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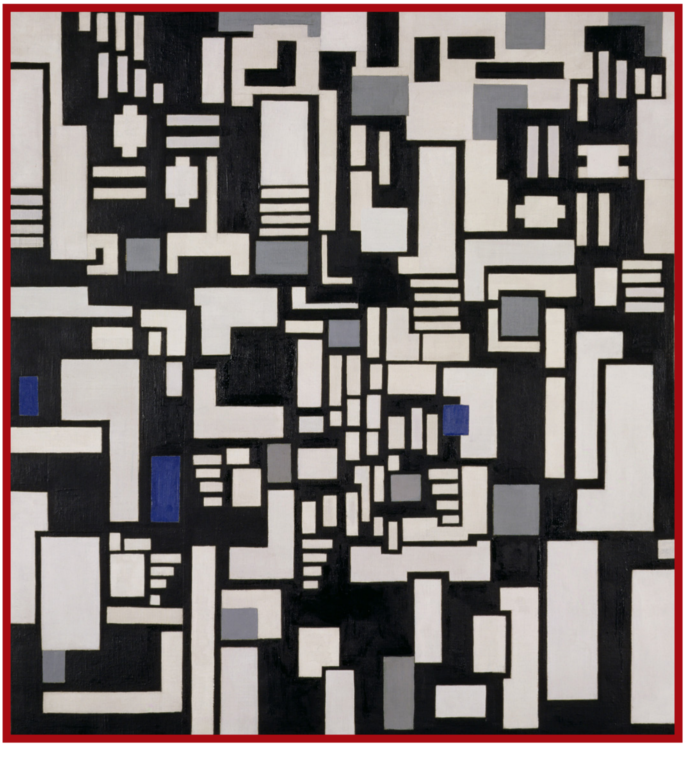

Edited by

Alexander Clark, Chris Fox, and Shalom Lappin

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For Camilla

לאחיי דוד ודניאל, ולאחותי נעמי באהבה ובהומור

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Martha Palmer is an Associate Professor in the Linguistics Department and the Computer Science Department of the University of Colorado at Boulder, as well as a Faculty Fellow of the Institute of Cognitive Science. She was formerly an Associate Professor in Computer and Information Sciences at the University of Pennsylvania. She has been actively involved in research in natural language processing and knowledge representation for 30 years and did her PhD in Artificial Intelligence at the University of Edinburgh in Scotland. She has a life-long interest in the use of semantic representations in natural language processing and is dedicated to the development of community-wide resources. She was the leader of the English, Chinese, and Korean PropBanks and the Pilot Arabic PropBank. She is now the PI for the Hindi/Urdu Treebank Project and is leading the English, Chinese, and Arabic sense-tagging and PropBanking efforts for the DARPA-GALE OntoNotes project. In addition to building state-of-the-art word-sense taggers and semantic role labelers, she and her students have also developed VerbNet, a public-domain rich lexical resource that can be used in conjunction with WordNet, and SemLink, a mapping from the PropBank generic arguments to the more fine-grained VerbNet semantic roles as well as to FrameNet Frame Elements. She is a past President of the Association for Computational Linguistics, and a past Chair of SIGHAN and SIGLEX, where she was instrumental in getting the Senseval/Semeval evaluations under way.

Ian Pratt-Hartmann studied Mathematics and Philosophy at Brasenose College, Oxford, and Philosophy at Princeton and Stanford Universities, gaining his PhD from Princeton in 1987. He is currently Senior Lecturer in the Department of Computer Science at the University of Manchester.

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Steve Renals received a BSc in Chemistry from the University of Sheffield in 1986, an MSc in Artificial Intelligence in 1987, and a PhD in Speech Recognition and Neural Networks in 1990, both from the University of Edinburgh. He is a Professor in the School of Informatics, University of Edinburgh, where he is the Director of the Centre for Speech Technology Research. From 1991 to 1992, he was a Postdoctoral Fellow at the International Computer Science Institute, Berkeley, CA, and was then an EPSRC Postdoctoral Fellow in Information Engineering at the University of Cambridge (1992–4). From 1994 to 2003, he was a Lecturer then Reader at the University of Sheffield, moving to the University of Edinburgh in 2003. His research interests are in the area of signal-based approaches to human communication, in particular speech recognition and machine learning approaches to modeling multi-modal data. He has over 150 publications in these areas.

Philip Resnik is an Associate Professor at the University of Maryland, College Park, with joint appointments in the Department of Linguistics and the Institute for Advanced Computer Studies. He completed his PhD in Computer and Information Science at the University of Pennsylvania in 1993. His research focuses on the integration of linguistic knowledge with data-driven statistical modeling, and he has done work in a variety of areas, including computational psycholinguistics, word-sense disambiguation, cross-language information retrieval, machine translation, and sentiment analysis.

Giorgio Satta received a PhD in Computer Science in 1990 from the University of Padua, Italy. He is currently a Full Professor at the Department of Information Engineering, University of Padua. His main research interests are in computational linguistics, mathematics of language and formal language theory.

For the years 2009–10 he is serving as Chair of the European Chapter of the Association for Computational Linguistics (EACL). He has joined the standing committee of the Formal Grammar conference (FG) and the editorial boards of the journals *Computational Linguistics*, *Grammars* and *Research on Language and Computation*. He has also served as Program Committee Chair for the Annual Meeting of the Association for Computational Linguistics (ACL) and for the International Workshop on Parsing Technologies (IWPT).

Helmut Schmid works as a Senior Scientist at the Institute for Natural Language Processing in Stuttgart with a focus on statistical methods for NLP. He developed a range of tools for tokenization, POS tagging, parsing, computational morphology, and statistical clustering, and he frequently used decision trees in his work.

Antal van den Bosch (MA, Tilburg University, The Netherlands, 1992; PhD, Computer Science, Universiteit Maastricht, The Netherlands, 1997) held Research Assistant positions at the experimental psychology labs of Tilburg University and the Université Libre de Bruxelles (Belgium) in 1993 and 1994. After his PhD project at the Universiteit Maastricht (1994–7), he returned to Tilburg University in 1997 as a postdoc researcher. In 1999 he was awarded a Royal Dutch Academy of Arts and Sciences fellowship, followed in 2001 and 2006 by two consecutively awarded Innovational Research funds of the Netherlands Organisation for Scientific Research. Tilburg University appointed him as Assistant Professor (2001), Associate Professor (2006), and Full Professor in Computational Linguistics and AI (2008). He is also a Guest Professor at the University of Antwerp (Belgium). He currently supervises five PhD students, and has graduated seven PhD students as co-supervisor. His research interests include memory-based natural language processing and modeling, machine translation, and proofing tools.

Prof. **Andy Way** obtained his BSc (Hons) in 1986, MSc in 1989, and PhD in 2001 from the University of Essex, Colchester, UK. From 1988 to 1991 he worked at the University of Essex, UK, on the Eurotra Machine Translation project. He joined Dublin City University (DCU) as a Lecturer in 1991 and was promoted to Senior Lecturer in 2001 and Associate Professor in 2006. He was a DCU Senior Albert College Fellow from 2002 to 2003, and has been an IBM Centers for Advanced Studies Scientist since 2003, and a Science Foundation Ireland Fellow since 2005. He has published over 160 peer-reviewed papers. He has been awarded grants totaling over €6.15 million since 2000, and over €6.6 million in total. He is the Centre for Next Generation Localisation co-ordinator for Integrated Language Technologies (ILT). He currently supervises eight students on PhD programs of study, all of whom are externally funded, and has in addition graduated 10 PhD and 11 MSc students. He is currently the Editor of the journal *Machine Translation*, President of the European Association for Machine Translation, and President-Elect of the International Association for Machine Translation.

Nick Webb is a Senior Research Scientist in the Institute for Informatics, Logics and Security Studies, at the University at Albany, SUNY, USA. Previously he was a Research Fellow in the Natural Language Processing Group at the University of Sheffield, UK, and a Research Officer at the University of Essex, UK, where he obtained a BSc in Computer Science (with a focus on Artificial Intelligence) and an MSc (in Computational Linguistics). His PhD from Sheffield concerns the analysis of dialogue corpora to build computational models of dialogue-act classification, and his research interests concern intelligent information access, including interactive question answering and dialogue systems.

Bonnie Webber was a Researcher at Bolt Beranek and Newman while working on the PhD she received from Harvard University in 1978. She then taught in the Department of Computer and Information Science at the University of Pennsylvania for 20 years before joining the School of Informatics at the University of Edinburgh. Known for research on discourse and on question answering, she is a Past President of the Association for Computational Linguistics, co-developer (with Aravind Joshi, Rashmi Prasad, Alan Lee, and Eleni Miltsakaki) of the Penn Discourse TreeBank, and co-editor (with Annie Zaenen and Martha Palmer) of the new electronic journal, *Linguistic Issues in Language Technology*.

Shuly Wintner is a Senior Lecturer at the Department of Computer Science, University of Haifa, Israel. His research spans various areas in computational linguistics, including formal grammars, morphology, syntax, development of language resources and machine translation, with a focus on Semitic languages. He has published over 60 scientific papers in computational linguistics. Dr Wintner is the Editor-in-Chief of the journal *Research in Language and Computation*.

Nianwen Xue is an Assistant Professor of Languages & Linguistics and Computer Science at Brandeis University. His research interests include syntactic and semantic parsing, machine translation, temporal representation and inference, Chinese-language processing, and linguistic annotation (Chinese Treebank, Chinese Proposition Bank, OntoNotes). He serves on the ACL SIGANN committee and co-organized the Linguistic Annotation Workshops (LAW II and LAW III) and the 2009 CoNLL Shared Task on Syntactic and Semantic Dependencies in Multiple Languages. He got his PhD in linguistics from the University of Delaware.

Preface

We started work on this handbook three years ago and, while bringing it to fruition has involved a great deal of work, we have enjoyed the process. We are grateful to our colleagues who have contributed chapters to the volume. Its quality is due to their labor and commitment. We appreciate the considerable time and effort that they have invested in making this venture a success. It has been a pleasure working with them.

We owe a debt of gratitude to our editors at Wiley-Blackwell, Danielle Descoteaux and Julia Kirk, for their unstinting support and encouragement throughout this project. We wish that all scientific-publishing projects were blessed with publishers of their professionalism and good nature.

Finally, we must thank our families for enduring the long period of time that we have been engaged in working on this volume. Their patience and good will has been a necessary ingredient for its completion.

The best part of compiling this handbook has been the opportunity that it has given each of us to observe in detail and in perspective the wonderful burst of creativity that has taken hold of our field in recent years.

Alexander Clark, Chris Fox, and Shalom Lappin
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Introduction

The field of computational linguistics (CL), together with its engineering domain of natural language processing (NLP), has exploded in recent years. It has developed rapidly from a relatively obscure adjunct of both AI and formal linguistics into a thriving scientific discipline. It has also become an important area of industrial development. The focus of research in CL and NLP has shifted over the past three decades from the study of small prototypes and theoretical models to robust learning and processing systems applied to large corpora. This handbook is intended to provide an introduction to the main areas of CL and NLP, and an overview of current work in these areas. It is designed as a reference and source text for graduate students and researchers from computer science, linguistics, psychology, philosophy, and mathematics who are interested in this area.

The volume is divided into four main parts. Part I contains chapters on the formal foundations of the discipline. Part II introduces the current methods that are employed in CL and NLP, and it divides into three subsections. The first section describes several influential approaches to Machine Learning (ML) and their application to NLP tasks. The second section presents work in the annotation of corpora. The last section addresses the problem of evaluating the performance of NLP systems. Part III of the handbook takes up the use of CL and NLP procedures within particular linguistic domains. Finally, Part IV discusses several leading engineering tasks to which these procedures are applied.

In Chapter 1 Shuly Wintner gives a detailed introductory account of the main concepts of formal language theory. This subdiscipline is one of the primary formal pillars of computational linguistics, and its results continue to shape theoretical and applied work. Wintner offers a remarkably clear guide through the classical language classes of the Chomsky hierarchy, and he exhibits the relations between these classes and the automata or grammars that generate (recognize) their members.

While formal language theory identifies classes of languages and their decidability (or lack of such), complexity theory studies the computational resources

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in time and space required to compute the elements of these classes. Ian Pratt-Hartmann introduces this central area of computer science in Chapter 2, and he takes up its significance for CL and NLP. He describes a series of important complexity results for several prominent language classes and NLP tasks. He also extends the treatment of complexity in CL/NLP from classical problems, like syntactic parsing, to the relatively unexplored area of computing sentence meaning and logical relations among sentences.

Statistical modeling has become one of the primary tools in CL and NLP for representing natural language properties and processes. In Chapter 3 Ciprian Chelba offers a clear and concise account of the basic concepts involved in the construction of statistical language models. He reviews probabilistic n-gram models and their relation to Markov systems. He defines and clarifies the notions of perplexity and entropy in terms of which the predictive power of a language model can be measured. Chelba compares n-gram models with structured language models generated by probabilistic context-free grammars, and he discusses their applications in several NLP tasks.

Part I concludes with Mark-Jan Nederhof and Giorgio Satta's discussion of the formal foundations of parsing in Chapter 4. They illustrate the problem of recognizing and representing syntactic structure with an examination of (non-lexicalized and lexicalized) context-free grammars (CFGs) and tabular (chart) parsing. They present several CFG parsing algorithms, and they consider probabilistic CFG parsing. They then extend their study to dependency grammar parsers and tree adjoining grammars (TAGs). The latter are mildly context sensitive, and so more formally powerful than CFGs. This chapter provides a solid introduction to the central theoretical concepts and results of a core CL domain.

Robert Malouf opens the first section of Part II with an examination of maximum entropy models in Chapter 5. These constitute an influential machine learning technique that involves minimizing the bias in a probability model for a set of events to the minimal set of constraints required to accommodate the data. Malouf gives a rigorous account of the formal properties of MaxEnt model selection, and exhibits its role in describing natural languages. He compares MaxEnt to support vector machines (SVMs), another ML technique, and he looks at its usefulness in part of speech tagging, parsing, and machine translation.

In Chapter 6 Walter Daelemans and Antal van den Bosch give a detailed overview of memory-based learning (MBL), an ML classification model that is widely used in NLP. MBL invokes a similarity measure to evaluate the distance between the feature vectors of stored training data and those of new events or entities in order to construct classification classes. It is a highly versatile and efficient learning framework that constitutes an alternative to statistical language modeling methods. Daelemans and van den Bosch consider modified and extended versions of MBL, and they review its application to a wide variety of NLP tasks. These include phonological and morphological analysis, part of speech tagging, shallow parsing, word disambiguation, phrasal chunking, named entity recognition, generation, machine translation, and dialogue-act recognition.

Helmut Schmid surveys decision trees in Chapter 7. These provide an efficient procedure for classifying data into descending binary branching subclasses, and they can be quickly induced from large data samples. Schmid points out that simple decision trees often exhibit instability because of their sensitivity to small changes in feature patterns of the data. He considers several modifications of decision trees that overcome this limitation, specifically bagging, boosting, and random forests. These methods combine sets of trees induced for a data set to achieve a more robust classifier. Schmid illustrates the application of decision trees to natural language tasks with discussions of grapheme conversion to phonemes, and POS tagging.

Alex Clark and Shalom Lappin characterize grammar induction as a problem in unsupervised learning in Chapter 8. They compare supervised and unsupervised grammar inference, from both engineering and cognitive perspectives. They consider the costs and benefits of both learning approaches as a way of solving NLP tasks. They conclude that, while supervised systems are currently more accurate than unsupervised ones, the latter will become increasingly influential because of the enormous investment in resources required to annotate corpora for training supervised classifiers. By contrast, large quantities of raw text are readily available online for unsupervised learning. In modeling human language acquisition, unsupervised grammar induction is a more appropriate framework, given that the primary linguistic data available to children is not annotated with sample classifications to be learned. Clark and Lappin discuss recent work in unsupervised POS tagging and grammar inference, and they observe that the most successful of these procedures are beginning to approach the performance levels achieved by state-of-the-art supervised taggers and parsers.

Neural networks are one of the earliest and most influential paradigms of machine learning. James B. Henderson concludes the first section of Part II with an overview in Chapter 9 of neural networks and their application to NLP problems. He considers multi-layered perceptrons (MLPs), which contain hidden units between their inputs and outputs, and recurrent MLPs, which have cyclic links to hidden units. These cyclic links allow the system to process unbounded sequences by storing copies of hidden unit states and feeding them back as input to units when they are processing successive positions in the sequence. In effect, they provide the system with a memory for processing sequences of inputs. Henderson shows how a neural network can be used to calculate probability values for its outputs. He also illustrates the application of neural networks to the tasks of generating statistical language models for a set of data, learning different sorts of syntactic parsing, and identifying semantic roles. He compares them to other machine learning methods and indicates certain equivalence relations that hold between neural networks and these methods.

In the second section (Chapter 10), Martha Palmer and Nianwen Xue address the central issue of corpus annotation. They compare alternative systems for marking corpora and propose clear criteria for achieving adequate results across distinct annotation tasks. They look at a number of important types of linguistic information that annotation encodes including, *inter alia*, POS tagging, deep and shallow syntactic parsing, coreference and anaphora relations, lexical meanings, semantic roles, temporal connections among propositions, logical entailments among propositions, and discourse structure. Palmer and Xue discuss the problems of securing reasonable levels of annotator agreement. They show how a sound and well-motivated annotation scheme is crucial for the success of supervised machine learning procedures in NLP, as well as for the rigorous evaluation of their performance.

Philip Resnik and Jimmy Lin conclude Part II with a discussion in the last section (Chapter 11) of methods for evaluating NLP systems. They consider both intrinsic evaluation of a procedure's performance for a specified task, and external assessment of its contribution to the quality of a larger engineering system in which it is a component. They present several ways to formulate precise quantitative metrics for grading the output of an NLP device, and they review testing sequences through which these metrics can be applied. They illustrate the issues of evaluation by considering in some detail what is involved in assessing systems for word-sense disambiguation and for question answering. This chapter extends and develops some of the concerns raised in the previous chapter on annotation. It also factors out and addresses evaluation problems that emerged in earlier chapters on the application of machine learning methods to NLP tasks.

Part III opens with Steve Renals and Thomas Hain's comprehensive account in chapter 12 of current work in automatic speech recognition (ASR). They observe that ASR plays a central role in NLP applications involving spoken language, including speech-to-speech translation, dictation, and spoken dialogue systems. Renals and Hain focus on the general task of transcribing natural conversational speech to text, and present the problem in terms of a statistical framework in which the problem of the speech recogniser is to find the most likely word sequence given the observed acoustics. The focus of the chapter is acoustic modeling based on hidden Markov models (HMMs) and Gaussian mixture models. In the first part of the chapter they develop the basic acoustic modeling framework that underlies current speech recognition systems, including refinements to include discriminative training and the adaptation to particular speakers using only small amounts of data. These components are drawn together in the description of a state-of-the-art system for the automatic transcription of multiparty meetings. The final part of the chapter discusses approaches that enable robustness for noisier or less constrained acoustic environments, the incorporation of multiple sources of knowledge, the development of sequence models that are richer than HMMs, and issues that arise when developing large-scale ASR systems.

In Chapter 13 Stephen Clark discusses statistical parsing as the probabilistic syntactic analysis of sentences in a corpus, through supervised learning. He traces the development of this area from generative parsing models to discriminative frameworks. Clark studies Collins' lexicalized probabilistic context-free grammars (PCFGs) as a particularly successful instance of these models. He examines the parsing algorithms, procedures for parse ranking, and methods for parse optimization that are commonly used in generative parse models like PCFG. Discriminative parsing does not model sentences, but provides a way of modeling