

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, $L^c(\mathbf{Z}; \lambda^c)$ is defined using the class-specific (state-specific) statistics \mathbf{Z} . It is shown below that maximizing $L^c(\mathbf{Z}; \lambda^c)$ over λ^c 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 $\theta \triangleq \{q_1 \dots q_T\}$ where $1 \leq q_t \leq N$. The sequence θ is a realization of the Markov chain with state priors $\{\pi_j, j = 1, 2, \dots, N\}$ and $N \times N$ state transition matrix $A = \{a_{ij}\}$. Rather than observing the states θ directly, we observe the stochastic outputs $\mathbf{X} \triangleq \{\mathbf{x}_1, \mathbf{x}_2, \dots, \mathbf{x}_T\}$ which are realizations from a set of state PDFs

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

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

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

The complete set of parameters defining the HMM are

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

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])

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

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

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

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

Hyun Soo Kim (M. Eng.)



Hidden Markov Models Baum Welch Algorithm:

Hidden Markov Models and Dynamical Systems Andrew M. Fraser, 2008-01-01 Presents algorithms for using HMMs and explains the derivation of those algorithms for the dynamical systems community

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 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

Hidden Markov Models: Applications In Computer Vision Horst Bunke, Terry Michael Caelli, 2001-06-04 Hidden Markov models HMMs originally emerged in the domain of speech recognition In recent years they have attracted growing interest in the area of computer vision as well This book is a collection of articles on new developments in the theory of HMMs and their application in computer vision It addresses topics such as handwriting recognition shape recognition face and gesture recognition tracking and image database retrieval This book is also published as a special issue of the International Journal of Pattern Recognition and Artificial Intelligence February 2001

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 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 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**

Models, Maximum Mutual Information Estimation, and the Speech Recognition Problem Yves Normandin,1991

Markov Models Source Wikipedia,2013-09 Please note that the content of this book primarily consists of articles available from Wikipedia or other free sources online Pages 90 Chapters Absorbing Markov chain Algorithmic composition Baum Welch algorithm Bernoulli scheme Burst error Dependability state model Detailed balance Discrete phase type distribution Dynamics of Markovian particles Dynamic Markov compression Entropy rate Examples of Markov chains Forward algorithm Forward backward algorithm Gene prediction GLIMMER Google matrix Hidden Markov model Iterative Viterbi decoding Kalman filter Language model Markovian discrimination Markov chain geostatistics Markov chain Monte Carlo Markov partition Markov property Markov switching multifractal Mark V Shaney Maximum entropy Markov model Models of DNA evolution Multiple sequence alignment PageRank Part of speech tagging Path dependence Population process Pop music automation Quantum Markov chain Queueing model Queueing theory Reinforcement learning Snakes and Ladders Soft output Viterbi algorithm Stochastic matrix Transiogram Variable order Bayesian network Variable order Markov model Excerpt The Kalman filter also known as linear quadratic estimation LQE is an algorithm that uses a series of measurements observed over time containing noise random variations and other inaccuracies and produces estimates of unknown variables that tend to be more precise than those based on a single measurement alone More formally the Kalman filter operates recursively on streams of noisy input data to produce a statistically optimal estimate of the underlying system state The filter is named for Rudolf Rudy E Kalman one of the primary developers of its theory The Kalman filter has numerous applications in technology A common application is for guidance navigation and control of vehicles particularly aircraft and spacecraft Furthermore the Kalman filter is a widely applied concept in time **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

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Markov Models for Pattern Recognition Gernot A. Fink, 2014-01-14 This thoroughly revised and expanded new edition now includes a more detailed treatment of the EM algorithm a description of an efficient approximate Viterbi training procedure a theoretical derivation of the perplexity measure and coverage of multi pass decoding based on n best search Supporting the discussion of the theoretical foundations of Markov modeling special emphasis is also placed on practical algorithmic solutions Features introduces the formal framework for Markov models covers the robust handling of probability quantities presents methods for the configuration of hidden Markov models for specific application areas describes important methods for efficient processing of Markov models and the adaptation of the models to different tasks examines algorithms for searching within the complex solution spaces that result from the joint application of Markov chain and hidden Markov models reviews key applications of Markov models

Incremental Learning of Discrete Hidden Markov Models German Florez-Larrahondo, 2005 We address the problem of learning

discrete hidden Markov models from very long sequences of observations Incremental versions of the Baum Welch algorithm that approximate the beta values used in the backward procedure are commonly used for this problem since their memory complexity is independent of the sequence length However traditional approaches have two main disadvantages the approximation of the beta values deviates far from the real values and the learning algorithm requires previous knowledge of the topology of the model This dissertation describes a new incremental Baum Welch algorithm with a novel backward procedure that improves the approximation of the values based on a one step lookahead in the training sequence and investigates heuristics to prune unnecessary states from an initial complex model Two new approaches for pruning greedy and controlled are introduced and a novel method for identification of ill conditioned models is presented Incremental learning of multiple independent observations is also investigated We justify the new approaches analytically and report empirical results that show they converge faster than the traditional Baum Welch algorithm using fewer computer resources Furthermore we demonstrate that the new learning algorithms converge faster than the previous incremental approaches and can be used to perform online learning of high quality models useful for classification tasks Finally this dissertation explores the use of the new algorithms for anomaly detection in computer systems that improve our previous research work on detectors based on hidden Markov models integrated into real world monitoring systems of high performance computers

Incremental Learning of Discrete Hidden Markov Models ,2005 We address the problem of learning discrete hidden Markov models from very long sequences of observations Incremental versions of the Baum Welch algorithm that approximate the beta values used in the backward procedure are commonly used for this problem since their memory complexity is independent of the sequence length However traditional approaches have two main disadvantages the approximation of the beta values deviates far from the real values and the learning algorithm requires previous knowledge of the topology of the model This dissertation describes a new incremental Baum Welch algorithm with a novel backward procedure that improves the approximation of the values based on a one step lookahead in the training sequence and investigates heuristics to prune unnecessary states from an initial complex model Two new approaches for pruning greedy and controlled are introduced and a novel method for identification of ill conditioned models is presented Incremental learning of multiple independent observations is also investigated We justify the new approaches analytically and report empirical results that show they converge faster than the traditional Baum Welch algorithm using fewer computer resources Furthermore we demonstrate that the new learning algorithms converge faster than the previous incremental approaches and can be used to perform online learning of high quality models useful for classification tasks Finally this dissertation explores the use of the new algorithms for anomaly detection in computer systems that improve our previous research work on detectors based on hidden Markov models integrated into real world monitoring systems of high performance computers

Modelling, Computation and Optimization in Information Systems and Management Sciences Hoai An Le

Thi,Tao Pham Dinh,Ngoc Thanh Nguyen,2015-05-07 This proceedings set contains 85 selected full papers presented at the 3rd International Conference on Modelling Computation and Optimization in Information Systems and Management Sciences MCO 2015 held on May 11 13 2015 at Lorraine University France The present part II of the 2 volume set includes articles devoted to Data analysis and Data mining Heuristic Meta heuristic methods for operational research applications Optimization applied to surveillance and threat detection Maintenance and Scheduling Post Crises banking and eco finance modelling Transportation as well as Technologies and methods for multi stakeholder decision analysis in public settings

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 policy and decision makers human factors engineers systems developers and users alike

Measurement Technology and its Application Prasad Yarlagadda, Yun Hae Kim, 2012-12-13 Selected peer reviewed papers from the 2012 International Conference on Measurement Instrumentation and Automation ICMIA 2012 September 15 16 2012 Guangzhou China **2**

New Approaches for Learning HMMs Hyun Soo Kim (M. Eng.), 2010 Hidden Markov Models HMMs are ubiquitously used in applications such as speech recognition and gene prediction that involve inferring latent variables given observations For the past few decades the predominant technique used to infer these hidden variables has been the Baum Welch algorithm This thesis utilizes insights from two related fields The first insight is from Angluin's seminal paper on learning regular sets from queries and counterexamples which produces a simple and intuitive algorithm that efficiently learns deterministic finite automata The second insight follows from a careful analysis of the representation of HMMs as matrices and realizing that matrices hold deeper meaning than simply entities used to represent the HMMs This thesis takes Angluin's approach and nonnegative matrix factorization and applies them to learning HMMs Angluin's approach fails and the reasons are discussed The matrix factorization approach is successful allowing us to produce a novel method of learning HMMs The new method is combined with Baum Welch into a hybrid algorithm We evaluate the algorithm by comparing its performance in learning selected HMMs to the Baum Welch algorithm We empirically show that our algorithm is able to perform better than the Baum Welch algorithm for HMMs with at most six states that have dense output and transition matrices For these HMMs our algorithm is shown to perform 22 65% better on average by the Kullback Liebler measure

Theory of Continuous-State Hidden Markov Models and Hidden Gauss-Markov Models, 2001 A general theory of continuous state hidden Markov models is developed with continuous state analogs of the Baum Viterbi and Baum Welch algorithms formulated for this class of models The algorithms are specialized to models with linear Gaussian densities thereby unifying the theory of hidden Markov models and Kalman filters The Baum and Viterbi algorithms for Gaussian models are shown to be implemented by two different formulations of the fixed interval Kalman smoother Moreover the measurement likelihoods obtained from the forward pass of the Baum algorithm and from the Kalman filter Innovation sequence are found to be equivalent A direct link between the Baum Welch algorithm and an existing expectation maximization algorithm for linear Gaussian models is demonstrated The general continuous state and Gaussian models are extended to incorporate mixture densities for the prior probability of the initial state For the Gaussian models a new expression for the cross covariance between time adjacent states is derived from the off diagonal block of the conditional joint covariance matrix and a parameter invariance structure

is observed when the system matrices are time invariant

Architectures, Languages, and Algorithms ,1989

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