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Measuring and Reasoning

In *Measuring and Reasoning*, Fred L. Bookstein examines the way ordinary arithmetic and numerical patterns are translated into scientific understanding, showing how the process relies on two carefully managed forms of argument:

- Abduction: the generation of new hypotheses to accord with findings that were surprising on previous hypotheses, and
- Consilience: the confirmation of numerical pattern claims by analogous findings at other levels of measurement.

These profound principles include an understanding of the role of arithmetic and, more importantly, of how numerical patterns found in one study can relate to numbers found in others. They are illustrated through numerous classic and contemporary examples arising in disciplines ranging from atomic physics through geosciences to social psychology.

The author goes on to teach core techniques of pattern analysis, including regression and correlation, normal distributions, and inference, and shows how these accord with abduction and consilience, first in the simple setting of one dependent variable and then in studies of image data for complex or interdependent systems. More than 200 figures and diagrams illuminate the text.

The book can be read with profit by any student of the empirical natural or social sciences and by anyone concerned with how scientists persuade those of us who are not scientists why we should credit the most important claims about scientific facts or theories.

Fred L. Bookstein is Professor of Morphometrics, Faculty of Life Sciences, University of Vienna, Austria; Professor of Statistics at the University of Washington, Seattle; and an emeritus Distinguished Research Professor at the University of Michigan. Since 1977 he has produced some 300 books, chapters, articles, and videotapes on various aspects of these methods and their applications in studies of normal and abnormal craniofacial growth in humans and other mammals, studies in the neuroanatomy and behavior of schizophrenia and fetal alcohol spectrum disorders, and evolutionary studies of hominids and ammonoids. He is especially interested in how statistical diagrams can convey the valid numerical patterns that characterize complicated systems like continental drift or fetal alcohol brain damage to the broad modern public. The figures in this book include many of his current favorites along these lines.

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Measuring and Reasoning

Numerical Inference in the Sciences

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For my daughters Victoria Bookstein and Amelia Bookstein Kyazze, who teach me how to work continually toward improving the world even while accommodating its constraints and ironies; and

for my grandsons Asher, Avi, and Keo and my granddaughter Yvette, although none of them can read yet, in hopes that they may be assigned a section or two of this when they get to college in 2027 or thereabouts; but mostly

for my dear wife Ede, who has encouraged me to meditate on these themes, and on the teaching of them, ever since the original seminars in our Ann Arbor living room 27 years ago. This book is the better for all your singing.

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Preface

For many years I have been concerned with the process by which scientists turn arithmetic into understanding. The word "process" here is meant in at least four different senses at the same time – algebraic, logical, cognitive, social. These correspond to at least four different disciplines that have hitherto considered parts of the puzzle in isolation, and so my arguments will jump back and forth among these four ways of speaking. There seems to be no standard name for this nexus in the literature of any of the fields that touch on it, and in the 20 or so years that I've been watching closely, as far as I know no popular book or scholarly monograph has appeared that focuses on these topics at any level. That this book has materialized in your lap in some copyrighted form (codex, Kindle, netbook, whatever) is evidence that editors and reviewers believe the gap to have been worth filling.

Before I was trying to consider these issues all together, I was trying to think them through separately. Over 35 years as a professional statistician and biometrician I have been employed to transform arithmetic into understanding in five main areas of scientific application: first, craniofacial biology, then gross neuroanatomy (the National Institutes of Health's "Human Brain Project"), then image-based anatomy of the whole organism (NIH's "Visible Human Project"), and, most recently, physical anthropology and organismal theoretical biology. Along the way there have been diversions: the science of fetal alcohol damage, analysis of war wounds to the heart, studies of hominid fossils. But I suspect nowadays that this material may be crucial to a broader range of applications than just those I've threaded it through personally. Likewise, the methodology seems richer and potentially more fruitful than any single scholar could oversee. It is time to weave the arguments together into a focused and coherent narrative capable of seeding further developments leveraging the efforts of others, not just me.

The volume you hold is not a scholarly monograph in the strict sense, an argument about one thing (a **mono**-graph), but instead an essay of somewhat experimental structure offering a set of core arguments drawn from interpretations of an idiosyncratic selection of main readings. This structure is different from all my earlier books but is in line with a spate of recent essays, for instance, Bookstein (2009a,b,c; 2013a,b),

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aimed at the less narrowly disciplinary reader. So the spirit of the expositions here is considerably less formal than the material being exposited. The first public presentations of these ideas outside of a classroom came at the conference "Measuring Biology" hosted by the Konrad Lorenz Institute for Evolution and Cognition Research, Altenberg, Austria, in 2008. (There is a review of the historical context of this conference in Appendix 2.B of Chapter 2.) Reactions of the people in the room to my argument were reassuring. Perhaps, I thought, the time had come to transport the argument out of its previous niche of course syllabus or colloquium presentations for delivery in the larger arena of printed dissemination, where a broader spectrum of colleagues and browsers might provide thoughtful, searching commentaries.

In this repackaged version the argument seems not to face much competition. It puzzles me that hardly any scholars pursuing social studies of science are looking at this arena. The formulas accompanying this topic are technically difficult from time to time, that is true, but never as hard as, say, philosophy of physics. Rather, they are *constructively* demanding in ways that only an insufficiently wise or overly strategic graduate student in science studies would choose to circumvent. It may also be the case that those aspects of science studies are most interesting to one's colleagues in science studies just where Nature or Clio is mumbling incomprehensibly, not, as in many of the examples here, where her message is clear and unequivocal. Still, whatever the reason, issues at the foundations of quantitative reasoning inhabit a true lacuna everywhere (except in the physical sciences, where things are too simple, owing to the miracle of exact laws).

In short, I think a book like this one is obviously needed, enough that I'm surprised nobody has written one before this. Readers of course decide things like this (the obviousness of the need, I mean) for themselves. For that frame of mind to be suitable, among its core stances should be one sketched effectively by University of Michigan philosopher Jack Meiland 30 years ago under the suggestively simplistic rubric of "college thinking." College thinking entails a constant concern for why one adopts the inferential heuristics and shortcuts one adopts: why one believes what one believes, why one reasons as one does, how one justifies one's own logical conclusions to oneself prior (it is hoped) to justifying them to others. In the area of "applied probability" this has been the concern of generations of cognitive scientists, with a Nobel Prize for one of them, Daniel Kahneman; but over here, where we deal with inferences about scientific claims rather than singular human decisions, there seems to be no matching literature at all.

At the core of scientific methodology have always lain concerns like these about the validity of empirical inferences. The subtype that is inference from *quantitative* data, our topic in this book, is easier to manage than the general case, yet serves to illustrate most of the themes from the broader context. Its study can never be begun too early, nor can students ever be trained to be too skeptical. Evidently the essential iconoclasm of topics like mine – the continual interruption of one's colleagues' arguments by the repeated challenge "Just *why* do you believe that that claim follows from your data, and how are the opposing or competing claims impeached?" – is ill-suited to the Intro. – Materials & Methods –Results – Discussion format of today's

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modal scientific article, as it requires threading across multiple exemplars. You don't win points from the anthropological reviewer, for instance, when you note that the way you are managing an inference in hominid evolution is exactly the same as the way somebody from the other side of campus handled an inference in the ecology of urban agriculture a couple of years back. Your reviewer cares only about anthropology, more's the pity. Then the issue of how numbers persuade independent of discipline is not a reasonable candidate for a peer-reviewed article in any of the disciplines so benefited. There remains mainly the possibility of a book-length argument like this one that claims citizenship in no field except its own. Compare Nassim Taleb's 2008 bestseller *The Black Swan,* likewise a book of applied quantitative reasoning (and likewise concerned with heuristics and their biases). I don't write as wittily as Taleb, whom I would like to meet some day, but the breadths of our nonoverlapping magisteria (his in finance and the madness of crowds, mine in the comparative natural sciences) seem to be commensurate.

This is not a book of "statistical methods," then, but instead a complement, or perhaps an antidote, to the whole shelfful of those. Most of the books on that shelf don't tell you where the numbers that are the objects of algebraic manipulation by the formulas there originated. Consider, for instance, the otherwise superb textbook *Statistics* by the late David Freedman and colleagues, the book we in Seattle use for our undergraduate service course – it never breathes a single hint about any of the rhetorics here at all. There are nevertheless some domains that, out of necessity or perhaps just by virtue of the vicissitudes of intellectual history, manifest a real concern for the empirical origin of the quantities on which further reasoning is based. The list of such fields includes epidemiology (Rothman et al., 2008), "multivariate calibration" (Martens and Næs, 1989), and observational astronomy (Harwit, 1981). In contrast, our topic is related only tangentially to a burgeoning scholarly literature on causation; see, for example, Pearl (2000/2009), who, like Freedman, pays remarkably little attention to the actual empirical origin of variables and their empirical information content.

My precursors are rather the great unclassifiable monographs about scientific reasoning as an intellectual or cognitive style: books such as Karl Pearson's *Grammar of Science* (1892/1911), E. T. Jaynes's posthumous *Probability Theory: The Logic of Science* of 2003, or, halfway in-between these, E. B. Wilson's *Introduction to Scientific Research,* still in print, from 1952. In its philosophy of science, though not its concern for arithmetic, my approach aligns well with that of Ziman (1978). Our topic has some ties to the "theory of knowledge" that is a component of today's International Baccalaureate curriculum for advanced high schools and Gymnasiums, and hence overlaps with the content of textbooks such as van de Lagemaat's *Theory of Knowledge for the IB Diploma* (2006). For multivariate analysis, a fundamental component of advanced protocols in this domain, W. J. Krzanowski's *Principles of Multivariate Analysis* of 1988 (revised edition, 2000) is a useful handbook. General biometrical discussions that show some awareness of these issues include two books by Richard Reyment (R. A. Reyment, *Multidimensional Palaeobiology,* 1991, and R. A. Reyment and K. G. Jöreskog, *Applied Factor Analysis in the Natural Sciences,*

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1993), *Model Selection and Multimodel Inference* by K. P. Burnham and D. R. Anderson (2002), Joseph Felsenstein's *Inferring Phylogenies* (2004), and my own *Morphometric Tools for Landmark Data* of 1991. But, in general, explicit discussions at adequate length of crucial issues in the rhetoric of quantitative inference are quite rare. Null-hypothesis statistical significance testing, by contrast, though appallingly widely known, is no kind of substitute argument at all, and is dismissed quite rudely throughout this volume, especially at Section L4.3.4, except for examples where the null is actually true.

The sociologist and methodologist Otis Dudley Duncan (1984), setting out a curriculum for applications of a similar rhetoric to a neighboring area, describes the strategy as one of "beads on a string . . . or perhaps nuts in a fruitcake." Regardless of the spatial/culinary metaphor, we can agree that our field is not "foundations of statistics," nor "foundations of metrology," nor philosophy of science per se. It is instead a collection of interrelated tropes, insights, and exemplars that I believe cumulate to an argument worth making independent of any intellectual or academic specialization. The text here does not require any subject-area knowledge by way of prerequisite. The puzzler page of *Saturday Review,* a once-popular American literary magazine, used to describe its most enthusiastic participants as having minds "well-furnished but not overstuffed," meaning widely read in the public arguments (mainly, but not entirely, political or aesthetic) of the past and present, but not pedantic on any single issue in particular; the same would apply to my intended reader. It would be helpful if you were sturdily independent of mind, at least outside of mathematics and physics, and if you had at least a mild curiosity for history of ideas and at least a modest acquaintance with some of the major ironies of philosophy of science as expressed in the 14 epigraphs to follow. A few of the examples in the book are practical enough that personal circumstances might be among the factors motivating a closer reading of these sections than others – sharing air with a smoker (Section 4.6), drinking alcohol during a pregnancy (Section 7.7), living in Seattle in an inadequately buttressed building (Section 3.3). Parts of this text will be within the reach of the good (meaning curious and open-minded, but also skeptical) high school student. Other fragments are appropriate for an undergraduate, and still others are appropriate as part of the catechism that is a doctoral dissertation defense. Few will find all of this easy going, but every reader should be able to follow the main line of argument at some level of engagement.

There are many diagrams here, some mine and some the original authors', some about facts and some about formulas. There are also many equations, perhaps more than some readers would like but none that are not mandated by the exposition in their vicinity. Part of my theme is that the formalisms of mathematics, even if they were your béte noire in the course of high school or college algebra or calculus, have by now become your friendly guide in exploring these domains of applied epistemology of science. A prior course in probability theory is not a disadvantage. A prior course in statistics probably *is* a disadvantage, as my views both contradict most of what you are likely to have been taught there and emphasize issues, like where measurements come from, that are not generally part of the syllabus of courses

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like those, but that end up framing those other syllabi in rather unfavorable terms. The better your grade in that introductory statistics course, the more you will need to unlearn.

The material here is flexible enough for more than one pedagogical context. I have used it as part of the core of a liberal arts education (College Honors program, University of Michigan, 1986–2004), as part of a graduate program in the life sciences (University of Vienna, from 2004 on), as part of an upperclass undergraduate course in linear modeling for applied mathematics and statistics majors (University of Washington, 2011), and as part of the freshman induction/indoctrination into the idea of college (University of Washington, 2007–2013). The graduate students work over the more advanced tools and the more complex examples of Part III along with discipline-customized versions of the forward-looking prophecies in Chapter 8. For American undergraduates, a semester's course on these principles can draw entirely from Chapters 1 through 4. Yet when Parts III and IV are included these same lectures and readings drive a sophisticated version of the same material at Vienna that challenges biology students right up through the predoctoral year.

Although I have never taught in a philosophy department, or in a science studies program for that matter, I suspect that the applied epistemology of numbers may likewise be a useful venue for introducing both the philosophy of science and the study of its social/cognitive aspects in general. Perhaps, in spite of what Platt avers (Section 3.4) about "mathematical" versus "logical" boxes, this is the tamest part of empirical scientific reasoning, the part that looks like physics in a particularly crucial cognitive aspect: it uses not the number line but real paper or real space as the sandbox for exploring forms of empirical understanding and modeling.

Thanks are due several institutions: the Honors College of the University of Michigan; the Faculty of Life Sciences of the University of Vienna; the Early Start Program of the College of Arts and Sciences at the University of Washington; Kanti Mardia's continuing Leeds Applied Statistical Workshop (which has listened with remarkable politeness to early versions of many of these ideas over the past decade); and the Konrad Lorenz Institute, Altenberg, Austria, along with its director, Gerd Müller. Still in Austria, I would like to thank Horst Seidler, currently Dean of the Faculty of Life Sciences, who in his previous role as Chair of the Department of Anthropology supported my early efforts to develop this material, both the epistemology and the morphometrics, into a curriculum with support from Austrian Federal Ministry of Science and Research project GZ200.093_I-VI_2004, "New Perspectives in Anthropological Studies." The examples from fetal alcohol science in Chapters 7 and 8 were supported by diverse grants from the erstwhile National Institute on Alcohol Abuse and Alcoholism (a division of the U.S. National Institutes of Health) to the Fetal Alcohol and Drug Unit (Ann Streissguth, founding director and principal investigator for most of the grants; Therese Grant, current director) in the Department of Psychiatry and Behavioral Sciences of the University of Washington. Major funding for presentations to one particularly diverse audience coalesced recently with the generous support of the European Union's Marie Curie program (Sixth European Framework Programme MRTMN-CT-2005-019564, "EVAN" [the European Virtual Anthropology

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Network], G. W. Weber, coordinator; F. Bookstein, task administrator). The work on random walks is supported at present by U.S. National Science Foundation grant DEB–1019583 to Joe Felsenstein and me.

I should acknowledge the 400 or so students who have taken my courses under titles like "Numbers and Reasons" over the quarter-century that these readings and their deconstructions have accrued. Beyond their ranks have been my audiences at the Konrad Lorenz Institute in 2006 and 2008, at the international meetings on Partial Least Squares PLS'07 (Ås, Norway) and PLS'09 (Beijing), at most of the annual conventions of the American Association of Physical Anthropology between 2000 and 2013, and at my Rohlf Medal Lecture at Stony Brook University on October 24, 2011. In encouraging me to pursue the work on Karl Pearson reported at the end of Chapter 7, English professor James Winn taught me a lot about close reading of texts the year I was Faculty Fellow at the Institute for the Humanities he directed at the University of Michigan before moving to Boston.

Warmest personal thanks are owed (and hereby offered) to Werner Callebaut, Katrin Schaefer, Verena Winiwarter, Philipp Mitteroecker, and Martin Fieder (all of Vienna); to Paul O'Higgins (York, UK); and to Michael Perlman, Joe Felsenstein, and Paul Sampson (Seattle) for the repeated discussions during which they negotiated the pedagogy and phrasing of much of this conceptual material with me. For innumerable conversations about numerical methods and methodologies, especially geometric morphometrics (the extended exemplar in Chapter 7), I am grateful to F. James Rohlf (Stony Brook University), Dennis Slice (Florida State University), Charles Oxnard (Western Australia and York), and Richard Reyment (Uppsala University, emeritus). For more than 20 years of endlessly patient software and hardware support I am deeply grateful to my long-term collaborator Bill Green of Bellingham, Washington, developer of `Edgewarp`.

I am grateful to all the authors and institutions who granted me permission to reproduce their graphical materials as part of this new text. To the best of our ability, specific acknowledgments according with the copyright owners' requirements are conveyed caption by caption.

The entire manuscript of this book was closely read in an earlier draft by my colleagues Clive Bowman (London, England) and Hermann Prossinger (Vienna, Austria), and it is far better by virtue of their efforts. I also thank three anonymous reviewers for the publisher and the gentle but principled editing of Lauren Cowles. Whatever solecisms, eccentricities, blunders, and gaps of logic or philosophy remain are, of course, entirely my own fault.

Many of the readings that underlie this syllabus were called to my attention by others. I'd welcome suggested additional or alternate readings and reinterpretations from any reader of this book. Please send your suggestions along with any other comments to `flbookst@uw.edu` or `fred.bookstein@univie.ac.at`.

Preparation of a "big book," even though a matter of a myriad of details over the year or so prior to publication, is otherwise a background task running over decades during which one's job is always to be doing something else. I am grateful for readers

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like you who are willing to foreground these thoughts, even for a little while. I hope that my text explains some things that you may have wondered about before, and points out other issues that you now wonder why you *didn't* wonder about before. In short, I hope these arguments of mine are worth the time you will spend letting them change the way you appreciate these remarkably widespread forms of scientific thinking.

Fred L. Bookstein
Vienna and Seattle, August 5, 2013

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Epigraphs

Here are collected a few wry aphorisms evoked from time to time in my main text. They appear to be fundamentally in agreement about how good science works, but they also highlight the risks involved.

1. It has been called the interocular traumatic test; you know what the data mean when the conclusion hits you between the eyes.
   – W. Edwards, H. Lindman, and L. J. Savage, 1963, p. 217

2. Trust in consilience is the foundation of the natural sciences.
   – E. O. Wilson, 1998, p. 11

3. I have sought knowledge. I have wished to understand the hearts of men. I have wished to know why the stars shine. And I have tried to apprehend the Pythagorean power by which numbers hold sway above the flux. A little of this, but not much, I have achieved.
   – Bertrand Russell, "What I Have Lived For,"
   prologue to his *Autobiography* (1967)

4. Science, no less than theology or philosophy, is the field for personal influence, for the creation of enthusiasm, and for the establishment of ideals of self-discipline and self-development. No man becomes great in science from the mere force of intellect, unguided and unaccompanied by what really amounts to moral force. Behind the intellectual capacity there is the devotion to truth, the deep sympathy with nature, and the determination to sacrifice all minor matters to one great end.
   – Karl Pearson, 1906, pp. 1–2

5. The enormous usefulness of mathematics in the natural sciences is something bordering on the mysterious, and there is no rational explanation for it. . . . It is not at all natural that 'laws of nature' exist, much less that man is able to discover them. . . . The miracle of the appropriateness of mathematics for the formulation of the laws of physics is a wonderful gift which we neither understand nor deserve.
   – Eugene Wigner, 1960, pp. 2, 5, 14

6. When you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind.
   – Sir William Thompson (Lord Kelvin), 1889,
   as cited by Kuhn (1961, p. 161)

7. The route from theory or law to measurement can almost never be travelled backwards. Numbers gathered without some knowledge of the regularity to be expected almost never speak for themselves. Almost certainly they remain just numbers.
   – Thomas Kuhn, 1961, pp. 174–175

8. Identical twins are much more similar than any microscopic sections from corresponding sites you can lay through either of them.
   – Paul Weiss, 1956,
   as quoted by Gerard (1958, p. 140)

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9. The first starting of a hypothesis and the entertaining of it, whether as a simple interrogation or with any degree of confidence, is an inferential step which I propose to call *abduction* [or *retroduction*]. I call all such inference by the peculiar name, *abduction*, because its legitimacy depends upon altogether different principles from those of other kinds of inference. The form of inference is this:
   - The surprising fact, C, is observed;
   - But if A were true, C would be a matter of course,
   - Hence, there is reason to suspect that A is true.

   – C. S. Peirce, 1903,
   as transcribed in Buchler, ed., 1940, p. 151

10. The time is past, if ever there was such a time, when you can just discover knowledge and turn it loose in the world and assume that you have done good.

    – Wendell Berry, 2000, p. 145

11. It is wrong, always, everywhere, and for anyone, to believe anything upon insufficient evidence.

    – William Kingdon Clifford, "The Ethics of Belief," 1877

12. The force of reason is a social force. . . . The problem of cognitive order *is* the problem of social order.

    David Bloor, 2011, pp. 3–4

13. But things got better. One day, a few months later, with a machine rattling off the results of a test I was trying to devise, I first felt the joy of being a scientist. Although I had not yet discovered anything, I realized that I had developed a reliable way to measure what I wanted to measure. Science consists largely of measurement. When the metaphorical ruler – what we call an assay – is in hand, results and happiness generally follow.

    Harold Varmus, 2009, p. 37

14. Die [wissenschaftliche] Tatsächlichkeit . . . liegt in einer solchen Lösung des Problems, die unter gegebenen Verhältnissen bei kleinster Denkwillkürlichkeit den stärksten Denkzwang bietet. Auf diese Weise stellt diese Tatsache ein stilgemäßes Aviso des Denkwiderstandes vor. Da das Trägertum des Denkstiles dem Denkkollektiv zukommt, können wir sie kurz als "denkkollektives Widerstandsaviso" bezeichnen.

    – Ludwik Fleck, 1935, p. 129

    In the standard translation:

    [Scientific] factuality . . . consists in just this kind of solution to the problem of minimizing thought caprice under given conditions while maximizing thought constraint. The fact thus represents a stylized signal of resistance in thinking. Because the thought style is carried by the thought collective, this "fact" can be designated in brief as the signal of resistance by the thought collective.

    – Ludwik Fleck, 1979, p. 98

    In other words, namely, mine,

14a. A scientific fact is a socially imposed constraint on speculative thought.

    – free précis/translation by the author

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