, 141]. If $\partial \overline{M} = S^{n-1}$, the resulting geometry is that of an asymptotically Euclidean manifold. In particular, $\mathbb{R}^n$ with the radial compactification fits into the framework of this example.

Example 5.4. As in the previous two examples, $\overline{M}$ is a compact manifold with smooth boundary $\partial \overline{M} = \{ r = 0 \}$. To construct our Lie algebra of vector fields $V = V_e$, we assume that we are given a smooth fibration $\pi: \partial \overline{M} \to B$, and we let $V_e$ to be the space of vector fields on $M$ that are tangent to the fibers of $\pi: \partial \overline{M} \to B$. By choosing a product coordinate system on a small open subset of the boundary, a local basis is then given by

$$(43) \quad r \partial_r, r \partial_{y_2}, \ldots, r \partial_{y_k}, \partial_{y_{k+1}}, \ldots, \partial_{y_n}.$$ 

Here $k$ is such that the fibers of $\pi: \partial \overline{M} \to B$ have dimension $n - k$. Thus, when $k = 1$ (so the fibration is over a point, that is, $\pi: \partial \overline{M} \to \{pt\}$), we recover our first example, Example 5.1. On the other hand, when $k = n$ (so the fibration is $\pi: \partial \overline{M} \to \partial \overline{M}$), we recover our second example, Example 5.2. For $n = 3$ and $k = 2$, we recover the edge differential operators of Example 2.2 (3) (see Equation (22)). We note that $\mathcal{V} := \mathcal{V}_e \subset \mathcal{V}_b =: \mathcal{W}$ yields a typical example of an anisotropic structure.

In general, in this example, the set of orbits is $I = \{ \alpha \} = B$, $Z_\alpha = \pi^{-1}(\alpha)$, and $G_\alpha = T_\alpha B \times \mathbb{R}$ is a solvable Lie group with $\mathbb{R}$ acting by dilations. The geometry is related to that of locally symmetric spaces. Differential operators of this kind appear in the study of behavior at the edge of boundary value problems. This example generalizes the second example (Example 5.2) and the same references are valid for this example as well. See however also [60] for possibly the first paper on this type of examples.

We conclude with some less standard examples.

Example 5.5. Let us assume that we are in the same framework as in the previous example, Example, 5.4, but we replace the fibration of $\partial \overline{M}$ with a foliation. Then the resulting Lie manifold may fail to satisfy Theorem 4.14. See however [137]. It is interesting to notice that in this case, the resulting class of Riemann manifolds leads naturally to the study of foliation algebras.

Our last example in this subsection is on a manifold with corners.

Example 5.6. Let $A \to \overline{M}$ be a Lie algebroid (we do not assume $\Gamma(\overline{M}; A) \subset \mathcal{V}_b$) and let $\phi: \overline{M} \to [0, \infty)$ be a smooth function such that $\{ \phi = 0 \} = \partial \overline{M}$. We define $\mathcal{V} := \phi \Gamma(\overline{M}; A)$. Then $(\overline{M}, \mathcal{V})$ defines a Lie manifold.

A related example deals with the $N$-body problem in Quantum Mechanics [48] and can be used to give a new proof of the classical HWZ-theorem on the essentials spectrum of these operators. This is too long and technical to include here, however.
5.2. **Index theory.** Let now \((\mathring{M}, A)\) be a Lie manifold and let \(f\) be the product of the defining functions of all its faces. We consider then the exact sequence
\[
0 \to f\Psi^{-1}(\mathcal{G}) \to \Psi^0(\mathcal{G}) \to \text{Symb} \to 0,
\]
which gives rise as before to the map \(\partial : K_1(\text{Symb}) \to K_0(I)\). The **Fredholm index problem** is in this case to compute
\[
\text{Tr}_* \circ \partial : K_1(\text{Symb}) \to \mathbb{Z}.
\]
Since \(\phi_* \circ \partial = \psi_*\), where \(\psi = \partial \phi \in H^1(\text{Symb})\), by Connes’ results, the Fredholm index problem is equivalent to computing the class of \(\psi\) in periodic cyclic homology. This is a difficult problem that is still largely unsolved. Undoubtedly, excision in cyclic theory will play an important role [39]. See also [30, 31, 32, 113, 114, 124, 123, 125, 138, 152]. Instead of this general problem, we shall look now at a particular, but relevant case [23, 24].

**Definition 5.7.** We say that a Lie manifold \((\mathring{M}, W)\) is asymptotically commutative if all vectors in \(W\) vanish on \(\partial \mathring{M}\) and all isotropy Lie algebras \(\ker(q_x)\) are commutative.

Let \(x_1, x_2, \ldots, x_k\) be the defining functions of all the hyperfaces of \(\mathring{M}\) and \(f = x_1^{a_1} x_2^{a_2} \cdots x_k^{a_k}\) for some positive integers \(a_j\). Then, for any Lie manifold, the product \((\mathring{M}, V) W := fV\) defines an asymptotically commutative Lie manifold \((\mathring{M}, W)\).

If \((\mathring{M}, W)\) is asymptotically commutative, then the algebra \(\text{Symb}\) is commutative. Its completion will be of the form \(C(\Omega)\), as in the work of Cordes [34, 35]. Since the algebra \(\text{Symb}\) is commutative in this case, it is possible then to compute the index of Fredholm operators using classical invariants [24]. As an application, one obtains also the index of Dirac operators coupled with potentials of the form \(f^{-1}V_0\), where \(V_0\) is invertible at infinity on any Lie manifold (not just asymptotically commutative) [24].

5.3. **Essential spectrum.** We now present some applications to essential spectra. We use the notation introduced in Subsection 4.3. The applications to essential spectra of operators are based on the fact that for a self-adjoint operator \(D\) we have that
\[
\lambda \in \sigma_{\text{ess}}(D) \iff D - \lambda \text{ is not Fredholm}.
\]
We shall consider the case of self-adjoint operators \(D\) affiliated to \(\mathfrak{A}(M, V)\) (that is, satisfying \((D + i)^{-1} \in \mathfrak{A}(M, V)\) [40, 53]). Then we can use Theorem 4.14 to study when \(D - \lambda\) is (or is not) Fredholm.

We shall use these ideas for the open manifolds modeled by the Lie algebra of vector fields \((\mathring{M}, V_b)\) of Example (5.1) and the associated positive Laplacian \(\Delta_M\) [83].

**Theorem 5.8.** Let \(\mathring{M}\) be a manifold with corners and let \((\mathring{M}, V_b)\) be the Lie manifold of Example (5.1). We endow \(M\), the interior of \(\mathring{M}\), with the induced metric. Let \(\Delta_M\) be the associated positive Laplacian on \(M\). Assuming that \(M \neq \mathring{M}\), we have
\[
\sigma(\Delta_M) = [0, \infty)
\]
A complete characterization of the spectrum (multiplicity of the spectral measure, discreteness of the point spectrum, absence of continuous singular spectrum) is wide open, in spite of its importance.
Similarly, let $\mathcal{D}$ be the Dirac operator associated to a $\text{Cliff}(A)$-bundle over $\overline{M}$. Then [116]

**Theorem 5.9.** The Dirac operator $\mathcal{D}$ on $M = \overline{M} \setminus \partial \overline{M}$ is invertible if, and only if, for any open face $F$ (including the interior face $M$), the associated Dirac operator $\mathcal{D}_F$, has no harmonic spinors (that is, it has zero kernel).

The proof uses Theorem 4.14 and the fact that the resulting operators $P_\alpha$ are also Dirac operators.

Many similar results were obtained in Quantum Mechanics by Georgescu and his collaborators [40, 53, 55]. In fact, certain problems related to the $N$–body problem can be formulated in terms of a suitable compactifications of $X := \mathbb{R}^3_n$ to a manifold with corners $\overline{M}$ on which $X$ still acts and such that the Lie algebra of vector fields $\mathcal{V}$ is obtained from the action of $X$ [54]. See also [48].

5.4. Hadamard well posedness on polyhedral domains. This type of application [13] is of a different nature and does not use pseudodifferential operators or other operator algebras. It uses only Lie manifolds and their geometry. Let then $\Omega \subset \mathbb{R}^n$ be an open, bounded subset of with boundary $\partial \Omega$. We shall consider the “simplest” boundary value problem on $\Omega$, the Poisson problem with Dirichlet boundary conditions:

\[
\begin{cases}
-\Delta u = f \\
u|_{\partial \Omega} = 0
\end{cases}
\]

We refer to [13] for further references and details not included here. Recall then the following classical result, which we shall refer to as the basic well-posedness theorem (for $\Delta$ on smooth domains)

**Theorem 5.10.** Let us assume that $\partial \Omega$ is smooth. Then the Laplacian $\Delta$ defines an isomorphism

$$
\Delta : H^{s+1}(\Omega) \cap \{u|_{\partial \Omega} = 0\} \to H^{s-1}(\Omega), \quad s \geq 0.
$$

A useful consequence (easy to contradict for non-smooth domains) is:

**Corollary 5.11.** If $f$ and $\partial \Omega$ are smooth, then the solution $u$ of the Poisson problem with Dirichlet boundary conditions is also smooth.

It has been known for a very long time that the basic well posedness theorem does not extend to the case when $\partial \Omega$ is non-smooth. This can be immediately seen from the following example.

**Example 5.12.** Let us assume that $\Omega$ is the unit square, that is $\Omega = (0,1)^2$. If $u$ is smooth, then $\partial^2 u(0,0) = 0 = \partial^2 u(0,0)$, and hence $f(0,0) = \Delta u(0,0) = 0$. By choosing $f(0,0) \neq 0$, we will thus obtain a solution $u$ that is not smooth.

In view of the many practical applications of the basic well-posedness theorem, we want to extend it in some form to non-smooth domains. Assume now $\Omega \subset \mathbb{R}^n$ is a polyhedral domain. Exactly what a polyhedral domain means in three dimensions is subject to debate. In this presentation, we shall use the definition in [13] in terms of stratified spaces (we refer to that paper–a version of which paper was first circulated in 2004 as an IMA preprint–for the exact definition). The key technical point in that paper is to replace the classical Sobolev spaces $H^m(\Omega)$, introduced in
Equation (33) with weighted versions as in Kondratiev’s paper [73]. Let us then denote by $\rho$ the distance function to the singular part of the boundary and define

$$K^m_a(\Omega) := \{ u, \rho^{|\alpha|-a}\partial^\alpha u \in L^2(\Omega), |\alpha| \leq m \}.$$ 

(Notice the appearance of the factor $\rho$!) Thus, in two dimensions, $\rho(x)$ is the distance from $x \in \Omega$ to the vertices of $\Omega$, whereas in three dimensions, $\rho(x)$ is the distance from $x \in \Omega$ to the set of edges of $\Omega$.

**Theorem 5.13.** Let $\Omega \subset \mathbb{R}^n$ be a bounded polyhedral domain and $m \in \mathbb{Z}_+$. Then there exists $\eta > 0$ such that

$$\Delta : K^{m+1}_{a+1}(\Omega) \cap \{ u|_{\partial\Omega} = 0 \} \rightarrow K^{m-1}_a(\Omega),$$

is an isomorphism for all $|a| < \eta$.

In two dimensions, this result is due to Kondratiev [73].

The proof of Theorem 5.13 is based on a study of the properties of a Lie manifold with boundary $\Sigma(\Omega)$ canonically associated to $\Omega$ by a blow-up procedure. The weighted Sobolev spaces $K^m_a(\Omega)$ can be shown to coincide with the usual Sobolev spaces associated to $\Sigma(\Omega)$. See [6] for the definition of Lie manifolds with boundary. General blow-up procedures for Lie manifolds were studied in [5]. It can be shown that the class of Lie manifolds satisfying Theorem 4.14 is closed under blow-ups with respect to tame Lie submanifolds. Since most practical applications deal with Lie manifolds that are obtained by such a blow-up procedure from a smooth manifold, that establishes Theorem 4.14 in most cases of interest.

The blow-up procedure is an inductive procedure that consists in successively replacing cones of the form $CL := [0,\epsilon) \times L/(\{0\} \times L)$ with their associated cylinders $[0,\epsilon) \times L$. The following two pictures show the effect of the blow-up for a two dimensional domain.

The first of the following two pictures shows examples of polyhedral domains that are manifolds with corners and of polyhedral domains that are not manifolds with corners. The second picture shows the effect of the blow-up of (part of) a simplex.
No well posedness result similar to Theorem 5.13 holds for the Neumann problem (normal derivative at the boundary is zero):

\[
\begin{aligned}
-\Delta u &= f \\
\partial_\nu u &= 0,
\end{aligned}
\]

where \( \nu \) is a continuous unit normal vector field at the boundary. In fact, in three dimensions, the above problem is never Fredholm.

Here is however a variant of Theorem 5.13 that has been proved useful in practice. Let us consider a polygonal domain \( \Omega \) and, for each vertex \( P \) of \( \Omega \), let us consider a function \( \chi_P \in C^\infty(\mathbb{R}^2) \) that is equal to 1 around the vertex \( P \), depends only on the distance to \( P \), and has small support. Let \( W_s \) be the linear span of the functions \( \chi_P \), where \( P \) ranges through the set of vertices of \( \Omega \). Let \( \{1\}^{\perp} \) be the space of functions with integral zero. Then we have the following result [87].

**Theorem 5.14.** Let \( \Omega \subset \mathbb{R}^2 \) be a connected, bounded polygonal domain and \( m \in \mathbb{Z}_+ \). Then there exists \( \eta > 0 \) such that

\[
\Delta : \left( K^m_{a+1}(\Omega) \cap \{\partial_\nu u = 0\} + W_s \right) \cap \{1\}^{\perp} \rightarrow K^{m-1}_{a-1}(\Omega) \cap \{1\}^{\perp},
\]

is an isomorphism for all \( 0 < a < \eta \).

The proof of this theorem is based on an index theorem on polygonal domains, more precisely, a relative index theorem as follows.

**Proof.** (Sketch) Let us denote by \( \Delta_a \) the operator for a fixed value of the weight \( a \). Then one knows by [73] (or an analysis similar to the one needed for the APS index formula), that \( \Delta_a \) is Fredholm if, and only if, \( a \neq k\pi/\alpha \), where \( k \in \mathbb{Z} \) and \( \alpha \) ranges through the values of the angles of our domain \( \Omega \). (For the Dirichlet problem one has a similar condition for \( a \), except that \( k \neq 0 \).) One sees that \( \Delta_0 \) is not Fredholm, but one can compute the relative index \( \text{ind}(\Delta_a) - \text{ind}(\Delta_{-a}) = -2n \), for \( a > 0 \) small, where \( n \) is the number of vertices of \( \Omega \) (anyone familiar with the APS theory will have no problem proving this crucial fact). By definition, \( \Delta_0^* = \Delta_{-a} \), and hence this gives \( \text{ind}(\Delta_a) = -n \). A standard energy estimate shows that \( \ker(\Delta_a) = 1 \) for \( a > 0 \), with the kernel given by the constants. This is enough to complete the proof. \( \square \)
Theorems 5.13 and 5.14 have found applications to optimal rates of convergence for the Finite Element Method in two and three dimensions \cite{14}, where optimal rates of convergence in three dimensions were obtained for the first time.

References


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