

3 Pseudodifferential operators

Let $0 < \rho \leq 1$, $0 \leq \delta < 1$, X open $\subset \mathbb{R}^n$. A pseudodifferential operator is a Fourier integral operator $A : C_0^\infty(X) \rightarrow \mathcal{D}'(X)$ of the form

$$(3.1) \quad Au(x) = \frac{1}{(2\pi)^n} \iint e^{i(x-y)\theta} a(x, y, \theta) u(y) dy d\theta, \quad u \in C_0^\infty(X),$$

where $a \in S_{\rho, \delta}^m(X \times X \times \mathbb{R}^n)$. We denote by $L_{\rho, \delta}^m(X)$ the space of these operators and we say that $A \in L_{\rho, \delta}^m(X)$ is of order $\leq m$ and of type (ρ, δ) .

Example 3.1 If A is a differential operator on X of order $\leq m$ with smooth coefficients, then $A \in L_{1,0}^m(X)$. In fact, if $A = \sum_{|\alpha| \leq m} a_\alpha(x) D_x^\alpha$, $a_\alpha \in C^\infty(X)$, then by Fourier's inversion formula we get

$$Au(x) = \int e^{ix\xi} a(x, \xi) \hat{u}(\xi) \frac{d\xi}{(2\pi)^n} = \iint e^{i(x-y)\xi} a(x, \xi) u(y) dy \frac{d\xi}{(2\pi)^n},$$

$a(x, \xi) = \sum_{|\alpha| \leq m} a_\alpha(x) \xi^\alpha \in S_{1,0}^m(X \times \mathbb{R}^n)$. Here the last integral first makes sense as an iterated one, but inserting $\chi(\varepsilon\xi)$, $\chi \in C_0^\infty$, $\chi(0) = 1$ and letting ε tend to 0, we see that the distribution kernel of A is given by the oscillatory integral

$$K_A(x, y) = \int e^{i(x-y)\xi} a(x, \xi) \frac{d\xi}{(2\pi)^n}.$$

Example 3.2 The inverse of $(1 - \Delta) : \mathcal{S}(\mathbb{R}^n) \rightarrow \mathcal{S}(\mathbb{R}^n)$, where $\mathcal{S}(\mathbb{R}^n)$ is the Schwartz space of test functions and $-\Delta = -\sum \frac{\partial^2}{\partial x_j^2} = \sum D_{x_j}^2$, is given by

$$Au(x) = (1 - \Delta)^{-1} u(x) = \int e^{ix\xi} \frac{1}{(1 + \xi^2)} \hat{u}(\xi) \frac{d\xi}{(2\pi)^n} \quad (\xi^2 = \sum \xi_j^2).$$

Hence $A \in L_{1,0}^{-2}(\mathbb{R}^n)$, and it is not a differential operator. From our generalities on FIO's we get

- 1) If $K_A \in \mathcal{S}(X \times X)$ is the distribution kernel of $A \in L_{\rho, \delta}^m(X)$, then $\text{sing supp}(K_A) \subset \Delta(X \times X) \stackrel{\text{def}}{=} \{(x, x) \in X \times X\}$ (= "the diagonal of $X \times X$ "). In fact $(x - y) \cdot \theta$ is a phase function and $d_\theta((x - y) \cdot \theta)$ vanishes precisely when $x = y$.
- 2) Since $d_{y, \theta}((x - y) \cdot \theta) \neq 0$ and $d_{x, \theta}((x - y) \cdot \theta) \neq 0$ when $\theta \neq 0$, the pseudodifferential operators in $L_{\rho, \delta}^m(X)$ are continuous $C_0^\infty(X) \rightarrow C^\infty(X)$ and have (unique) continuous extensions $\mathcal{E}'(X) \rightarrow \mathcal{D}'(X)$. (We will not distinguish between these extensions and the original operators.)

Microlocal Analysis For Differential Operators An Introduction

Robert S. Strichartz



Microlocal Analysis For Differential Operators An Introduction:

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An Introduction to Semiclassical and Microlocal Analysis André Bach, 2013-03-14 The following lecture notes correspond to a course taught for several years first at the University of Paris Nord France and then at the University of Bologna Italy They are mainly addressed to nonspecialists in the subject and their purpose is to present in a pedagogical way most of the techniques used in the microlocal treatment of semiclassical problems coming from quantum physics Both the standard Coo pseudodifferential calculus and the analytic microlocal analysis are developed in a context that remains intentionally global so that only the relevant difficulties of the theory are encountered The main originality lies in the fact that we derive all the main features of analytic microlocal analysis from a single a priori estimate which turns out to be elementary once the Coo pseudodifferential calculus is established Various detailed exercises are given at the end of the main chapters most of them being easily solvable by students Besides illustrating the main results of the lecture their aim is also to introduce the reader to various further developments of the theory such as the functional calculus of pseudodifferential operators properties of the analytic wave front set Gevrey classes the use of coherent states the notion of semiclassical measures WKB constructions Applications to the study of the Schrödinger operator are also discussed in the text so that they may help the understanding of new notions or general results where they appear by replacing them in the context of quantum mechanics

Elementary Introduction to the Theory of Pseudodifferential Operators Xavier Saint Raymond, 2018-02-06 In the 19th century the Fourier transformation was introduced to study various problems of partial differential equations Since 1960 this old tool has been developed into a well organized theory called microlocal analysis that is based on the concept of the pseudo differential operator This book provides the fundamental knowledge non specialists need in order to use microlocal analysis It is strictly mathematical in the sense that it contains precise definitions statements of theorems and complete proofs and follows the usual method of pure mathematics The book explains the origin of the theory i e Fourier transformation presents an elementary construction of distribution theory and features a careful exposition of standard pseudodifferential theory Exercises historical notes and bibliographical references are included to round out this essential book for mathematics students engineers physicists and mathematicians who use partial differential equations and advanced mathematics instructors

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Precise Spectral Asymptotics Victor Ivrii, 2013-03-14 The problem of spectral asymptotics in particular the problem of the asymptotic distribution of eigenvalues is one of the central problems in the spectral theory of partial differential operators moreover it is very important for the general theory of partial differential operators I started working in this domain in 1979 after R Seeley found a remainder estimate of the same order as the then hypothetical second term for the Laplacian in domains with boundary and M Shubin and B M Levitan suggested that I should try to prove Weyl's conjecture During the past fifteen years I have not left the topic although I had such intentions in 1985 when the methods I invented seemed to fail to provide further progress and only a couple of not very exciting problems remained to be solved However at that time I made the step toward local semiclassical spectral asymptotics and rescaling and new horizons opened

Microlocal Analysis, Sharp Spectral Asymptotics and Applications I Victor Ivrii, 2019-09-12 The prime goal of this monograph which comprises a total of five volumes is to derive sharp spectral asymptotics for broad classes of partial differential operators using techniques from semiclassical microlocal analysis in particular propagation of singularities and to subsequently use the variational estimates in small domains to consider domains with singularities of different kinds In turn the general theory results and methods developed is applied to the Magnetic Schrödinger operator miscellaneous problems and multiparticle quantum theory In this volume the general microlocal semiclassical approach is developed and microlocal and local semiclassical spectral asymptotics are derived

Pseudo-differential Operators and the Nash-Moser Theorem Patrick Gérard, An important feature is the elementary and self contained character of the text to which many exercises and an introductory Chapter 0 with basic material have been added This makes the book readable by graduate students or researchers from one subject who are interested in becoming familiar with the other It can also be used as a textbook for a graduate course on nonlinear PDE or geometry

BOOK JACKET Noncommutative Microlocal Analysis Michael E. Taylor, 1984

Semiclassical Analysis Maciej Zworski, 2012 Semiclassical Analysis provides PDE techniques based on the classical quantum particle wave correspondence These techniques include such well known tools as geometric optics and the Wentzel Kramers Brillouin approximation

Geometric Scattering Theory Richard B. Melrose, 1995-07-28 These lecture notes are intended as a non technical overview of scattering theory

A Guide to Distribution Theory and Fourier Transforms Robert S. Strichartz, 2003 This important book provides a concise exposition of the basic ideas of the theory of distribution and Fourier transforms and its application to partial differential equations The author clearly presents the ideas precise statements of theorems and explanations of ideas behind the proofs Methods in which techniques are used in applications are illustrated and many problems are included The book also introduces several significant recent topics including pseudodifferential operators wave front sets wavelets and quasicrystals Background mathematical prerequisites have been kept to a minimum with only a knowledge of multidimensional calculus and basic complex variables needed to fully understand the concepts in the book *A Guide to Distribution Theory and Fourier Transforms* can serve as a textbook for parts

of a course on Applied Analysis or Methods of Mathematical Physics and in fact it is used that way at Cornell *Partial Differential Equations IV* Yuri Vladimirovich Egorov, Mikhail Aleksandrovich Shubin, 1993 *Asymptotic Analysis in General Relativity* Thierry Daudé, Dietrich Häfner, Jean-Philippe Nicolas, 2018-01-11 Introduction to modern methods for classical and quantum fields in general relativity Thierry Daudé, Dietrich Häfner and Jean-Philippe Nicolas Geometry of black hole spacetimes Lars Andersson, Thomas B.äckdahl and Pieter Blue An introduction to Quantum Field Theory on curved spacetimes Christian Gerard A minicourse on microlocal analysis for wave propagation Andras Vasy An introduction to conformal geometry and tractor calculus with a view to applications in general relativity Sean N. Curry and A. Rod Gover

Observation and Control for Operator Semigroups Marius Tucsnak, George Weiss, 2009-03-13 This book studies observation and control operators for linear systems where the free evolution of the state can be described by an operator semigroup on a Hilbert space. It includes a large number of examples coming mostly from partial differential equations.

D-modules and Microlocal Calculus Masaki Kashiwara, 2003 The original title of this work translated as *Foundation of Algebraic Analysis* Kashiwara, Kyoto U. Japan changed the title to more precisely reflect the nature of the text's contents and to signal his belief that the microlocal point of view helps concrete calculations as powerfully as the Cauchy integral formula provides the values of many definite integrals. Chapters cover basic properties of D-modules, characteristic varieties, construction of D-modules, their functorial properties, regular holonomic systems, b-functions, ring of formal microdifferential operators, microlocal analysis of holonomic systems, and microlocal calculus of b-functions. Translated from the Japanese work Daisuke Kashiwara, 2000. Annotation copyrighted by Book News, Inc., Portland, OR. *Microlocal Analysis And Complex Fourier Analysis* Keiko Fujita, Takahiro Kawai, 2002-12-12 This book is a collection of original papers on microlocal analysis, Fourier analysis in the complex domain, generalized functions, and related topics. Most of the papers originate from the talks given at the conference Prospects of Generalized Functions in November 2001 at RIMS, Kyoto. Reflecting the fact that the papers except M. Morimoto's one are dedicated to Mitsuo Morimoto, the subjects considered in this book are interdisciplinary just as Morimoto's works are. The historical backgrounds of the subjects are also discussed in depth in some contributions. Thus this book should be valuable not only to the specialists in the fields but also to those who are interested in the history of modern mathematics such as distributions and hyperfunctions. **Lectures on Linear Partial Differential Equations**

Grigoriĭ Il'ich Eskin, 2011 This is a reader-friendly, relatively short introduction to the modern theory of linear partial differential equations. An effort has been made to present complete proofs in an accessible and self-contained form. The first three chapters are on elementary distribution theory and Sobolev spaces. The following chapters study the Cauchy problem for parabolic and hyperbolic equations, boundary value problems for elliptic equations, heat trace asymptotics, and scattering theory. **Analysis On Manifolds** James R. Munkres, 1997-07-07 A readable introduction to the subject of calculus on arbitrary surfaces or manifolds. Accessible to readers with knowledge of basic calculus and linear algebra. Sections include

series of problems to reinforce concepts *Hangzhou Lectures on Eigenfunctions of the Laplacian* Christopher D. Sogge, 2014-03-10 Based on lectures given at Zhejiang University in Hangzhou China and Johns Hopkins University this book introduces eigenfunctions on Riemannian manifolds Christopher Sogge gives a proof of the sharp Weyl formula for the distribution of eigenvalues of Laplace Beltrami operators as well as an improved version of the Weyl formula the Duistermaat Guillemin theorem under natural assumptions on the geodesic flow Sogge shows that there is quantum ergodicity of eigenfunctions if the geodesic flow is ergodic Sogge begins with a treatment of the Hadamard parametrix before proving the first main result the sharp Weyl formula He avoids the use of Tauberian estimates and instead relies on sup norm estimates for eigenfunctions The author also gives a rapid introduction to the stationary phase and the basics of the theory of pseudodifferential operators and microlocal analysis These are used to prove the Duistermaat Guillemin theorem Turning to the related topic of quantum ergodicity Sogge demonstrates that if the long term geodesic flow is uniformly distributed most eigenfunctions exhibit a similar behavior in the sense that their mass becomes equidistributed as their frequencies go to infinity *Variational Problems in Materials Science* Gianni Dal Maso, Antonio de Simone, Franco Tomarelli, 2006-06-23 This volume contains the proceedings of the international workshop Variational Problems in Materials Science Coverage includes the study of BV vector fields path functionals over Wasserstein spaces variational approaches to quasi static evolution free discontinuity problems with applications to fracture and plasticity systems with hysteresis or with interfacial energies evolution of interfaces multi scale analysis in ferromagnetism and ferroelectricity and much more

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