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Vector Measures

J. Diestel and J. J. Uhl, Jr.

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FOREWORD

Much of the work on Banach spaces done in the 1930's resulted from investigating how much of real variable theory might be extended to functions taking values in such spaces. Members of E. H. Moore's school of general analysis at Chicago, including Graves and Hildebrandt, and functional analysts in Italy and Poland (Orlicz in particular) had already done pioneer work in convergence of functions, certain aspects of integration and differentiation, and the relationships between various convergence properties for series. In the 1930's Hildebrandt's group in Ann Arbor and Tamarkin's at Brown expanded the effort in the U.S.A., the strong Russian school developed, and the influence of the Polish group spread, via Banach's book, more deeply and widely. In developing integration and differentiation theory for functions defined on Euclidean space to a Banach space B in the period subsequent to Bochner's 1933 papers the important pioneer figures were Dunford and Gel'fand.

It was in the study of differentiation of functions on Euclidean figures that the role of the character of B emerged. Although some functions, such as Bochner integrals, were differentiable a.e. regardless of B, many were not, their differentiability depending on the characteristics of their range spaces; more precisely, it depended on what properties the function developed for its range set as a subset of B. (Clarkson invented uniformly convex spaces for the purpose of universal differentiation; reflexive spaces reappeared on the stage for the same purpose.) Moreover differentiation, aside from its intrinsic interest, was fundamental in efforts to represent linear operators by means of integrals, and when operations from spaces of functions whose domains were an abstract space were to be represented, differentiation had to be replaced by Radon-Nikodým theorems. Here Dunford led by proving the earliest R-N theorem (N. Dunford, *Integration and linear operations*, Trans. Amer. Math. Soc. **40** (1936), 474–494) and by giving the first proof of a R-N theorem, now well known, when B is a dual space (N. Dunford and B. J. Pettis, *Linear operations on summable functions*, Trans. Amer. Math. Soc. **47** (1940), 323–392; second proof). The study of Banach-space-valued functions waned in the 1940's, was revived and partly redirected by the deep work of Grothendieck, and generally relapsed again until late in the 1960's. Since then vigorous work by many here and in various parts of Europe and elsewhere has produced a flourishing body

of results, a considerable amount of which has been organized and presented in the present volume in useful and no doubt fertile form. The notion of vector measures can be made central to a study of Banach-space-valued functions (series, integrals, differentiation, R-N theorems), to the representation and classification of linear operations between certain kinds of spaces, and the classification of Banach spaces. This is the view presented by the authors of this work, who display very effectively the interplay between properties of B and properties of vector measures taking their values in B, to the understanding of which they have themselves contributed substantially in recent years. Those who now or in the future work with Banach-space-valued functions or in the classification of geometric properties of Banach spaces, as well as those who have done so in the past, should be grateful to Professors Diestel and Uhl for their substantial contribution.

B. J. PETTIS

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INTRODUCTION

It seems to be well forgotten that many of the first ideas in geometry, basis theory and isomorphic theory of Banach spaces have vector measure-theoretic origins. Equally well forgotten is the fact that much of the early interest in weak and weak* compactness was motivated by vector measure-theoretic considerations.

In 1936, J. A. Clarkson introduced the notion of uniform convexity to prove that absolutely continuous functions on a Euclidean space with values in a uniformly convex Banach space are the integrals of their derivatives. At the same time, Clarkson used vector measure-theoretic ideas to prove that many familiar Banach spaces do not admit equivalent uniformly convex norms.

N. Dunford and A. P. Morse, in 1936, introduced the notion of a boundedly complete basis to prove that absolutely continuous functions on a Euclidean space with values in a Banach space with a boundedly complete basis are the integrals of their derivatives. Shortly thereafter Dunford was able to recognize the Dunford-Morse theorem and the Clarkson theorem as genuine Radon-Nikodým theorems for the Bochner integral. This was the first Radon-Nikodým theorem for vector measures on abstract measure spaces.

B. J. Pettis, in 1938, made his contribution to the Orlicz-Pettis theorem for the purpose of proving that weakly countably additive vector measures are norm countably additive.

In 1938, I. Gel'fand used vector measure-theoretic methods to prove that $L_1[0, 1]$ is not isomorphic to a dual of a Banach space.

In 1939, Pettis showed that the notions of weak and weak* compactness are intimately related to the problem of differentiating vector-valued functions on Euclidean space. Dunford and Pettis, in 1940, built on their earlier work to represent weakly compact operators on L_1 and the general operator from L_1 to a separable dual space by means of a Bochner integral. By means of their integral representation they were able to prove that L_1 has the property now known as the Dunford-Pettis property.

Then came the war. By the end of the war, the love affair between vector measure theory and Banach space theory had cooled. They began to drift down separate paths. Neither prospered. Much of Banach space theory became lost in the mazes of the theory of locally convex spaces. The work in vector measure theory became

little more than formal generalizations of the scalar theory. Representation theory for operators on function spaces became the vogue. But all too often these representation theories gave no new information about the operators they represented. During the fifties and early sixties the theory of vector measures languished in sterility.

There were one or two bright spots. In the mid-fifties, A. Grothendieck used the then ignored vector measure theory of the late thirties and early forties to launch a monumental study of linear operators. The repercussions of Grothendieck's work are still being felt today. Also in the mid-fifties, Grothendieck and (independently) R. G. Bartle, N. Dunford and J. T. Schwartz studied operators on spaces of continuous functions and proved the first important theorems in the theory of vector measures in some fifteen years. But the unfortunate truth is that, aside from I. Kluvanek and a few others, no one followed their lead.

In the early sixties, largely through the pioneering work of A. Pełczyński and J. Lindenstrauss, Banach space theory came back to life and today has re-emerged as a deep and vigorous area of mathematical inquiry. Vector measure theory did not come around so quickly.

In the mid-sixties, N. Dinculeanu gave an intensive study of many of the theorems of vector measure theory that had been proven between 1950 and 1965. Dinculeanu's monograph was the catalytic agent that the theory of vector measures needed. Upon the appearance of Dinculeanu's book, interest in vector measures began to grow. It was not long before a number of mathematicians addressed themselves to the basic unsolved problems of vector measure theory. The study of the Radon-Nikodým theorem for the Bochner integral and the Orlicz-Pettis theorem served to re-establish the links between vector measures and the analytic, geometric and isomorphic theory of Banach spaces. Today the theory of vector measures stands as a hearty cousin and proud servant of the theory of Banach spaces. This survey is a report on how this has come about.

We endeavor to give a comprehensive survey of the theory of vector measures as we see it. It is our overriding desire to emphasize the fruitful (and we think exciting) interplay between properties of Banach spaces and measures taking values in Banach spaces. Thus the exposition of the relationships among vector measures, operators on L_1, operators on spaces of bounded measurable functions, topological structure of Banach spaces and geometric structure of Banach spaces is our unifying theme. We feel that any attempt to divorce vector measures from these latter areas would wallow in artificiality.

This survey is written for the student as well as the advanced mathematician. Much of it originated in lectures given by the authors at Kent State University and the University of Illinois. Other parts of the survey have grown from conversations with our colleagues in the classroom and other places where mathematicians gravitate to talk. We assume that the reader has some familiarity with basic Banach space theory as presented in Chapters II, V and VI of *Linear operators* by Dunford and Schwartz[1] and with basic measure theory as presented in Bartle's *Elements of integration* or Halmos's *Measure theory*. Other than this, this survey is self-contained.

[1]It may be noted that much of this survey is an outgrowth of Chapters IV and VI of Dunford and Schwartz.

The first chapter deals with countably additive and finitely additive vector measures. The basic behavior of countably additive measures is presented from the viewpoint of the fundamental work of Bartle, Dunford and Schwartz and Kluvanek. We base the theory of finitely additive vector measures on Rosenthal's lemma. With the help of this lemma, we examine the roles of the spaces c_0 and l_∞ in the theory of vector measures. Included here are the Vitali-Hahn-Saks-Nikodým theorem and the Nikodým boundedness theorem for finitely additive vector measures.

The second chapter, which is for the most part independent of Chapter I, is devoted to measurable functions with values in Banach spaces and the problem of integrating them. The Bochner integral receives most of the attention, but basic material on the Pettis, Dunford and Gel'fand integrals is found in this chapter.

The Radon-Nikodým theorem for the Bochner integral is the subject of Chapter III. We try to follow the genetic approach of treating the Radon-Nikodým theorem and L_1 operator theory as one unified theory. The analytic (i.e., topological) aspects of the Radon-Nikodým theorem are found here. The roles of compact operators on L_1, weakly compact operators on L_1, reflexive spaces, separable dual spaces and weakly compactly generated dual spaces in the Radon-Nikodým property are also discussed here.

Chapter IV continues with a potpourri of applications of the Radon-Nikodým theorem for the Bochner integral. The duals of the L_p-spaces of Bochner integrable functions are derived and weak compactness in the space of Bochner integrable functions is discussed. The relationship between differentiable vector-valued functions of a real variable and the Radon-Nikodým theorem is next. Then the relationship between the classical integral operators on L_p and the Bochner integral is surveyed. The chapter concludes with the Lewis Stegall theorem on complemented subspaces of L_1.

Martingales of Bochner integrable functions headline Chapter V. In addition to martingale convergence theorems, we observe a basic phenomenon in the theory of vector measures. Through a meld of the Radon-Nikodym theorem, elementary martingale theory, and geometry of Banach spaces, we see the Radon-Nikodým property transfer itself from an analytic property of Banach spaces to a geometric property of Banach spaces. This is the link between geometry and measure theory in Banach spaces.

Structural properties of operators on spaces of continuous functions $C(\Omega)$ are under scrutiny in Chapter VI. The basic work of Bartle, Dunford and Schwartz and Grothendieck is discussed from the viewpoint of Chapter I in the first part. The second part deals with absolutely summing and nuclear operators on $C(\Omega)$ and their relationship with the Radon-Nikodým theorem. Included here is a discussion of Pietsch integral operators on Banach spaces.

The seventh chapter builds on the martingale theory of Chapter V to give an exposition of the repercussions of the Radon-Nikodým theorem in the geometry of Banach spaces. Studied here are the relationships among the Radon-Nikodým theorem, the Kreĭn-Mil'man theorem, properties of strongly exposed points, and other extreme point phenomena. This chapter can be read directly after Chapter V.

Tensor products of Banach spaces and how the Radon-Nikodým theorem can be used within the theory of tensor products to study Banach spaces is the theme of Chapter VIII.

Chapter IX concludes the survey with a discussion of the Liapounoff convexity theorem and other geometric properties of the range of a vector measure.

At the end of each chapter is a section called "Notes and remarks." These sections, which are modeled after similiar sections in Dunford and Schwartz, attempt to discuss the original and subsequent versions of the results presented in the chapter in question. Sometimes they contain additional results, often with proofs, that could not be fitted into the main text. In each of these sections, there is an attempt to discuss additional results that bear on the theorems presented in the text. Sometimes these discussions contain terminology that is not defined in the text. Usually the terminology is standard. When in doubt, the reader should consult the appropriate reference.

We envision that this survey will be useful in a variety of ways. Those who want to study the Radon-Nikodým theorem and its relation to the topological and geometric structure of Banach spaces should read Chapters II, III, V and VII. Those who have an additional interest in applications of the Radon-Nikodým theorem may also want to look at Chapters IV, VI and VIII. Those who want to study measures of unbounded variation can read Chapter I, the first part of Chapter VI and Chapter IX. We have attempted to minimize the introduction of weighty terminology and notation. Thus it should be possible for someone who has not read the early chapter to be able to understand the content of a theorem in a late chapter with a minimum of frustration and page turning. We hope that this will make this survey useful for spot references.

The numbering of theorems is the same as in Dunford and Schwartz; thus Theorem V.2.6 is the sixth numbered item in the second section of the fifth chapter. Within the second section of the fifth chapter this theorem is referred to as Theorem 6; within the other sections of the fifth chapter this theorem is referred to as Theorem 2.6. Elsewhere it is referred to as V.2.6.

We hope our terminology is standard. To prevent any doubt let us fix some terminology. When we say that (Ω, Σ, μ) is a measure space, we mean that μ is an extended real-valued nonnegative countably additive measure defined on a σ-field Σ of subsets of a point set Ω. The triple (Ω, Σ, μ) is called a finite measure space if it is a measure space and $\mu(\Omega)$ is finite. A subset of a Banach space is called relatively norm (weakly) compact if its norm (weak) closure is norm (weakly) compact. A subset of a Banach space is called conditionally weakly compact if every sequence in it has a weakly Cauchy subsequence. If X and Y are Banach spaces, $\mathscr{L}(X, Y)$ stands for the space of bounded linear operators from X to Y; the space X contains a copy of Y if X has a subspace that is linearly homeomorphic to Y. There is one theorem that will be used from time to time and that may be unfamiliar to some readers. This is Stone's representation theorem which says that if $\mathscr{F}$ is a field of subsets of a point set Ω, then there is a compact Hausdorff space Ω_1, a field Σ_1 consisting of subsets of Ω_1 that are both closed and open, and there is a Boolean isomorphism between $\mathscr{F}$ and $\mathscr{F}_1$. The field $\mathscr{F}_1$ will be called the Stone representation algebra of $\mathscr{F}$.

Some readers may find some serious omissions in this survey. We deal with finite measure spaces only. Many of the theorems we present here have extensions to more general situations; some do not. When a theorem has an extension to more general situations, its extension is usually a routine extension. We feel that captur-

ing this extra bit of generality is not worth the space and its inclusion would obscure the exposition in a mass of trivial details.

Although we treat in detail the representation of operators on L_1, L_∞ and $C(\Omega)$, the representation of the general operator on L_p for $1 < p < \infty$ is conspicuously absent. Our reason for this is that we do not know any applications of this representation theory. However we do study some important classes of operators on L_p.

A third omission is the integration and differentiation theory for functions that are not norm (strongly) measurable. We are quick to admit that an extensive theory exists for such functions. We know of very few honest applications of this theory. Additional omissions include measures with values in linear topological spaces other than Banach spaces, orthogonally scattered measures, vector-valued stochastic processes (other than martingales) and the lifting theory for vector-valued functions. A very serious omission is most of the material found in the monograph of Igor Kluvanek and Greg Knowles (*Vector measures and control systems*, North-Holland, Amsterdam, 1976). Those who desire more material on the range of a vector measure than found in Chapter IX or who want to study infinite dimensional control theory should consult this spendid volume.

During the preparation of this survey, we have been helped immeasurably by a number of our colleagues who have freely contributed their advice and criticism. A partial list of those to whom we owe our heartfelt thanks is: R. G. Bartle, W. J. Davis, M. M. Day, L. Dor, G. A. Edgar, B. T. Faires, T. Figiel, J. Hagler, R. E. Huff, J. A. Johnson, W. B. Johnson, N. J. Kalton, R. Kaufman, I. Kluvanek, G. Knowles, D. R. Lewis, H. B. Maynard, P. D. Morris, T. J. Morrison, R. E. Olson, N. T. Peck, A. Pełczyński, A. L. Peressini, B. J. Pettis, R. R. Phelps, H. P. Rosenthal, E. Saab, C. J. Seifert, T. W. Starbird, F. E. Sullivan, J. B. Turett and A. Vento.

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As we progressed in the study of the history of the basic theorems of the theory of vector measures, we were not surprised by learning that most of them, in one way or another, have their origins in the fertile mind of one man, B. J. Pettis, who was kind enough to give us the benefit of his wisdom on many matters and to agree to write the foreword. To this mathematician and gentleman we dedicate our work.

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