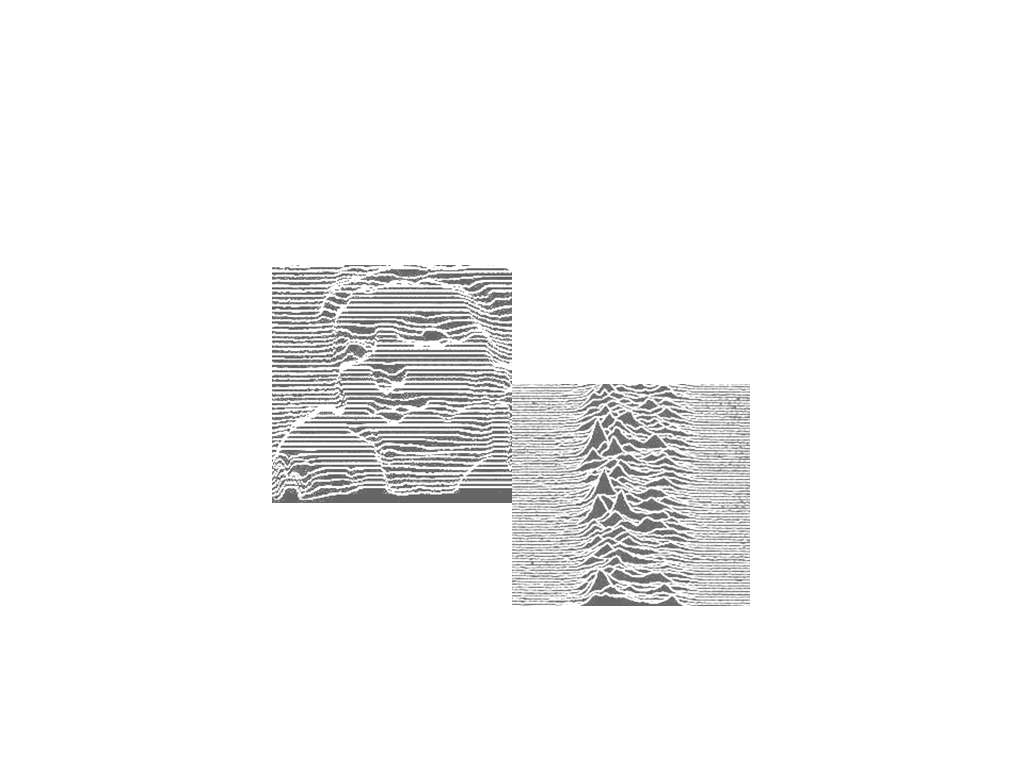
**Statistical**

**Optimization**

**in**



**Speech**

**Recognition**

**Joseph Picone**

**Statistical Optimization**

**in Speech Recognition**

Joseph Picone

Modern speech recognition systems are testaments to advances in machine learning as they optimize every aspect of the system using statistically-based learning algorithms. Optimization has allowed this technology to achieve unprecedented levels of performance. This book presents a unified view of this optimization, focusing on such techniques as expectation-maximization, hidden Markov modeling and discriminative training. Theory is presented in a clear and straightforward manner, so readers can easily access and apply the material.

Joseph Picone has conducted research in the field of speech processing for more than 25 years in the industrial, academic and government sectors. He founded the Institute for Signal and Information Processing which is well-known for producing public domain speech and signal processing technology and providing innovative solutions over the Internet.

Statistical Optimization in  
Speech Recognition

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J. Picone, *Fundamentals of Speech Recognition*, 1998

J. Picone, *et al*., *Pattern Recognition in Java*, 1998

J. Picone, A. Ganapathiraju and J. Hamaker, *Risk Minimization in Speech Recognition*, 2003

J. Picone, *Statistical Optimization in Speech Recognition*, 2009

J. Picone, *Perspectives on Engineering Management*, 2010

**Statistical Optimization in** Joseph Picone

**Speech Recognition**

The ISIP Press

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**DEDICATION**

To Mary Ann, Mary Frances, and Ann Marie, for their love and sacrifices that allowed me to spend many years away from home chasing dreams

To Rafid, Scott, Rick, Paul, Julie, Aravind, Jon and many other ISIP members who contributed to this work and continue to motivate me to chase my dreams

To Demetrius, Walt, Joe, George, Raja, Jack, Barb, Joe, Mark and many other colleagues who helped me turn some of those dreams into reality

And to Jack for challenging me to dream about speech processing over a frozen cup of coffee in the middle of a cold Chicago winter many, many years ago…

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[Chapter 2 Features 9](#_Toc190239790)

[2.1. My Second ASR 9](#_Toc190239791)

[Chapter 3 Something Else 9](#_Toc190239792)

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Preface

Optimization has played an enormously significant role in speech processing, particularly speech recognition. Virtually all successful speech technology today, including speech compression for cellular phones, speech synthesis for interactive voice response systems, and, speech recognition, employ some form of an optimization algorithm rooted in statistics to estimate parameters. I was first introduced to optimization theory as a college student in the late 1970’s, when a minimum mean square error approach to parameter estimation was used to model the speech signal as a digital filter. The technique, known as linear prediction, offered the promise of making digital speech processing a reality, because it was computationally efficient as well as effective. There was great hope that this optimization process could uncover hidden structure in the signal, a critical requirement for pattern recognition applications such as speech recognition.

More powerful techniques were beginning to emerge at this time, but they exceeded the computational resources available to most researchers. As high-speed computing became cost-effective over the next decade, the field quickly advanced by exploiting optimization principles (more precisely data-driven supervised training) in every aspect of the speech problem. Today, modern speech recognition systems use tens of thousands of hours of speech data to train millions of parameters to achieve unprecedented levels of performance.

Speech has always been a good application…

It is the goal of this book to provide some perspective on these optimization techniques. This book is not intended to be a comprehensive treatment of modern speech recognition technology, because the field has become too vast to make that possible. State of the art systems draw heavily on many fields including linguistics, signal processing, and natural language processing, and involve hundreds of steps to train and adapt high performance models. A comprehensive textbook can only give a cursory treatment of the basics and cannot do justice to the many practical issues that must be dealt with to achieve success.

Instead, this book focuses on a single theme, optimization, and discusses how this principle is applied to each major component of a speech recognition system. It is intended for those who are not familiar with speech recognition and can perhaps gain some knowledge that can be applied to other domains. It is also geared towards people new to the field who would like to gain some perspective on the evolution of the field. Optimization has been a recurring theme in the past 20 years. Significant amounts of research have focused on new parameter estimation techniques designed to minimize error rates.

Central to this book is the concept of hidden Markov modeling. This has been the driving force in speech recognition for the past 30 years. But it is the goal of this book to emphasize the optimization and robust parameter estimation aspects of this approach, not to focus on the details of how a state of the art speech recognition system is constructed using this approach.

Readers should be familiar with the basics of probability theory, information theory and pattern recognition. Whenever possible, we attempt to make the explanations and derivations self-contained so the book can server as a useful reference book. We also include, where appropriate, discussions of practical issues that are essential to realizing an effective implementation of an algorithm.

The book is organized into three sections. First, we discuss basic statistical optimization theory and introduce the basic components of a speech recognition system. ncepts of speech recognitionhow research directions are evolving

From the early days of LPC…

This book is designed to give a uniform treatment to the theory of optimization.

This book evolved from many years of experience teaching speech processing courses at the graduate level extending back to the mid-1980’s when our focus was more on dynamic programming and signal processing. One of the greatest influences on this book was the work done by a small, dedicated research group known as the Institute for Signal and Information Processing, which can be accessed from the URL *http://www.ece.msstate.edu/research/isip*. It was here we developed one of the first open source speech recognition systems, funded by the National Science Foundation and the Department of Defense. We also developed a wealth of educational materials, all available from the ISIP web site, that have been instrumental in formulating clear and concise ways to explain various aspects of the speech recognition problem. Many students have contributed to these materials over the years, and all deserve thanks for their hard work and excellent contributions. Many guests visited our lab, participated in our summer workshops, used our software, and gave us excellent feedback. Their feedback was also instrumental in understanding how to convey this material.

The second significant influence on this book was the pioneering research my colleagues Aravind Ganapathiraju and Jon Hamaker performed as graduate students at ISIP. Aravind’s work on Support Vector Machines laid the groundwork for the unified view presented here. Jon’s work on risk minimization provided a valuable perspective on Bayesian methods. They started the tradition of Philosophical Fridays – a time when anyone could get up on a soapbox as long as they brought the bagels and coffee.

Special thanks go to … for reviewing and commenting on this manuscript. I should also express a note of thanks to Microsoft for providing Word 2007, which made it possible to prepare this manuscript in a relatively straightforward manner. It only took about twice the amount of time it would have taken in Adobe Framemaker ☺

Joseph Picone

*Crawford, Mississippi*

*February 2008*

Three sections: philosophical ramblings, organization of the book, thanks.

How I can write a

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# Intro

This is a test…

## My First ASR

# Features

## My Second ASR

# Something Else

What is this book?

What is covered in the book?

This is the preface. I hope it is really good because it needs to be.

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