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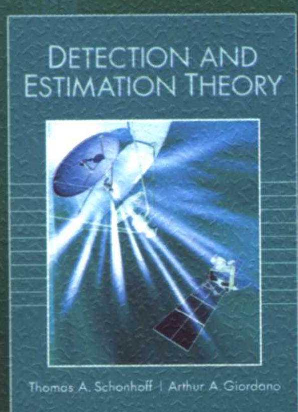
英文版

信号检测与估计
——理论与应用

Detection and Estimation
Theory and Its Applications



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信号检测与估计

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Detection and Estimation Theory and Its Applications

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Detection and Estimation

Theory and Its Applications

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Publishing House of Electronics Industry
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内容简介

信号检测与估计是研究在噪声、干扰和信号共存的环境中如何正确发现、辨别和测量信号的技术，广泛应用于雷达和无线通信等领域。本书详细讲解了信号检测与估计的理论知识与实践应用，共分为四个部分。第一部分概述后续章节需要用到的基础知识，第二部分讲述检测理论的基础概念，包括二元假设检验、备择假设检验、具有随机参量的复合假设检验及非参量检验等。第三部分介绍单参数和多参数的估值方法以及波形估计理论。第四部分介绍某些理论的特定应用。全书共19章，各章都附有大量例题和习题，并给出数个MATLAB计算机仿真实验，以加深读者对于抽象理论的理解，便于读者实践掌握。

本书可作为高等院校通信类、信息类、电子类和控制类等专业的研究生或高年级本科生的专业教材，也可作为相关科研人员的参考用书。

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序

2001年7月间，电子工业出版社的领导同志邀请各高校十几位通信领域方面的老师，商量引进国外教材问题。与会同志对出版社提出的计划十分赞同，大家认为，这对我国通信事业、特别是对高等院校通信学科的教学工作会很有好处。

教材建设是高校教学建设的主要内容之一。编写、出版一本好的教材，意味着开设了一门好的课程，甚至可能预示着一个崭新学科的诞生。20世纪40年代MIT林肯实验室出版的一套28本雷达丛书，对近代电子学科、特别是对雷达技术的推动作用，就是一个很好的例子。

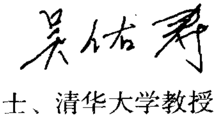
我国领导部门对教材建设一直非常重视。20世纪80年代，在原教委教材编审委员会的领导下，汇集了高等院校几百位富有教学经验的专家，编写、出版了一大批教材；很多院校还根据学校的特点和需要，陆续编写了大量的讲义和参考书。这些教材对高校的教学工作发挥了极好的作用。近年来，随着教学改革不断深入和科学技术的飞速进步，有的教材内容已比较陈旧、落后，难以适应教学的要求，特别是在电子学和通信技术发展神速、可以讲是日新月异的今天，如何适应这种情况，更是一个必须认真考虑的问题。解决这个问题，除了依靠高校的老师和专家撰写新的符合要求的教科书外，引进和出版一些国外优秀电子与通信教材，尤其是有选择地引进一批英文原版教材，是会有好处的。

一年多来，电子工业出版社为此做了很多工作。他们成立了一个“国外电子与通信教材系列”项目组，选派了富有经验的业务骨干负责有关工作，收集了230余种通信教材和参考书的详细资料，调来了100余种原版教材样书，依靠由20余位专家组成的出版委员会，从中精选了40多种，内容丰富，覆盖了电路理论与应用、信号与系统、数字信号处理、微电子、通信系统、电磁场与微波等方面，既可作为通信专业本科生和研究生的教学用书，也可作为有关专业人员的参考材料。此外，这批教材，有的翻译为中文，还有部分教材直接影印出版，以供教师用英语直接授课。希望这些教材的引进和出版对高校通信教学和教材改革能起一定作用。

在这里，我还要感谢参加工作的各位教授、专家、老师与参加翻译、编辑和出版的同志们。各位专家认真负责、严谨细致、不辞辛劳、不怕琐碎和精益求精的态度，充分体现了中国教育工作者和出版工作者的良好美德。

随着我国经济建设的发展和科学技术的不断进步，对高校教学工作会不断提出新的要求和希望。我想，无论如何，要做好引进国外教材的工作，一定要联系我国的实际。教材和学术专著不同，既要注意科学性、学术性，也要重视可读性，要深入浅出，便于读者自学；引进的教材要适应高校教学改革的需要，针对目前一些教材内容较为陈旧的问题，有目的地引进一些先进的和正在发展中的交叉学科的参考书；要与国内出版的教材相配套，安排好出版英文原版教材和翻译教材的比例。我们努力使这套教材能尽量满足上述要求，希望它们能放在学生们的课桌上，发挥一定的作用。

最后，预祝“国外电子与通信教材系列”项目取得成功，为我国电子与通信教学和通信产业的发展培土施肥。也恳切希望读者能对这些书籍的不足之处、特别是翻译中存在的问题，提出意见和建议，以便再版时更正。



中国工程院院士、清华大学教授

“国外电子与通信教材系列”出版委员会主任

出 版 说 明

进入21世纪以来，我国信息产业在生产和科研方面都大大加快了发展速度，并已成为国民经济发展的支柱产业之一。但是，与世界上其他信息产业发达的国家相比，我国在技术开发、教育培训等方面都还存在着较大的差距。特别是在加入WTO后的今天，我国信息产业面临着国外竞争对手的严峻挑战。

作为我国信息产业的专业科技出版社，我们始终关注着全球电子信息技术的发展方向，始终把引进国外优秀电子与通信信息技术教材和专业书籍放在我们工作的重要位置上。在2000年至2001年间，我社先后从世界著名出版公司引进出版了40余种教材，形成了一套“国外计算机科学教材系列”，在全国高校以及科研部门中受到了欢迎和好评，得到了计算机领域的广大教师与科研工作者的充分肯定。

引进和出版一些国外优秀电子与通信教材，尤其是有选择地引进一批英文原版教材，将有助于我国信息产业培养具有国际竞争能力的技术人才，也将有助于我国国内在电子与通信教学工作中掌握和跟踪国际发展水平。根据国内信息产业的现状、教育部《关于“十五”期间普通高等教育教材建设与改革的意见》的指示精神以及高等院校老师们反映的各种意见，我们决定引进“国外电子与通信教材系列”，并随后开展了大量准备工作。此次引进的国外电子与通信教材均来自国际著名出版商，其中影印教材约占一半。教材内容涉及的学科方向包括电路理论与应用、信号与系统、数字信号处理、微电子、通信系统、电磁场与微波等，其中既有本科专业课程教材，也有研究生课程教材，以适应不同院系、不同专业、不同层次的师生对教材的需求，广大师生可自由选择和自由组合使用。我们还将与国外出版商一起，陆续推出一些教材的教学支持资料，为授课教师提供帮助。

此外，“国外电子与通信教材系列”的引进和出版工作得到了教育部高等教育司的大力支持和帮助，其中的部分引进教材已通过“教育部高等学校电子信息科学与工程类专业教学指导委员会”的审核，并得到教育部高等教育司的批准，纳入了“教育部高等教育司推荐——国外优秀信息科学与技术系列教学用书”。

为做好该系列教材的翻译工作，我们聘请了清华大学、北京大学、北京邮电大学、南京邮电大学、东南大学、西安交通大学、天津大学、西安电子科技大学、电子科技大学、中山大学、哈尔滨工业大学、西南交通大学等著名高校的教授和骨干教师参与教材的翻译和审校工作。许多教授在国内电子与通信专业领域享有较高的声望，具有丰富的教学经验，他们的渊博学识从根本上保证了教材的翻译质量和专业学术方面的严格与准确。我们在此对他们的辛勤工作与贡献表示衷心的感谢。此外，对于编辑的选择，我们达到了专业对口；对于从英文原书中发现的错误，我们通过与作者联络、从网上下载勘误表等方式，逐一进行了修订；同时，我们对审校、排版、印制质量进行了严格把关。

今后，我们将进一步加强同各高校教师的密切关系，努力引进更多的国外优秀教材和教学参考书，为我国电子与通信教材达到世界先进水平而努力。由于我们对国内外电子与通信教育的发展仍存在一些认识上的不足，在选题、翻译、出版等方面的工作中还有许多需要改进的地方，恳请广大师生和读者提出批评及建议。

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Preface

Detection and estimation theory has an extensive history with numerous published journal references and textbooks. These subjects are inter-related but are typically treated in separate textbooks. In this textbook, detection and estimation theory are both addressed, allowing the reader to learn when detection theory applies and alternatively when estimation theory applies. Important applications of the theory illustrate where detection and estimation theory have been put to practical use. A common framework for both topics is established by first reviewing probability and communication concepts. Augmentation of the theory is accomplished via MATLAB® software[1] providing insight into theoretical topics both by introducing many worked examples and in presenting problem sets that permit the reader to gain a deeper understanding.

This textbook is designed for use in a graduate-level course in a communications curriculum or as a reference text for practicing engineers. In the presentation, a comprehensive unified theory of detection and estimation theory is developed. By addressing both detection and estimation theory in the same volume, the strong coupling and often blurring of these fields of study can be appreciated. In order to modernize classical topics, the textbook focuses on discrete signal processing with continuous signal presentations included to demonstrate uniformity and consistency of the results. The early chapters in the text present fundamental concepts in detection and estimation theory whereas later chapters treat specialized topics that illustrate the application of the previously developed general principles. These later chapters represent a small subset of topics extracted from a continually expanding universe of topics that could be investigated. The intent here is to provide the reader sufficient knowledge to enable further contributions to be made thereby advancing this field of study.

The MATLAB m-file and Simulink® routines[2]are constructed to enhance the learning experience and to demonstrate the practicality of the theoretical concepts. In the beginning of each m-file the input and output variables used along with pertinent comments are provided. Simulations are particularly helpful to produce performance results that are not analytically tractable. Prior knowledge of MATLAB is helpful but not essential. The MATLAB software developed by the authors includes both computational and simulation routines with specialized toolboxes avoided for simplicity. All of the required m-files and Simulink routines are available to the reader.

[1]MATLAB is a registered trademark of Mathworks, Inc.

[2]Simulink is a registered trademark of Mathworks, Inc.

The text is divided into four sections: Part I: Review chapters, Part II: Detection chapters, Part III: Estimation chapters and Part IV: Applications. A brief overview of each chapter is provided as follows.

PART I: REVIEW CHAPTERS

Chapters 1–3 establish a common framework for the rest of the text. These chapters summarize concepts that are extensively treated in other textbooks but are provided here to reacquaint the reader with these topics and introduce a consistent notation used throughout the text.

Chapter 1 provides a review of probability theory covering both discrete and continuous cases. Important subject matter includes random variables, moments, conditional probability distributions and probability density functions, statistical independence, characteristic functions, and functions of random variables and multiple random variables. Other topics essential in the treatment of detection and estimation theory include Bayes' theorem and Gaussian random variables. Computer generation of random variables with specific distributions using MATLAB represent a first step in analysis and simulation of more complex evaluations. To spur interest in estimation theory, an example of mean square error estimation concludes the chapter.

Chapter 2 extends the development of probability theory to stochastic processes. Concepts of stationarity and ergodicity are reviewed enabling the description of autocorrelation, cross-correlation, and power spectral density. Continuous and discrete time random signals are discussed along with the important case of white Gaussian noise. MATLAB examples are provided to supplement the theory.

Chapter 3 is a review of linear system theory involving stochastic processes. The sampling theorem establishes the connection between continuous and discrete random processes. The correspondence between baseband and bandpass signal representations for nonrandom and random signals is described where complex variables are required. The Karhunen–Loeve series expansion is presented to address the case of non-white noise. Finally, envelope statistics for noise alone and signal plus noise allows the computation of false alarm and detection probabilities.

PART II: DETECTION CHAPTERS

Chapters 4–9 present fundamental concepts in detection theory. Both single and multiple samples are discussed for the case where two alternative hypotheses exist. Later chapters expand the results to multiple hypotheses and to instances where the detected signals possess random parameters. The last chapter in this section introduces nonparametric detection.

Chapter 4 addresses the case of a binary hypothesis with single discrete samples. In the first part of this chapter specific detection criteria introduced includes maximum *a posteriori*, (MAP) maximum likelihood (ML) and Bayes. It is noted that the ML approach is a special case of MAP detection and the Bayes criteria introduces the concept of cost to the MAP approach. Additional criteria of minimax, Neyman–Pearson, and sequential detection are covered in later sections. The chapter concludes with an example that compares important detection theory criteria when the noise obeys a Gaussian distribution and when the noise follows a Poisson distribution.

Chapter 5 treats the situation where multiple samples are available in the two-hypothesis case. Examples of multiple measurements are discussed and a review of the detection criteria described in Chapter 4 is reexamined for the multiple sample case. This chapter then develops the optimum Bayes detector for a signal embedded in additive Gaussian noise. This detector is a correlator that compares the likelihood (or log-likelihood) to a threshold. For completeness, the extension to continuous signals in both white Gaussian noise and colored Gaussian noise is addressed next. Utilizing the optimum detector structure for binary signals in white Gaussian noise, the bit error rate performance for any general correlation, including both antipodal and orthogonal signaling, is computed. The chapter concludes with a discussion of a sequential detector and its performance.

In Chapter 6 it is assumed that optimum detector is sought for a received signal where, in general, the signal amplitude, phase, frequency, and time of arrival are unknown due to channel-introduced anomalies. Likelihood ratios and detector structures are developed assuming that the noise is complex Gaussian distributed and that various combinations of these unknown quantities occur. Bit error rate performance accompanies selected cases such as unknown phase, frequency and time of arrival. This chapter also illustrates an example, *via* Simulink, where the channel is nonlinear and the received phase is unknown.

Chapter 7 assumes that multiple pulses are utilized in the detection process. This situation is commonly found in radar applications and in selected communications cases. Once again, following the approach in Chapter 6, the received signal amplitude, phase, frequency, and time of arrival are, in general, unknown. The distinction in this chapter is that the multiple pulses are apt to arise from independent channels resulting in a received diversity that can be utilized in the detector. Detector structures are developed for both square law and linear combining. The pulse amplitudes may exhibit either Rayleigh or Rician fading.

Chapter 8 treats the case of multiple hypotheses. The detection criteria here are principally focused on the Bayes and MAP approaches with the last section of the chapter devoted to sequential detection. The concept of an erasure is introduced corresponding to the case where it is better to make no decision than an incorrect one. Error rate performance, obtained analytically in tractable cases and by Simulink otherwise, is provided for pulse amplitude modulation, frequency shift keying, and quadrature amplitude modulation, where the channel may be linear or nonlinear.

Nonparametric detection, described in Chapter 9, is mostly based on *ad hoc* tests. Common approaches include the sign test and the Wilcoxon test. Asymptotic relative efficiency is defined as a method of comparing detector performance. For Gaussian statistics the linear detector was previously shown to be optimum and is a common structure utilized here. The chapter concludes by mentioning a few additional nonparametric techniques.

PART III: ESTIMATION CHAPTERS

Chapters 10–14 present estimation theory. The relationship between estimation and detection theory is explained as follows: detection theory ordinarily involves a discrete set of hypotheses, such as signal present or not, whereas estimation theory typically attempts to estimate a parameter where the signal is assumed to be present. Estimation theory is based both on parametric and nonparametric methods. For parametric estimation, covered in Chapters 11 and 12, both parameter and waveform estimation techniques are described where the distributions of the observables may be known or unknown. Chapters 13 and 14 address the case of linear estimation where knowledge of the distributions is unavailable.

Chapter 10 presents fundamental topics in parametric estimation theory. Important properties of estimators including unbiasdness, consistency, invariance, sufficiency and minimum variance are described. The Cramer–Rao bound is developed to enable a bound on the minimum variance of the estimate to be ascertained. To provide a parallel approach to detection criteria methods, common estimation techniques such as Bayes, MAP, and ML methods are discussed. It is explained that Bayes estimation requires the largest amount of information, using a cost function, and ML estimation requires the least amount of information. Selecting a cost function in Bayes estimation that is the square of the difference between the parameter and its estimate results in a mean square error estimate. The chapter concludes with a performance comparison of common estimators.

Estimation of specific parameters such as amplitude, phase, time of arrival, and frequency, corresponding to similar topics in Chapter 6, are discussed in Chapter 11. The noise is commonly assumed to be Gaussian but is not required to be white. Invoking the Karhunen–Loeve expansion to produce a set of uncorrelated data samples develops the non-white Gaussian case. Emphasis is placed on MAP and ML methods with computation of the Cramer–Rao bound. Simultaneous parameter estimation and the Fisher information matrix, which is a generalization of the Cramer–Rao bound, are presented. The chapter concludes with a discussion of the Whittle approximation used when the exact log-likelihood is not obtainable but a good approximation, often referred to as the asymptotic ML estimate, can be found.

In Chapter 12 the single parameter estimation problem is extended to the case of multiple parameters. MAP and ML estimates are computed by use of a discrete linear observation model based on the parameters to be estimated. For both the MAP and ML estimates it is found that the estimates are unbiased, each with a Fisher information matrix showing that the estimates also have minimum variance. The remaining sections address sequential estimation assuming white Gaussian noise and a more general case for Gaussian noise samples that are correlated. The sequential estimation cases are a simple version of a Kalman filter, where estimates are formed from each new observation and a prior estimate.

Chapter 13 presents Wiener filters and is the first chapter on distribution free estimation, where at most only second-order moments are known. Minimizing the mean square error between samples of the original signal and its estimate initially derives the Wiener filter. The general solution for the discrete Wiener filter coefficients is shown to be the normal equations. These equations indicate the relationship in terms of the Wiener filter coefficients, the autocorrelation of the measurements, and the crosscorrelation of the measured and desired signals. The orthogonality principle is presented to provide a geometric interpretation of the minimization procedure and is used to simplify the minimization computations. Autoregressive techniques are discussed where the current measurement estimate is determined from a weighted linear combination of a finite set of prior measurements. Waveform estimation in the continuous case formed from mean square error computations is shown to result in the Wiener–Hopf equations. Both a direct solution and a whitened filter approach are developed.

Chapter 14 presents the Kalman recursive estimation algorithm. This algorithm provides an unbiased, minimum error variance recursive estimator for nonstationary signals and noise. Linear least squares and weighted least squares methods are presented first to allow progressively more complicated schemes developed later as Kalman recursive estimation and Kalman recursive estimation based on a system dynamic model. In the Kalman algorithm the filter coefficients are recursively computed in terms of the Kalman gain and in conjunction with recursive updates of the current and predicted error covariance matrices. A system dynamic model is then introduced and applied in the case of signal estimation *via* the Kalman algorithm. For completeness the continuous Kalman estimation algorithm is described and similar computations to the discrete case are given. The Kalman filter is known to be the optimum linear estimator for Gaussian signals and noise and the optimum linear mean square error estimator in non-Gaussian signals and noise. In the nonlinear case an extended Kalman filter is presented that is obtained by linearization around a previous state or signal. The chapter concludes with a description of ongoing research involving more general cases.

PART IV: APPLICATION CHAPTERS

Chapters 15–19 present specific applications and extensions of the theory developed to this point. Chapter 15 addresses detection and estimation in non-Gaussian noise. Chapter 16 describes spread spectrum signaling over fading, multipath channels such as those encountered in mobile communications. Multi-user detection where multiple users simultaneously utilize the communication resources is covered in Chapter 17. Chapter 18 introduces low probability of intercept communications using spread spectrum signaling. Chapter 19 presents classical and advanced spectral estimation procedures and algorithms.

Chapter 15 extends the classical and extensively analyzed Gaussian noise case to impulse or non-Gaussian noise prevalent in many physical channels such as the atmospheric radio noise channel. A variety of channel models developed from specific assumptions of the channel environment lead to amplitude probability distributions such as the Hall model, mixture model, Middleton Class A and B models, and empirical models. Unlike the Gaussian model, where the optimum detector is linear, the impulsive noise channel results in an optimum nonlinear detector such as the bandpass limiter and log-correlator. Bit error rate performance is computed for various combinations of channel models and detector structures. An important estimation problem involves the determination of the rms to average envelope value, which is a single parameter that characterizes impulsive noise channels.

Spread spectrum communications presented in Chapter 16 is a well-established communication technique used in numerous military and commercial communications systems such as the mobile communications system summarized in Appendix I. Spread spectrum methods such as direct sequence spreading are often required to operate in fading, multipath channels. The detector structures are more complex than the additive white Gaussian noise case and typically lead to implementations such as the Rake receiver that can utilize the additional information, thus improving error rate performance. Bit error rate performance for binary and M-ary orthogonal signals is obtained for receiver structures with known channel parameters that utilize the diversity in the presence of Rayleigh or Rician channel fading. When the channel parameters such as the amplitude or phase are unknown, noncoherent Rake receivers are developed in conjunction with bit error rate performance.

Chapter 17 addresses multi-user or multiple access communications involving large numbers of simultaneous users that produce multiple access interference. The early sections of this chapter describe code division multiple access, where the received signal may be received synchronously or asynchronously. In the asynchronous case various detector structures designed to mitigate the multiple access interference are presented. The receiver structures and associated performance are obtained for the decorrelating detector, a minimum mean square error detector, and the statistical decorrelator detector. The chapter closes with a discussion of coding theory and its impact on multi-user communications.

Low probability of intercept communications, discussed in Chapter 18, is presented with a view toward both the communicator and the interceptor. Detector structures that are considered include the energy detector, filter bank combiner, and the feature detector. For the energy detector, probabilities of detection and false alarm are computed parametric in post detection signal to noise ratio assuming either Gaussian or impulsive noise channel models. For the impulsive noise channel, the energy detector performance is obtained with and without a noise limiting nonlinearity.

Chapter 19 on spectrum estimation begins with a detailed discussion of classical periodogram techniques implemented by the fast Fourier transform. Data windowing options such as the Bartlett, Welch, and Blackman and Tukey methods are summarized, followed by a discussion of Capon's minimum variance estimation. Parametric spectral estimation techniques prevalent in speech and image processing include autoregressive, autoregressive moving average, and moving average spectral estimation. Eigenvalue-based methods involving an eigenvalue analysis of the autocorrelation matrix of the received signal embedded in noise are then introduced. Related methods then discussed include Pisarenko harmonic decomposition, multiple signal classification dubbed MUSIC, and minimum norm spectral estimation. The chapter ends with a comparison of power spectral estimation performance for commonly used techniques.

This book can be used in graduate classes once fundamental concepts summarized in the review chapters have been mastered. The material in Chapters 1–14 has been presented over 25 years in classes at Worcester Polytechnic Institute (WPI), with earlier draft forms of this text for the last 12 years. The application chapters are designed to demonstrate the depth and wealth of the subject matter. It is hoped that these chapters will spawn further reader interest available in the vast body of published literature.

For potential teachers of this subject, it might be of interest to know that when teaching this course at WPI, the first coauthor rearranges the chapters. Typically, Chapter 1 is assumed to be known by the students and is covered only with assigned problems. The first lecture immediately delves into detection theory with Chapter 4. Subsequently, Chapter 2 is quickly reviewed and then the subject of estimation theory in Chapter 10 is introduced. The author has found that alternating detection and estimation theory chapters enables students to more easily grasp those concepts that are common; it also ensures that one of the topics is not given short shrift by not being covered as completely as the other, a common problem when this subject is introduced in one semester.

After Chapter 10 is presented, the final review Chapter 3 is covered in more depth than the first two review chapters, and a return to detection theory in Chapter 5 is presented. The teacher usually stays with detection theory in Chapters 6 and 7 before returning to estimation theory in Chapters 11 and 12. All of these chapters are covered in some depth.

Detection theory is taken up again with Chapter 8. This chapter is important to fields such as communications, but since it offers relatively little to the detection theory story, it is covered in less depth and at a faster pace than the preceding lectures. Finally, the important but often ignored subject of nonparametric detection is introduced in Chapter 9.

The remainder of the semester is devoted to Wiener and Kalman filtering, presented in Chapters 13 and 14, respectively, as is practicable. Although this approach is certainly ambitious and challenging, it has been found that graduate students who are well-prepared in probability theory usually perform adequately. (This course has the deserved reputation of being one of the most difficult in the graduate program.)

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