A Modified Baum–Welch Algorithm for Hidden Markov Models with Multiple Observation Spaces

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***Abstract*—In this paper, we derive an algorithm similar to the well-known Baum–Welch algorithm for estimating the parameters of a hidden Markov model (HMM). The new algorithm allows the observation PDF of each state to be defined and estimated using a different feature set. We show that estimating parameters in this manner is equivalent to maximizing the likelihood function for the standard parameterization of the HMM defined on the input data space. The processor becomes optimal if the state-dependent feature sets are sufficient statistics to distinguish each state individually from a common state.**

***Index Terms*—Baum–Welch algorithm, class-specific, EM algorithm, expectation-maximization, Gaussian mixtures, hidden Markov model (HMM), parameter estimation, sufficient statistics.**

I. Introduction

THE class-specific method was recently developed as a method of dimensionality reduction in classification [1], [2]. Unlike other methods of dimension reduction, it is based on sufficient statistics and results in no *theoretical* loss of performance. Performance is always lost going from theory to practice due to (1) loss of information when reducing data to features, and (2) approximation of the theoretical feature PDFs. There is always a tradeoff between the desire to retain as much information as possible (by increasing the feature dimension) and the desire to obtain better PDF estimates (by decreasing the dimension). The class-specific method obtains a better compromise by allowing more information to be kept for a given maximum feature dimension. It does this by assigning a separate feature set to each class. Now we extend the idea further to the problem of HMM modeling when each state of the HMM may have its own approximate sufficient statistic.

II. Mathematical Results

We show in this section that the class-specific HMM is merely a different way to parameterize the likelihood function of the conventional HMM. Let $L(\mathbf{X};\lambda)$ be the likelihood function defined for the input data $\mathbf{X}$. A special class-specific likelihood function, $L^s(\mathbf{Z};\lambda^s)$ is defined using the class-specific (state-specific) statistics $\mathbf{Z}$. It is shown below that maximizing $L^s(\mathbf{Z};\lambda^s)$ over λ^s is equivalent to maximizing $L(\mathbf{X};\lambda)$ over λ with special constraints. While it is not necessary for $\mathbf{Z}$ to be sufficient for this to be true, the processor constructed from class-specific sufficient statistics will be optimal, provided there is no PDF estimation error.

A. Standard Parameterization and Notation

We consider a set of state occurrences $\boldsymbol{\theta} \triangleq \{q_1 \ldots q_T\}$ where $1 \le q_t \le N$. The sequence $\boldsymbol{\theta}$ is a realization of the Markov chain with state priors $\{\pi_j, j = 1,2 \ldots N\}$ and $N \times N$ state transition matrix $A = \{a_{ij}\}$. Rather than observing the states $\boldsymbol{\theta}$ directly, we observe the stochastic outputs $\mathbf{X} \triangleq \{\mathbf{x}_1, \mathbf{x}_2 \ldots \mathbf{x}_T\}$ which are realizations from a set of state PDFs

$$p_j(\mathbf{x}) \triangleq p(\mathbf{x}|H_j), \quad j = 1,2 \ldots N$$

where H_j is the condition that state j is true. We assume the observations are independent, thus

$$p(\mathbf{X}|\boldsymbol{\theta}) = \prod_{t=1}^{T} p_{q_t}(\mathbf{x}_t).$$

The complete set of parameters defining the HMM are

$$\lambda \triangleq [\{\pi_j\}, \{a_{ij}\}, \{p_j(\,)\}]$$

where $\sum_{j=1}^{N} \pi_j = 1$, $\sum_{j=1}^{N} a_{ij} = 1$. The likelihood function is the joint density of the observation sequence given the model parameters and is written (see [3, Eq. 17])

$$\begin{aligned} L(\mathbf{X};\lambda) \triangleq p(\mathbf{X};\lambda) &= \sum_{\boldsymbol{\theta}} p(\mathbf{x},\boldsymbol{\theta};\lambda) \\ &= \sum_{\boldsymbol{\theta}} \pi_{q_1} p_{q_1}(\mathbf{x}_1;\lambda) \prod_{t=2}^{T} a_{q_{t-1}q_t} p_{q_t}(\mathbf{x}_t;\lambda) \end{aligned} \tag{1}$$

where $\sum_{\boldsymbol{\theta}}$ is a summation over all possible state sequences of length T. The maximum likelihood (ML) estimate of λ is defined as

$$\hat{\lambda} \triangleq \arg\max_{\lambda} L(\mathbf{X};\lambda). \tag{2}$$

We use notation similar to Rabiner [3] with the exception that we represent state PDFs as $p_j(\cdot)$, and observations as $\mathbf{x}_t$. In the paper, functions beginning with the letters "b" and "p" always denote PDFs. The letter "b" is reserved for components of mixture PDFs and "p" is used for all other PDFs. The exception is any function carrying the superscript "s" which is *not* a PDF.

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Hidden Markov Models Baum Welch Algorithm

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Hidden Markov Models Baum Welch Algorithm:

Hidden Markov Models Robert J. Elliott,Lakhdar Aggoun,John B. Moore,1995 The authors begin with discrete time and discrete state spaces From there they proceed to cover continuous time and progress from linear models to nonlinear models and from completely known models to only partially known models **Hidden Markov Models and Dynamical Systems** Andrew M. Fraser,2008-01-01 This text provides an introduction to hidden Markov models HMMs for the dynamical systems community It is a valuable text for third or fourth year undergraduates studying engineering mathematics or science that includes work in probability linear algebra and differential equations The book presents algorithms for using HMMs and it explains the derivation of those algorithms It presents Kalman filtering as the extension to a continuous state space of a basic HMM algorithm The book concludes with an application to biomedical signals This text is distinctive for providing essential introductory material as well as presenting enough of the theory behind the basic algorithms so that the reader can use it as a guide to developing their own variants **Hidden Markov Models** Przemyslaw Dymarski,2011-04-19 Hidden Markov Models HMMs although known for decades have made a big career nowadays and are still in state of development This book presents theoretical issues and a variety of HMMs applications in speech recognition and synthesis medicine neurosciences computational biology bioinformatics seismology environment protection and engineering I hope that the reader will find this book useful and helpful for their own research **Hidden Markov Models in Finance and other Applications** Nguyet Nguyen,2026-03-17 This book provides fundamental concepts and algorithms of the Hidden Markov Model HMM and its applications in finance such as stock price predictions and other areas such as speech recognition Their wide range uses make HMMs very attractive to researchers in both academia and industry Only a basic knowledge of probability statistics and programming is necessary and readers will learn the concepts and algorithms of the HMM through definitions real life examples and R code Key Features A comprehensive introduction to the concepts and algorithms of Hidden Markov Models HMMs Real world examples that can be worked through using a calculator or R Applications across disciplines including finance bioinformatics and speech recognition Fully annotated R code for hands on learning and practical implementation

Hidden Markov Models and Applications Nizar Bouguila,Wentao Fan,Manar Amayri,2022-05-19 This book focuses on recent advances approaches theories and applications related Hidden Markov Models HMMs In particular the book presents recent inference frameworks and applications that consider HMMs The authors discuss challenging problems that exist when considering HMMs for a specific task or application such as estimation or selection etc The goal of this volume is to summarize the recent advances and modern approaches related to these problems The book also reports advances on classic but difficult problems in HMMs such as inference and feature selection and describes real world applications of HMMs from several domains The book pertains to researchers and graduate students who will gain a clear view of recent developments related to HMMs and their applications *Hidden Markov Model* Fouad Sabry,2023-07-01 What Is Hidden Markov Model A

hidden Markov model often known as an HMM is a type of statistical Markov model In an HMM the system being represented is considered to be a Markov process which we will refer to as it with states that cannot be observed thus the name hidden In order to fulfill one of the requirements for the definition of HMM there must be a measurable process whose results are influenced by those of another process in a certain way Since it is not possible to directly see the objective here is to learn about via observing HMM contains the additional criterion that the result of an event that occurs at a certain time must be influenced solely by the outcome of an event that occurs at that time and that the outcomes of an event that occurs at and at must be conditionally independent of at provided that it occurs at a particular time How You Will Benefit I Insights and validations about the following topics Chapter 1 Hidden Markov model Chapter 2 Markov chain Chapter 3 Viterbi algorithm Chapter 4 Expectation maximization algorithm Chapter 5 Baum Welch algorithm Chapter 6 Metropolis Hastings algorithm Chapter 7 Bayesian network Chapter 8 Gibbs sampling Chapter 9 Mixture model Chapter 10 Forward algorithm II Answering the public top questions about hidden markov model III Real world examples for the usage of hidden markov model in many fields Who This Book Is For Professionals undergraduate and graduate students enthusiasts hobbyists and those who want to go beyond basic knowledge or information for any kind of hidden markov model What is Artificial Intelligence Series The artificial intelligence book series provides comprehensive coverage in over 200 topics Each ebook covers a specific Artificial Intelligence topic in depth written by experts in the field The series aims to give readers a thorough understanding of the concepts techniques history and applications of artificial intelligence Topics covered include machine learning deep learning neural networks computer vision natural language processing robotics ethics and more The ebooks are written for professionals students and anyone interested in learning about the latest developments in this rapidly advancing field The artificial intelligence book series provides an in depth yet accessible exploration from the fundamental concepts to the state of the art research With over 200 volumes readers gain a thorough grounding in all aspects of Artificial Intelligence The ebooks are designed to build knowledge systematically with later volumes building on the foundations laid by earlier ones This comprehensive series is an indispensable resource for anyone seeking to develop expertise in artificial intelligence *Hidden Markov Models* João Paulo Coelho,Tatiana M. Pinho,José Boaventura-Cunha,2019-08-02 This book presents in an integrated form both the analysis and synthesis of three different types of hidden Markov models Unlike other books on the subject it is generic and does not focus on a specific theme e g speech processing Moreover it presents the translation of hidden Markov models concepts from the domain of formal mathematics into computer codes using MATLAB The unique feature of this book is that the theoretical concepts are first presented using an intuition based approach followed by the description of the fundamental algorithms behind hidden Markov models using MATLAB This approach by means of analysis followed by synthesis is suitable for those who want to study the subject using a more empirical approach Key Selling Points Presents a broad range of concepts related to Hidden Markov Models HMM from simple problems to advanced

theory Covers the analysis of both continuous and discrete Markov chains Discusses the translation of HMM concepts from the realm of formal mathematics into computer code Offers many examples to supplement mathematical notation when explaining new concepts **Data Mining, Southeast Asia Edition** Jiawei Han,Jian Pei,Micheline Kamber,2006-04-06 Our ability to generate and collect data has been increasing rapidly Not only are all of our business scientific and government transactions now computerized but the widespread use of digital cameras publication tools and bar codes also generate data On the collection side scanned text and image platforms satellite remote sensing systems and the World Wide Web have flooded us with a tremendous amount of data This explosive growth has generated an even more urgent need for new techniques and automated tools that can help us transform this data into useful information and knowledge Like the first edition voted the most popular data mining book by KD Nuggets readers this book explores concepts and techniques for the discovery of patterns hidden in large data sets focusing on issues relating to their feasibility usefulness effectiveness and scalability However since the publication of the first edition great progress has been made in the development of new data mining methods systems and applications This new edition substantially enhances the first edition and new chapters have been added to address recent developments on mining complex types of data including stream data sequence data graph structured data social network data and multi relational data A comprehensive practical look at the concepts and techniques you need to know to get the most out of real business data Updates that incorporate input from readers changes in the field and more material on statistics and machine learning Dozens of algorithms and implementation examples all in easily understood pseudo code and suitable for use in real world large scale data mining projects Complete classroom support for instructors at www mkp com datamining2e companion site *Intelligent Human Systems Integration 2019* Waldemar Karwowski,Tareq Ahram,2019-01-05 This book presents cutting edge research on innovative human systems integration and human machine interaction with an emphasis on artificial intelligence and automation as well as computational modeling and simulation It covers a wide range of applications in the area of design construction and operation of products systems and services including lifecycle development and human technology interaction The book describes advanced methodologies and tools for evaluating and improving interface usability new models and case studies and best practices in virtual augmented and mixed reality systems with a special focus on dynamic environments It also discusses various factors concerning the human user hardware and artificial intelligence software Based on the proceedings of the 2nd International Conference on Intelligent Human Systems Integration IHSI 2019 held on February 7 10 2019 in San Diego California USA the book also examines the forces that are currently shaping the nature of computing and cognitive systems such as the need to reduce hardware costs the importance of infusing intelligence and automation the trend toward hardware miniaturization and power reduction the need for a better assimilation of computation in the environment and social concerns regarding access to computers and systems for people with special needs It offers a timely survey and a practice oriented reference guide for

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