

## THE HAAR MEASURE

MATH 519

### I. MEASURE THEORY BACKGROUND

In this section, we give a brief review of the measure theory which will be used in later sections. We use [R, Chapters 1 and 2] as our main resource.

A  $\sigma$ -algebra on a set  $X$  is a collection  $\mathcal{M}$  of subsets of  $X$  such that  $\emptyset \in \mathcal{M}$ , if  $S \in \mathcal{M}$ , then  $X \setminus S \in \mathcal{M}$ , and if a countable collection  $S_1, S_2, \dots \in \mathcal{M}$ , then  $\bigcup_{i=1}^{\infty} S_i \in \mathcal{M}$ . That is,  $\mathcal{M}$  is closed under complements and countable unions, and contains the empty set. A measure on a set  $X$  with  $\sigma$ -algebra  $\mathcal{M}$  is a function  $\mu : \mathcal{M} \rightarrow \mathbb{R}_{\geq 0} \cup \{\infty\}$  such that, if  $\{S_i\}_{i \geq 1}$  is a countable collection of pairwise disjoint elements of  $\mathcal{M}$ , then

$$\mu\left(\bigcup_{i=1}^{\infty} S_i\right) = \sum_{i=1}^{\infty} \mu(S_i),$$

where we define  $a + \infty = \infty$  for any  $a \in \mathbb{R}_{\geq 0} \cup \{\infty\}$ . In this case, the triple  $(X, \mathcal{M}, \mu)$  is called a measure space, and the elements of  $\mathcal{M}$  are called measurable sets. We will assume that measures are not trivial, that is, they take a nonzero value on some measurable set.

If  $X$  is a topological space, then the smallest  $\sigma$ -algebra containing all of the open sets of  $X$  is called the *Borel  $\sigma$ -algebra*, which we denote by  $\mathcal{B}$ . The elements of  $\mathcal{B}$  are called *Borel sets*, and a measure defined on  $\mathcal{B}$  is called a *Borel measure*.

Consider  $\mathbb{R}$  with the standard metric topology,  $\mathbb{R}_{\geq 0}$  with the subspace topology, and consider the collection of Borel sets of  $\mathbb{R}_{\geq 0}$ . If  $(X, \mathcal{M}, \mu)$  is a measure space, a function  $f : X \rightarrow \mathbb{R}_{\geq 0}$  is called measurable if for every Borel set  $S$  in  $\mathbb{R}_{\geq 0}$ ,  $f^{-1}(S) \in \mathcal{M}$ . That is,  $f$  is measurable if the inverse image of any Borel set is a measurable set. In the case that  $X$  is a topological space and  $\mathcal{M}$  is the Borel  $\sigma$ -algebra on  $X$ , note that any continuous function  $f : X \rightarrow \mathbb{R}_{\geq 0}$  is also measurable. In general, if  $(Y, \mathcal{N}, \nu)$  is any other measure space, then we call  $f : X \rightarrow Y$  measurable if  $A \in \mathcal{N}$  implies  $f^{-1}(A) \in \mathcal{M}$ .

Let  $(X, \mathcal{M}, \mu)$  be a measure space, and  $S \in \mathcal{M}$ . Define  $\mathbf{1}_S$  to be the characteristic function on  $S$ , so  $\mathbf{1}_S(x) = 1$  when  $x \in S$  and  $\mathbf{1}_S(x) = 0$  if  $x \notin S$ . A simple function on  $X$  is a function  $h : X \rightarrow \mathbb{R}_{\geq 0}$  which can be written as

$$h(x) = \sum_{i=1}^m \alpha_i \mathbf{1}_{S_i}(x), \quad \text{for distinct } \alpha_i \in \mathbb{R}_{>0}, \text{ pairwise disjoint } S_i \in \mathcal{M}.$$

That is, a simple function is a non-negative measurable function which takes a finite number of positive real values. For any  $A \in \mathcal{M}$  and any simple function  $h = \sum_{i=1}^m \alpha_i \mathbf{1}_{S_i}$  on  $X$ , we define

$$\int_A h \, d\mu = \sum_{i=1}^m \alpha_i \mu(A \cap S_i).$$

# Measure Theory Measure Theory

**Paul R. Halmos**

## **Measure Theory**

**Measure Theory** Donald L. Cohn, 2013-07-13 Intended as a self contained introduction to measure theory this textbook also includes a comprehensive treatment of integration on locally compact Hausdorff spaces the analytic and Borel subsets of Polish spaces and Haar measures on locally compact groups This second edition includes a chapter on measure theoretic probability theory plus brief treatments of the Banach Tarski paradox the Henstock Kurzweil integral the Daniell integral and the existence of liftings Measure Theory provides a solid background for study in both functional analysis and probability theory and is an excellent resource for advanced undergraduate and graduate students in mathematics The prerequisites for this book are basic courses in point set topology and in analysis and the appendices present a thorough review of essential background material

**Measure Theory and Integration** Debarra G., 1981

**Measure Theory and Integration** M.M.

Rao, 2018-10-03 Significantly revised and expanded this authoritative reference text comprehensively describes concepts in measure theory classical integration and generalized Riemann integration of both scalar and vector types providing a complete and detailed review of every aspect of measure and integration theory using valuable examples exercises and applications With more than 170 references for further investigation of the subject this Second Edition provides more than 60 pages of new information as well as a new chapter on nonabsolute integrals contains extended discussions on the four basic results of Banach spaces presents an in depth analysis of the classical integrations with many applications including integration of nonmeasurable functions Lebesgue spaces and their properties details the basic properties and extensions of the Lebesgue Carath odory measure theory as well as the structure and convergence of real measurable functions covers the Stone isomorphism theorem the lifting theorem the Daniell method of integration and capacity theory Measure Theory and Integration Second Edition is a valuable reference for all pure and applied mathematicians statisticians and mathematical analysts and an outstanding text for all graduate students in these disciplines

*Measure Theory* D. H. Fremlin, 2000

**Probability and Measure Theory** Robert B. Ash, Catherine A. Doleans-Dade, 2000 Probability and Measure Theory Second Edition is a text for a graduate level course in probability that includes essential background topics in analysis It provides extensive coverage of conditional probability and expectation strong laws of large numbers martingale theory the central limit theorem ergodic theory and Brownian motion Clear readable style Solutions to many problems presented in text Solutions manual for instructors Material new to the second edition on ergodic theory Brownian motion and convergence theorems used in statistics No knowledge of general topology required just basic analysis and metric spaces Efficient organization

**Measure Theory** J.L. Doob, 2012-12-06 This book was planned originally not as a work to be published but as an excuse to buy a computer incidentally to give me a chance to organize my own ideas n what measure theory every would be analyst should learn and to detail my approach to the subject When it turned out that Springer Verlag thought that the point of view in the book had general interest and offered to publish it I was forced to try to write more clearly and search for

errors The search was productive Readers will observe the stress on the following points The application of pseudometric spaces Pseudo metric rather than metric spaces are applied to obviate the artificial replacement of functions by equivalence classes a replacement that makes the use of almost everywhere either improper or artificial The words function and the set on which a function has values at least  $E$  can be taken literally in this book Pseudometric space properties are applied in many contexts For example outer measures are used to pseudometrize classes of sets and the extension of a finite measure from an algebra to a  $\sigma$  algebra is thereby reduced to finding the closure of a subset of a pseudo metric space [Measure Theory](#) Vladimir I. Bogachev, 2007-01-15 Measure theory is a classical area of mathematics born more than two thousand years ago Nowadays it continues intensive development and has fruitful connections with most other fields of mathematics as well as important applications in physics This book gives an exposition of the foundations of modern measure theory and offers three levels of presentation a standard university graduate course an advanced study containing some complements to the basic course the material of this level corresponds to a variety of special courses and finally more specialized topics partly covered by more than 850 exercises Volume 1 Chapters 1–5 is devoted to the classical theory of measure and integral Whereas the first volume presents the ideas that go back mainly to Lebesgue the second volume Chapters 6–10 is to a large extent the result of the later development up to the recent years The central subjects of Volume 2 are transformations of measures conditional measures and weak convergence of measures These three topics are closely interwoven and form the heart of modern measure theory The organization of the book does not require systematic reading from beginning to end in particular almost all sections in the supplements are independent of each other and are directly linked only to specific sections of the main part The target readership includes graduate students interested in deeper knowledge of measure theory instructors of courses in measure and integration theory and researchers in all fields of mathematics The book may serve as a source for many advanced courses or as a reference [Measure Theory](#) Carlos S Kubrusly, 2007 This contemporary first course focuses on concepts and ideas of Measure Theory highlighting the theoretical side of the subject Its primary intention is to introduce Measure Theory to a new generation of students whether in mathematics or in one of the sciences by offering them on the one hand a text with complete rigorous and detailed proofs sketchy proofs have been a perpetual complaint as demonstrated in the many Amazon reader reviews critical of authors who omit trivial steps and make not so obvious it is obvious remarks On the other hand Kubrusly offers a unique collection of fully hinted problems On the other hand Kubrusly offers a unique collection of fully hinted problems The author invites the readers to take an active part in the theory construction thereby offering them a real chance to acquire a firmer grasp on the theory they helped to build These problems at the end of each chapter comprise complements and extensions of the theory further examples and counterexamples or auxiliary results They are an integral part of the main text which sets them apart from the traditional classroom or homework exercises JARGON BUSTER measure theory Measure theory investigates the conditions under which

integration can take place It considers various ways in which the size of a set can be estimated This topic is studied in pure mathematics programs but the theory is also foundational for students of statistics and probability engineering and financial engineering Designed with a minimum of prerequisites intro analysis and for Ch 5 linear algebra Includes 140 classical measure theory problems Carefully crafted to present essential elements of the theory in compact form

**Geometric Measure Theory** Frank Morgan,2014-05-19 Geometric measure theory is the mathematical framework for the study of crystal growth clusters of soap bubbles and similar structures involving minimization of energy Morgan emphasizes geometry over proofs and technicalities and includes a bibliography and abundant illustrations and examples This Second Edition features a new chapter on soap bubbles as well as updated sections addressing volume constraints surfaces in manifolds free boundaries and Besicovitch constant results The text will introduce newcomers to the field and appeal to mathematicians working in the field

**Measure Theory and Probability Theory** Krishna B. Athreya, Soumendra N. Lahiri, 2006-07-27 This is a graduate level textbook on measure theory and probability theory The book can be used as a text for a two semester sequence of courses in measure theory and probability theory with an option to include supplemental material on stochastic processes and special topics It is intended primarily for first year Ph D students in mathematics and statistics although mathematically advanced students from engineering and economics would also find the book useful Prerequisites are kept to the minimal level of an understanding of basic real analysis concepts such as limits continuity differentiability Riemann integration and convergence of sequences and series A review of this material is included in the appendix The book starts with an informal introduction that provides some heuristics into the abstract concepts of measure and integration theory which are then rigorously developed The first part of the book can be used for a standard real analysis course for both mathematics and statistics Ph D students as it provides full coverage of topics such as the construction of Lebesgue Stieltjes measures on real line and Euclidean spaces the basic convergence theorems L p spaces signed measures Radon Nikodym theorem Lebesgue's decomposition theorem and the fundamental theorem of Lebesgue integration on R product spaces and product measures and Fubini Tonelli theorems It also provides an elementary introduction to Banach and Hilbert spaces convolutions Fourier series and Fourier and Plancherel transforms Thus part I would be particularly useful for students in a typical Statistics Ph D program if a separate course on real analysis is not a standard requirement Part II chapters 6 13 provides full coverage of standard graduate level probability theory It starts with Kolmogorov's probability model and Kolmogorov's existence theorem It then treats thoroughly the laws of large numbers including renewal theory and ergodic theorems with applications and then weak convergence of probability distributions characteristic functions the Levy Cramer continuity theorem and the central limit theorem as well as stable laws It ends with conditional expectations and conditional probability and an introduction to the theory of discrete time martingales Part III chapters 14 18 provides a modest coverage of discrete time Markov chains with countable and general state spaces MCMC continuous time discrete space jump Markov

processes Brownian motion mixing sequences bootstrap methods and branching processes It could be used for a topics seminar course or as an introduction to stochastic processes Krishna B Athreya is a professor at the departments of mathematics and statistics and a Distinguished Professor in the College of Liberal Arts and Sciences at the Iowa State University He has been a faculty member at University of Wisconsin Madison Indian Institute of Science Bangalore Cornell University and has held visiting appointments in Scandinavia and Australia He is a fellow of the Institute of Mathematical Statistics USA a fellow of the Indian Academy of Sciences Bangalore an elected member of the International Statistical Institute and serves on the editorial board of several journals in probability and statistics Soumendra N Lahiri is a professor at the department of statistics at the Iowa State University He is a fellow of the Institute of Mathematical Statistics a fellow of the American Statistical Association and an elected member of the International Statistical Institute

### **Measure Theory**

**and Integration** G De Barra,2003-07-01 This text approaches integration via measure theory as opposed to measure theory via integration an approach which makes it easier to grasp the subject Apart from its central importance to pure mathematics the material is also relevant to applied mathematics and probability with proof of the mathematics set out clearly and in considerable detail Numerous worked examples necessary for teaching and learning at undergraduate level constitute a strong feature of the book and after studying statements of results of the theorems students should be able to attempt the 300 problem exercises which test comprehension and for which detailed solutions are provided Approaches integration via measure theory as opposed to measure theory via integration making it easier to understand the subject Includes numerous worked examples necessary for teaching and learning at undergraduate level Detailed solutions are provided for the 300 problem exercises which test comprehension of the theorems provided

### **Handbook of Measure Theory E.**

Pap,2002-10-31 The main goal of this Handbook is to survey measure theory with its many different branches and its relations with other areas of mathematics Mostly aggregating many classical branches of measure theory the aim of the Handbook is also to cover new fields approaches and applications which support the idea of measure in a wider sense e g the ninth part of the Handbook Although chapters are written of surveys in the various areas they contain many special topics and challenging problems valuable for experts and rich sources of inspiration Mathematicians from other areas as well as physicists computer scientists engineers and econometrists will find useful results and powerful methods for their research The reader may find in the Handbook many close relations to other mathematical areas real analysis probability theory statistics ergodic theory functional analysis potential theory topology set theory geometry differential equations optimization variational analysis decision making and others The Handbook is a rich source of relevant references to articles books and lecture notes and it contains for the reader's convenience an extensive subject and author index

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Donald L. Cohn,2013-06-29 Intended as a self contained introduction to measure theory this textbook also includes a comprehensive treatment of integration on locally compact Hausdorff spaces the analytic and Borel subsets of Polish spaces and Haar

measures on locally compact groups Measure Theory provides a solid background for study in both harmonic analysis and probability theory and is an excellent resource for advanced undergraduate and graduate students in mathematics The prerequisites for this book are courses in topology and analysis **Real Analysis** Elias M. Stein,Rami Shakarchi,2005-04-03 Real Analysis is the third volume in the Princeton Lectures in Analysis a series of four textbooks that aim to present in an integrated manner the core areas of analysis Here the focus is on the development of measure and integration theory differentiation and integration Hilbert spaces and Hausdorff measure and fractals This book reflects the objective of the series as a whole to make plain the organic unity that exists between the various parts of the subject and to illustrate the wide applicability of ideas of analysis to other fields of mathematics and science After setting forth the basic facts of measure theory Lebesgue integration and differentiation on Euclidian spaces the authors move to the elements of Hilbert space via the L2 theory They next present basic illustrations of these concepts from Fourier analysis partial differential equations and complex analysis The final part of the book introduces the reader to the fascinating subject of fractional dimensional sets including Hausdorff measure self replicating sets space filling curves and Besicovitch sets Each chapter has a series of exercises from the relatively easy to the more complex that are tied directly to the text A substantial number of hints encourage the reader to take on even the more challenging exercises As with the other volumes in the series Real Analysis is accessible to students interested in such diverse disciplines as mathematics physics engineering and finance at both the undergraduate and graduate levels Also available the first two volumes in the Princeton Lectures in Analysis **Measure Theory and Probability** Malcolm Adams,Victor Guillemin,2013-04-17 the text is user friendly to the topics it considers and should be very accessible Instructors and students of statistical measure theoretic courses will appreciate the numerous informative exercises helpful hints or solution outlines are given with many of the problems All in all the text should make a useful reference for professionals and students The Journal of the American Statistical Association **Measure Theory** Paul R. Halmos,2013-12-19 Useful as a text for students and a reference for the more advanced mathematician this book presents a unified treatment of that part of measure theory most useful for its application in modern analysis Coverage includes sets and classes measures and outer measures Haar measure and measure and topology in groups From the reviews Will serve the interested student to find his way to active and creative work in the field of Hilbert space theory MATHEMATICAL REVIEWS **Introduction to Measure and Probability** J. F. C. Kingman,S. J. Taylor,2008-11-20 The authors believe that a proper treatment of probability theory requires an adequate background in the theory of finite measures in general spaces The first part of their book sets out this material in a form that not only provides an introduction for intending specialists in measure theory but also meets the needs of students of probability The theory of measure and integration is presented for general spaces with Lebesgue measure and the Lebesgue integral considered as important examples whose special properties are obtained The introduction to functional analysis which follows covers the material such as the various notions

of convergence which is relevant to probability theory and also the basic theory of L2 spaces important in modern physics The second part of the book is an account of the fundamental theoretical ideas which underlie the applications of probability in statistics and elsewhere developed from the results obtained in the first part A large number of examples is included these form an essential part of the development Probability Theory and Elements of Measure Theory Heinz Bauer,1981

Measure and integration theory Probability theory Continuation of measure and integration theory Further development of probability theory **Measure, Integration, and Functional Analysis** Robert B. Ash,2014-05-10 Measure Integration and Functional Analysis deals with the mathematical concepts of measure integration and functional analysis The fundamentals of measure and integration theory are discussed along with the interplay between measure theory and topology Comprised of four chapters this book begins with an overview of the basic concepts of the theory of measure and integration as a prelude to the study of probability harmonic analysis linear space theory and other areas of mathematics The reader is then introduced to a variety of applications of the basic integration theory developed in the previous chapter with particular reference to the Radon Nikodym theorem The third chapter is devoted to functional analysis with emphasis on various structures that can be defined on vector spaces The final chapter considers the connection between measure theory and topology and looks at a result that is a companion to the monotone class theorem together with the Daniell integral and measures on topological spaces The book concludes with an assessment of measures on uncountably infinite product spaces and the weak convergence of measures This book is intended for mathematics majors most likely seniors or beginning graduate students and students of engineering and physics who use measure theory or functional analysis in their work

**Measure Theory and Fine Properties of Functions** Lawrence Craig Evans,Ronald F. Gariepy,1991-12-18 This book provides a detailed examination of the central assertions of measure theory in n dimensional Euclidean space and emphasizes the roles of Hausdorff measure and the capacity in characterizing the fine properties of sets and functions Topics covered include a quick review of abstract measure theory theorems and differentiation in  $M^n$  lower Hausdorff measures area and coarea formulas for Lipschitz mappings and related change of variable formulas and Sobolev functions and functions of bounded variation The text provides complete proofs of many key results omitted from other books including Besicovitch's Covering Theorem Rademacher's Theorem on the differentiability a.e. of Lipschitz functions the Area and Coarea Formulas the precise structure of Sobolev and BV functions the precise structure of sets of finite perimeter and Alexandroff's Theorem on the twice differentiability a.e. of convex functions Topics are carefully selected and the proofs succinct but complete which makes this book ideal reading for applied mathematicians and graduate students in applied mathematics

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