PROBABILITY AND FORENSIC EVIDENCE

This book addresses the role of statistics and probability in the evaluation of forensic evidence, including both theoretical issues and applications in legal contexts. It discusses what evidence is and how it can be quantified, how it should be understood, and how it is applied (and, sometimes, misapplied).

After laying out their philosophical position, the authors begin with a detailed study of the likelihood ratio. Following this grounding, they discuss applications of the likelihood ratio to forensic questions, in the abstract and in concrete cases. The analysis of DNA evidence in particular is treated in great detail. Later chapters concern Bayesian networks, frequentist approaches to evidence, the use of belief functions, and the thorny subject of database searches and familial searching. Finally, the authors provide commentary on various recommendation reports for forensic science.

Written to be accessible to a wide audience of applied mathematicians, forensic scientists, and scientifically-oriented legal scholars, this book is a must-read for all those interested in the mathematical and philosophical foundations of evidence and belief.

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Theory, Philosophy, and Applications

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Preface

Uncertainty is an unavoidable and essential ingredient of almost all applications of forensic science. Traces may carry information on who or what left them, by which activity they arose, and several other questions. In many cases there is no way to uniquely identify the only possible source or activity. This means that, while these forensic traces can reduce our uncertainty, they cannot be expected to eliminate it.

Probability theory and statistics are mathematical disciplines that are concerned with uncertainty in many different ways. It is, therefore, to be expected that probability theory and statistics are crucial for understanding the philosophy, theory, and practice of forensic science. This book offers an in-depth discussion about what the mathematical disciplines of probability theory and statistics can contribute to forensic science, and more specifically about the interpretation of evidence.

The diversity of the discipline of forensic science is reflected in the hugely varying nature of the subjects we treat in this book. On the one hand, there is a chapter discussing a number of concrete legal cases, and on the other hand there are chapters which are very theoretical in nature, and for which it is yet unclear whether or not their conclusions will in the future be relevant in the practice of forensic science. This is only natural. Any instance of applied mathematics can only be done in an idealized situation. If mathematics has anything to say about forensics, then it must do so with great care, realizing its limitations, and taking into account the inevitable gap between theory and practice.

At the same time, the applied mathematician should not be too modest either. Identifying correct ways of reasoning in the presence of uncertainty, for instance, is absolutely crucial for forensic science, and mathematics has a lot to say about this. Furthermore, although the details of a probabilistic model of a given situation may be somewhat unrealistic, probability theory will very often be able to draw general conclusions with many practical implications. Forensic science benefits a lot from mathematical and probabilistic modeling, but mathematics itself is also challenged by forensic science, leading to new concepts, ideas, and paradigms. Such interplay

between theory and practice has been a driving force for the development of mathematics over the centuries, and the particular discipline discussed in this book is no exception.

Apart from the daily practice and the theory of forensic science, philosophy plays a very important role in this book. Probability theory and statistics alike cannot be applied or even developed without reflection about their meaning and interpretation. For instance, if we want to make an assessment about the probability that a given suspect is the donor of a particular DNA profile, or is guilty of a certain crime, then we first must come to terms with the meaning of the word "probability" here. What exactly does such a probability mean? Similarly, we must decide which statistical paradigm is suitable for our purposes, which forces us to think about what statistical evidence really is.

Philosophy is so important that we feel that we need to start with it. One cannot use concepts that are not, in one way or another, well defined and explained. Apart from the opening chapter on philosophical issues concerning the interpretation of probability, statistics, and of forensic science itself, there are many chapters and sections in the book where philosophical issues are discussed and commented upon. For instance, the reader will find philosophical positions about statistical evidence in Chapters 2 and 3, about the nature of evidence in Chapter 3, about Bayesian networks in Chapter 6, about match probabilities in Chapter 7, about the concept of being a contributor to a DNA mixture in Chapter 8, about significance tests and p-values in Chapter 9, and about an extension of probability theory in Chapter 13.

We hope that the book is found interesting and useful for mathematicians, forensic scientists, and to some extent perhaps also for legal representatives, albeit probably in different ways. We have tried to introduce the basic concepts extensively at a calm pace, with many elementary, not necessarily forensic examples. We fully acknowledge though that there are chapters and sections that will be very demanding for non-mathematicians. Our advice to such readers is to simply skip these parts, and read the "Summary and conclusions" sections at the end of each chapter. We have tried to summarize the main findings in each chapter in an accessible way for a large audience. Of course, it will often not be possible to summarize the conclusions of a full chapter in, say, one page, but in any case the "Summary and conclusions" sections mention the concepts which have been studied and discussed. Hopefully they serve a purpose for those who do not read the full text. Many a conclusion can be understood in itself, without understanding the detailed mathematics leading to it.

This book is also particularly useful as a textbook for a course. We have used it ourselves for a full-semester course, "Forensic Probability and Statistics", taught at VU University, at the MSc level of mathematics. The collected set of exercises that we have made for this course can be obtained from the authors upon request.

To improve the readability of the text, we have mostly postponed bibliographical notes to the end of each chapter. Obviously, we have made use of ideas of many of our colleagues, but we found article-style referencing in the main text not so suitable for this book. Sometimes we deviate from this habit though, for instance when we use a quote from the literature, or when the historical development of a particular subject is important for the actual content. For instance, a discussion of the so-called database controversy in Chapter 11 would be virtually impossible without an account of the various positions held by a large number of researchers in the past. Our reference policy reflects the fact that we look at forensic science from a mathematical perspective. We have included references whenever we think that they are important for our message and our approach, or when certain concepts we use are further explained there. Obviously this means that our list of references is not to be considered a complete list for forensic science at large.

Next we explain the content and composition of the book. As mentioned before, we start with our philosophical position on probability, statistics, evidence, and forensic science. After that, in Chapter 2, we introduce and study the likelihood ratio in great detail. The likelihood ratio quantifies evidence for one hypothesis relative to another one, which we believe is the fundamental notion of statistical evidence. In Chapter 3 we further investigate the nature of the likelihood ratio, and we argue that a likelihood ratio is very different from a conventional statistical parameter. Indeed, we argue that it is an epistemic concept, an expression on our knowledge of the world, rather than an expression about the world itself.

After the first three chapters, the basis of our position and approach has been laid out, and we then continue with our first applications to forensic questions. First, we do that in idealized circumstances in Chapter 4, and after that we discuss applications to a number of concrete legal cases. The last chapter in this second block of three chapters is devoted to Bayesian networks, in order to investigate their usefulness in dealing with dependencies between various pieces of evidence.

In the next two chapters, we will follow a more specific forensic path, by discussing the mathematics of forensic DNA analysis in great detail.

In the two chapters to follow we compare the evidential interpretation of the likelihood ratio to more standard frequentist notions, like p-values and Neyman–Pearson theory. Our conclusions not only touch forensic science, but also have implications for statistical evidence at large. Frequentist notions can be useful if properly understood and interpreted, but we will find that they are not suitable for statistical evidential quantifications.

After that we move our attention to database searches and familial searching, a subject that has seen considerable debate and confusion. We also discuss belief functions and their applications in forensic science. Belief functions generalize probability distributions, and there are reasons why this is sometimes useful and

perhaps even necessary, since not all (lack of) knowledge can be properly described by probabilities. Finally, in the last chapter, we comment on six recommendation reports for various aspects of forensic science, and we investigate how the recommendations relate to the theory and philosophy as developed in the book.

This is not a book about technical statistical and probabilistic issues. We have tried to select those topics that we think will have lasting value, and of course we were also to some extent led by our own preferences. Concepts are more important for us than mathematical technicalities. Forensic science is a field with rapidly developing technical possibilities, and as such its needs will also change. But the concepts that we discuss in this book will remain valuable, we expect. Indeed, at all times we will need to think about what probability and statistics have to say about evidence, and this book addresses this question in great detail.

Most of this book was written during many visits of the authors to leisure park ‘n Kaps in Tubbergen, in the beautiful region of Twente in the east of the Netherlands. The park offers excellent working conditions, allowing for many hours of undisturbed, concentrated work.