

## MAXIMAL FUNCTIONS MEASURING SMOOTHNESS: COUNTEREXAMPLES

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UDC 517

We consider two main maximal operators measuring smoothness. For all possible values of the parameters, we give simple examples of bounded compactly supported functions that show quite clearly the difference between these maximal operators. Bibliography: 3 titles.

## 1. INTRODUCTION

Along with the classical Hardy–Littlewood maximal function

$$Mf(x) = \sup_{Q \ni x} \frac{1}{|Q|} \int_Q |f|,$$

another maximal function  $f^\sharp$  was introduced in the 1970s by Fefferman and Stein:

$$f^\sharp(x) = \sup_{Q \ni x} \frac{1}{|Q|} \int_Q |f - f_Q|.$$

Hereafter  $Q$  stands for a cube with sides parallel to the coordinate axes and  $f_Q$  is the mean value of a function  $f$  over  $Q$ . Recall that the classical space of functions of bounded mean oscillation  $BMO$  consists exactly of functions  $f$  such that  $f^\sharp \in L^\infty(\mathbb{R}^n)$ . Apparently, this fact was one of the motivations for introducing the function  $f^\sharp$  (see [3]); however, it turned out to be useful also in other problems, such as estimation (in particular, weight estimation) of singular integral operators.

The space  $BMO$  contains unbounded functions, so the maximal function  $f^\sharp$  can be essentially smaller than  $f$  (and the more so  $Mf$ ) at some points. The well-known Fefferman–Stein theorem says, however, that the functions  $f^\sharp$  and  $Mf$  are of the same magnitude “on the average”: if  $1 < p < \infty$  and  $Mf \in L^p$ , then  $\|f^\sharp\|_p \asymp \|Mf\|_p$  with constants depending on  $p$  only. For a proof of this result, see, e.g., [1].

In 1978, Calderon and Scott [2] introduced maximal functions similar to  $f^\sharp$  that measure the smoothness of  $f$ :

$$M_{k,p,s}f(x) = \sup_{Q \ni x} \inf_{\deg(\pi) \leq k} \frac{1}{|Q|^{\frac{1}{p}}} \left( \frac{1}{|Q|} \int_Q |f - \pi|^p \right)^{\frac{1}{p}}. \quad (1.1)$$

In this definition,  $k$  is a nonnegative integer,  $1 \leq p < \infty$ , and  $Q$  is still an arbitrary cube with sides parallel to the coordinate axes. The inner infimum is over all polynomials  $\pi$  of degree at most  $k$ . The parameter  $s \geq 0$  should be understood as a measure of smoothness; in this paper, we confine ourselves to integer values of  $s$ .

Such maximal functions do indeed deserve their name, since, as shown by Calderon and Scott (see [2]),

$$|\nabla^s f| \leq M_{s-1,1,s}f \leq M|\nabla^s f|,$$

where  $\nabla^s f$  is the gradient of  $f$  of order  $s$  (in fact, Calderon and Scott proved only the left inequality; for a proof of the right one, see [1]). Moreover, if  $M_{s-1,p,s}f \in L^q$  for  $q > 1$ , then  $f$  has all weak derivatives  $D^\alpha f$ ,  $|\alpha| = s$ , and they lie in  $L^q$ . For detailed proofs of these results, see [1].

In the case of zero smoothness, when  $s = 0$  and  $k = 0$ , Definition (1.1) coincides with the definition of the maximal function  $f^\sharp$ . One can also prove that for  $s = 0$ , strictly positive values  $k > 0$  in Definition (1.1) give rise to maximal functions comparable to  $f^\sharp$  (see [1]). Namely, for every  $k > 0$  there exists a polynomial  $\pi$  of degree at most  $k$  such that  $C_1 M_{k,p,0}(f - \pi) \leq f^\sharp \leq C_2 M_{k,p,0}(f - \pi)$ . We see that in the case  $s = 0$ , it is natural to consider only two maximal operators of the form (1.1),  $f^\sharp$  and  $Mf$ .

In the case of positive smoothness  $s$ , a similar situation occurs, namely, there are two naturally distinguished operators,  $M_{s-1,p,s}$  and  $M_{s,p,s}$ , which will be denoted by  $M_{s,p}^1 f$  and  $M_{s,p}^2 f$ , respectively. It is clear that in general the function  $M_{s,p}^1 f$  can be pointwise smaller than  $M_{s,p}^2 f$ . However, a problem arises concerning a relation between

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# Maximal Functions Measuring Smoothness

**RJ Shavelson**



## **Maximal Functions Measuring Smoothness:**

Maximal Functions Measuring Smoothness Ronald A. DeVore, Robert C. Sharpley, 1984 Maximal functions which measure the smoothness of a function are introduced and studied from the point of view of their relationship to classical smoothness and their use in proving embedding theorems extension theorems and various results on differentiation New spaces of functions which generalize Sobolev spaces are introduced

Maximal Functions Measuring Smoothness De Vore Ronald A., Ronald A. DeVore, Robert C. Sharpley, 1984

**Maximal Function Methods for Sobolev Spaces** Juha Kinnunen, Juha Lehtinen, Antti Vähäkangas, 2021-08-02 This book discusses advances in maximal function methods related to Poincaré and Sobolev inequalities pointwise estimates and approximation for Sobolev functions Hardy's inequalities and partial differential equations Capacities are needed for fine properties of Sobolev functions and characterization of Sobolev spaces with zero boundary values The authors consider several uniform quantitative conditions that are self improving such as Hardy's inequalities capacity density conditions and reverse Hölder inequalities They also study Muckenhoupt weight properties of distance functions and combine these with weighted norm inequalities notions of dimension are then used to characterize density conditions and to give sufficient and necessary conditions for Hardy's inequalities At the end of the book the theory of weak solutions to the  $p$ -Laplace equation and the use of maximal function techniques in this context are discussed The book is directed to researchers and graduate students interested in applications of geometric and harmonic analysis in Sobolev spaces and partial differential equations

**Recent Advances in Harmonic Analysis and Applications** Dmitriy Bilyk, Laura De Carli, Alexander Petukhov, Alexander M. Stokolos, Brett D. Wick, 2012-10-16 Recent Advances in Harmonic Analysis and Applications features selected contributions from the AMS conference which took place at Georgia Southern University Statesboro in 2011 in honor of Professor Konstantin Oskolkov's 65th birthday The contributions are based on two special sessions namely Harmonic Analysis and Applications and Sparse Data Representations and Applications Topics covered range from Banach space geometry to classical harmonic analysis and partial differential equations Survey and expository articles by leading experts in their corresponding fields are included and the volume also features selected high quality papers exploring new results and trends in Muckenhoupt Sawyer theory orthogonal polynomials trigonometric series approximation theory Bellman functions and applications in differential equations Graduate students and researchers in analysis will be particularly interested in the articles which emphasize remarkable connections between analysis and analytic number theory The readers will learn about recent mathematical developments and directions for future work in the unexpected and surprising interaction between abstract problems in additive number theory and experimentally discovered optical phenomena in physics This book will be useful for number theorists harmonic analysts algorithmists in multi dimensional signal processing and experts in physics and partial differential equations

**Theory and Applications of Differentiable Functions of Several Variables** S. M. Nikol'skii, 1990

**Sobolev Spaces in Mathematics I** Vladimir

Maz'ya, 2008-12-02 This volume marks the centenary of the birth of the outstanding mathematician of the 20th century Sergey Sobolev. It includes new results on the latest topics of the theory of Sobolev spaces, partial differential equations, analysis and mathematical physics. **Besov Regularity of Stochastic Partial Differential Equations on Bounded Lipschitz Domains** Petru A. Cioica, 2015-03-01 Stochastic partial differential equations (SPDEs) for short are the mathematical models of choice for space-time evolutions corrupted by noise. Although in many settings it is known that the resulting SPDEs have a unique solution, in general this solution is not given explicitly. Thus, in order to make those mathematical models ready to use for real-life applications, appropriate numerical algorithms are needed. To increase efficiency, it would be tempting to design suitable adaptive schemes based, e.g., on wavelets. However, it is not a priori clear whether such adaptive strategies can outperform well-established uniform alternatives. Their theoretical justification requires a rigorous regularity analysis in so-called non-linear approximation scales of Besov spaces. In this thesis, the regularity of semi-linear second-order SPDEs of Itô type on general bounded Lipschitz domains is analysed. The non-linear approximation scales of Besov spaces are used to measure the regularity with respect to the space variable, the time regularity being measured first in terms of integrability and afterwards in terms of Hölder norms. In particular, it is shown that in specific situations the spatial Besov regularity of the solution in the non-linear approximation scales is generically higher than its corresponding classical Sobolev regularity. This indicates that it is worth developing spatially adaptive wavelet methods for solving SPDEs instead of using uniform alternatives. **Multi-Layer Potentials and Boundary Problems** Irina Mitrea, Marius Mitrea, 2013-01-05 Many phenomena in engineering and mathematical physics can be modeled by means of boundary value problems for a certain elliptic differential operator in a given domain. When the differential operator under discussion is of second order, a variety of tools are available for dealing with such problems, including boundary integral methods, variational methods, harmonic measure techniques, and methods based on classical harmonic analysis. When the differential operator is of higher order, as is the case, e.g., with anisotropic plate bending, when one deals with a fourth-order operator, only a few options could be successfully implemented. In the 1970s, Alberto Calderón, one of the founders of the modern theory of Singular Integral Operators, advocated the use of layer potentials for the treatment of higher-order elliptic boundary value problems. The present monograph represents the first systematic treatment based on this approach. This research monograph lays for the first time the mathematical foundation aimed at solving boundary value problems for higher-order elliptic operators in non-smooth domains using the layer potential method and addresses a comprehensive range of topics dealing with elliptic boundary value problems in non-smooth domains, including layer potentials, jump relations, non-tangential maximal function estimates, multi-traces, and extensions, boundary value problems with data in Whitney Lebesgue spaces, Whitney Besov spaces, Whitney Sobolev-based Lebesgue spaces, Whitney Triebel-Lizorkin spaces, Whitney Sobolev-based Hardy spaces, Whitney BMO and Whitney VMO spaces. **Nonlinear Partial Differential Equations and Related Topics** Arina A. Arkhipova, Alexander I. Nazarov, Nina

Nikolaevna Ural't'seva, 2010 St Petersburg PDE seminar special session dedicated to N N Uraltseva's 75th anniversary June 2009 P vi

Theory of Function Spaces III Hans Triebel, 2006-09-10 This book may be considered as the continuation of the monographs Tri and Tri with the same title It deals with the theory of function spaces of type  $s, s, B$  and  $F$  as it stands at the beginning of this century These two scales of  $p, q$  spaces cover many well known spaces of functions and distributions such as Hölder Zygmund spaces fractional and classical Sobolev spaces Besov spaces and Hardy spaces On the one hand this book is essentially self contained On the other hand we concentrate principally on those developments in recent times which are related to the nowadays numerous applications of function spaces to some neighboring areas such as numerics signal processing and fractal analysis to mention only a few of them Chapter 1 in Tri is a self contained historically oriented survey of the function spaces considered and their roots up to the beginning of the 1990s entitled How to measure smoothness Chapter 1 of the present book has the same heading indicating continuity As far as the history is concerned we will now be very brief restricting ourselves to the essentials needed to make this book self contained and readable We complement Tri Chapter 1 by a few points omitted there But otherwise we jump to the 1990s describing more recent developments Some of them will be treated later on in detail

Theory of Function Spaces II Hans Triebel, 2010-05-18 Function Spaces and Applications Michael Cwikel, Jaak Peetre, Yoram Sagher, Hans E. Wallin, 2006-11-15 This seminar is a loose continuation of two previous conferences held in Lund 1982 1983 mainly devoted to interpolation spaces which resulted in the publication of the Lecture Notes in Mathematics Vol 1070 This explains the bias towards that subject The idea this time was however to bring together mathematicians also from other related areas of analysis To emphasize the historical roots of the subject the collection is preceded by a lecture on the life of Marcel Riesz

*Morrey and Campanato Meet Besov, Lizorkin and Triebel* Wen Yuan, Winfried Sickel, Dachun Yang, 2010-09-02 During the last 60 years the theory of function spaces has been a subject of growing interest and increasing diversity Based on three formally different developments namely the theory of Besov and Triebel Lizorkin spaces the theory of Morrey and Campanato spaces and the theory of  $Q$  spaces the authors develop a unified framework for all of these spaces As a byproduct the authors provide a completion of the theory of Triebel Lizorkin spaces when  $p$

**Theory of Besov Spaces** Yoshihiro Sawano, 2018-11-04 This is a self contained textbook of the theory of Besov spaces and Triebel Lizorkin spaces oriented toward applications to partial differential equations and problems of harmonic analysis These include a priori estimates of elliptic differential equations the  $T_1$  theorem pseudo differential operators the generator of semi group and spaces on domains and the Kato problem Various function spaces are introduced to overcome the shortcomings of Besov spaces and Triebel Lizorkin spaces as well The only prior knowledge required of readers is familiarity with integration theory and some elementary functional analysis Illustrations are included to show the complicated way in which spaces are defined Owing to that complexity many definitions are required The necessary terminology is provided at the outset and the theory of distributions  $L^p$  spaces the Hardy Littlewood maximal operator and

the singular integral operators are called upon. One of the highlights is that the proof of the Sobolev embedding theorem is extremely simple. There are two types for each function space: a homogeneous one and an inhomogeneous one. The theory of function spaces which readers usually learn in a standard course can be readily applied to the inhomogeneous one. However, that theory is not sufficient for a homogeneous space; it needs to be reinforced with some knowledge of the theory of distributions. This topic, however subtle, is also covered within this volume. Additionally, related function spaces: Hardy spaces, bounded mean oscillation spaces, and Hölder continuous spaces are defined and discussed, and it is shown that they are special cases of Besov spaces and Triebel-Lizorkin spaces.

**Twelve Papers in Analysis**, 1980-12-31 **Catalogue, Books and Journals in Advanced Mathematics** American Mathematical Society, 1985

**Handbook of the Geometry of Banach Spaces** William B. Johnson, Joram Lindenstrauss, 2001. The Handbook presents an overview of most aspects of modern Banach space theory and its applications. The up-to-date surveys authored by leading research workers in the area are written to be accessible to a wide audience. In addition to presenting the state of the art of Banach space theory, the surveys discuss the relation of the subject with such areas as harmonic analysis, complex analysis, classical convexity, probability theory, operator theory, combinatorics, logic, geometric measure theory, and partial differential equations. The Handbook begins with a chapter on basic concepts in Banach space theory which contains all the background needed for reading any other chapter in the Handbook. Each of the twenty-one articles in this volume, after the basic concepts chapter, is devoted to one specific direction of Banach space theory or its applications. Each article contains a motivated introduction as well as an exposition of the main results, methods, and open problems in its specific direction. Most have an extensive bibliography. Many articles contain new proofs of known results as well as expositions of proofs which are hard to locate in the literature or are only outlined in the original research papers. As well as being valuable to experienced researchers in Banach space theory, the Handbook should be an outstanding source for inspiration and information to graduate students and beginning researchers. The Handbook will be useful for mathematicians who want to get an idea of the various developments in Banach space theory.

[Handbook of the Geometry of Banach Spaces](#), 2003-05-06 **Handbook of the Geometry of Banach Spaces** **Modern Methods in Operator Theory and Harmonic Analysis** Alexey Karapetyants, Vladislav Kravchenko, Elijah Liflyand, 2019-08-28. This proceedings volume gathers selected peer-reviewed papers from the Modern Methods Problems and Applications of Operator Theory and Harmonic Analysis VIII OTHA 2018 conference which was held in Rostov-on-Don, Russia, in April 2018. The book covers a diverse range of topics in advanced mathematics including harmonic analysis, functional analysis, operator theory, function theory, differential equations, and fractional analysis, all fields that have been intensively developed in recent decades. Direct and inverse problems arising in mathematical physics are studied, and new methods for solving them are presented. Complex multiparameter objects that require the involvement of operators with variable parameters and functional spaces with fractional and even variable exponents make these approaches all the more

relevant Given its scope the book will especially benefit researchers with an interest in new trends in harmonic analysis and operator theory though it will also appeal to graduate students seeking new and intriguing topics for further investigation

**Harmonic Analysis and Partial Differential Equations** Jose Garcia-Cuerva, 2006-11-14 The programme of the Conference at El Escorial included 4 main courses of 3 4 hours Their content is reflected in the four survey papers in this volume see above Also included are the ten 45 minute lectures of a more specialized nature

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