

**Colour Terms, Syntax and Bayes  
Modelling Acquisition and Evolution**

Mike Dowman

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School of Information Technologies,  
Faculty of Science,  
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Supervised by Associate Professor Judy Kay

# Colour Terms, Syntax and Bayes: Modelling Acquisition and Evolution

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## *Abstract*

This thesis investigates language acquisition and evolution, using the methodologies of Bayesian inference and expression-induction modelling, making specific reference to colour term typology, and syntactic acquisition. In order to test Berlin and Kay's (1969) hypothesis that the typological patterns observed in basic colour term systems are produced by a process of cultural evolution under the influence of universal aspects of human neurophysiology, an expression-induction model was created. Ten artificial people were simulated, each of which was a computational agent. These people could learn colour term denotations by generalizing from examples using Bayesian inference, and the resulting denotations had the prototype properties characteristic of basic colour terms. Conversations between these people, in which they learned from one-another, were simulated over several generations, and the languages emerging at the end of each simulation were investigated. The proportion of colour terms of each type correlated closely with the equivalent frequencies found in the World Colour Survey, and most of the emergent languages could be placed on one of the evolutionary trajectories proposed by Kay and Maffi (1999). The simulation therefore demonstrates how typological patterns can emerge as a result of learning biases acting over a period of time.

Further work applied the minimum description length form of Bayesian inference to modelling syntactic acquisition. The particular problem investigated was the acquisition of

the dative alternation in English. This alternation presents a learnability paradox, because only some verbs alternate, but children typically do not receive reliable evidence indicating which verbs do not participate in the alternation (Pinker, 1989). The model presented in this thesis took note of the frequency with which each verb occurred in each subcategorization, and so was able to infer which subcategorizations were conspicuously absent, and so presumably ungrammatical. Crucially, it also incorporated a measure of grammar complexity, and a preference for simpler grammars, so that more general grammars would be learned unless there was sufficient evidence to support the incorporation of some restriction. The model was able to learn the correct subcategorizations for both alternating and non-alternating verbs, and could generalise to allow novel verbs to appear in both constructions. When less data was observed, it also overgeneralized the alternation, which is a behaviour characteristic of children when they are learning verb subcategorizations. These results demonstrate that the dative alternation is learnable, and therefore that universal grammar may not be necessary to account for syntactic acquisition. Overall, these results suggest that the forms of languages may be determined to a much greater extent by learning, and by cumulative historical changes, than would be expected if the universal grammar hypothesis were correct.

# ***Preface***

The aim of this thesis is to show how linguistic phenomena which have been identified by other researchers can be explained. The results reported in this thesis were obtained by running simulations on computers, and comparing the outputs of these simulations to data reported in published sources. Therefore, the research involved no empirical data collection. This thesis attempts to provide explanations of a number of phenomena which have been identified as a result of empirical investigations, and subsequently reported in the literature. However, while this thesis contains discussions of many empirical findings, and of analyses of empirical data, it is not concerned with these analyses in themselves, or with the correctness of the data on which they are based. For example, much of this thesis relies heavily on Kay and Maffi's (1999) analysis of the data of the World Colour Survey, which is discussed in detail in section 2.1. Kay and Maffi's analysis remains controversial (Levinson, 2001), but I do not attempt to analyse the primary data myself. That would go beyond the scope of this thesis, so instead I simply tried to create a computer model which would account for the emergence of colour term systems corresponding to those which Kay and Maffi reported were attested in the World Colour Survey.

While criticisms have been made of Kay and Maffi's work (many of which are discussed in section 2.1 below), a wealth of empirical data supports their general conclusions. The basis of most of the criticisms seems to be that Kay and Maffi's

analysis does not take account of the full complexity of colour term systems, especially in that it excludes non-basic colour terms, and that it ignores the secondary connotations of basic colour terms. However, neither of those factors would seem to in any way invalidate the results which Kay and Maffi did report. Hence it would seem that, even if some of the details of Kay and Maffi's analyses turn out to be incorrect, that is unlikely to greatly affect the validity of the work presented in this thesis. Many other issues relating to this thesis remain controversial, such as exactly what neurophysiological mechanisms underlie colour vision, and whether the dative alternation can be explained in terms of semantic regularities. However, like with the controversies surrounding colour term typology, resolving these issues concerning empirical findings goes beyond the scope of this thesis. Further empirical findings may necessitate a revision of this work, but at present it is only possible to work on the basis of the results which have been published up to this point.

While the research for this thesis relied entirely on computer modelling, its actual subject matter lies within linguistics, and to some extent related disciplines such as psychology. Hence the thesis has been written so that it should be, as far as possible, understandable by a general linguistic audience. At the same time, I have tried to explicate linguistic terminology whenever possible, for the benefit of non-linguists. In general, where specific technical issues arise, I have tried to make them as accessible as possible, but a description of some aspects of the research necessitates the use of mathematical concepts and related notation which are likely to be unfamiliar to many readers interested in the subject matter of the thesis. This thesis makes considerable use of techniques from statistics and machine learning, in particular Bayesian inference and minimum description length. However, while some attempt is made to justify why these techniques were chosen, actually demonstrating why they are

effective machine learning techniques, or why, for example, Bayes' rule is correct, goes beyond the scope of this thesis. It can be said that, while this thesis uses machine learning, it is not about machine learning itself, and hence I have tried to restrict discussion of the machine learning literature to the minimum necessary.

All of the thesis is my own original work, except where explicit reference is made to other work. However, portions of the thesis have been published, and I have presented results at a number of conferences, and given some other talks. A full list of this research activity appears below (on all of which I am the sole author, except where noted otherwise). In general, the publications do not correspond exactly to particular parts of this thesis, but Chapter 9 is essentially an expanded version of the 2000 Cognitive Science Society conference paper, while parts of the other five papers are reproduced in Chapters 1 to 8.

## Publications

2003	Modeling Language as a Product of Learning and Social Interactions. <i>Cognitive Systems</i> , Volume 6, issue 1.
2003	Explaining Color Term Typology as the Product of Cultural Evolution using a Multi-agent Model. In <i>Proceedings of the Twenty-Fifth Annual Meeting of the Cognitive Science Society</i> . Cognitive Science Society.
2002	Modelling the Acquisition of Colour Words. In B. McKay and J. Slaney (eds.) <i>Advances in Artificial Intelligence</i> . Berlin: Springer-Verlag.
2001	A Bayesian Approach to Colour Term Semantics. <i>Lingu@scene</i> , Volume 1.
2001	<i>A Bayesian Approach to Colour Term Semantics</i> . Technical Report Number 528. Sydney: Basser Department of Computer Science, University of Sydney. (This is a more technical version of the lingu@scene paper above.)
2000	Addressing the Learnability of Verb Subcategorizations with Bayesian Inference. In Gleitman, L. R. & Joshi, A. K. (Eds.) <i>Proceedings of the Twenty-Second Annual Conference of the Cognitive Science Society</i> . Mahwah, New Jersey, USA: Lawrence Erlbaum Associates.

## Other Conference talks and presentations

2002	Modelling the Evolution of Basic Colour Terms. Talk given as part of the <i>Language in Time Symposium</i> , University of Western Australia, 25-27 June.
2002	A Bayesian Model of Colour Term Acquisition and Typology. Talk given at <i>Australian Linguistics Society Conference</i> , Macquarie University, Sydney, 13-14 July.
2002	Bayesian Learning of Linguistic Categories. Talk given at <i>European Society for the Study of Cognitive Systems Special Workshop on Multidisciplinary Aspects of Learning</i> , Paris, 17-19 January.
2002	<i>Explaining Language Typology using a Multiple Agent Model</i> . Talk given at Department of Computer Science and Software Engineering, University of Western Australia, 28 June.
2000	A Bayesian Model of Syntactic Acquisition. Talk given at <i>Australian Linguistics Society Conference</i> , University of Melbourne, 7-9 July.
2000	<i>Learning Verb Subcategorizations - A Case Study for the Acquisition of Syntax</i> . Departmental Seminar, Department of Linguistics, University of Sydney, 3 March.
1999	A Minimum Encoding Inference Approach to Theoretical Syntax. Talk given at <i>Australian Machine Learning Workshop</i> , Australian National University, Canberra, 22-23 November. Co-authored with Jon Patrick.
1999	Syntax: Accounting for Acquisition and Change. Talk given at <i>Postgraduate Students' Conference</i> , Department of Linguistics, University of Sydney, 23 September.

During the course of my Ph.D. I have received help from an awful lot of people, and I'd like to thank them all. Some people have helped me out with relevant literature, others have given me feedback on my papers or have had helpful discussions with me about my research. Others have just given me much needed encouragement along the way. I will probably will forget to mention some people who should be here, but I would like to thank Judy Akinbolu, Stephen Anthony, Brett Baker, Tony Belpaeme, Nils Bruin, Cassily Charles, Garry Cottrel, Gerhard Dalenoort, David Dowe, Mark Dras, Michelle Ellefson, Jeff Elman, Eva Endrey-Walder, Bill Foley, Alexander Francis, Roslyn Frank, Yukari Fujiwara, John Goldsmith, Paul Green-Armytage, Tom Griffiths, Joost van Hamel, Catherine Harris, Timo Honkela, Jim Hurford, Simon Kirby, Bill Labov, Johan Lammens, Darren Ler, Andrew Lum, Sinead Lyle, Rob MacLaury, Que Chi Luu, Chris Manning, Vladimir Novikov, Adam Blaxter Paliwala, Jon Patrick, Sam Pickering, David Powers, Hong Liang Qiao, Christine Rakvin, Jacqueline van der Schaaf, Jane Simpson, Kenny Smith, Josie Spongberg, Anders Steinvall, Kimie Takahashi, Tania Tsatralis. I have had three supervisors during the course of my Ph.D., but Judy Kay deserves special thanks as she has supervised most of it, and I probably would never have completed without her help. I should also give special thanks to Mark Ellison, who supervised my undergraduate dissertation (Dowman,1998), and without whom I probably would never have got interested in minimum description length, Bayesian inference, or any other form of computer modelling. And I could not have done some of the hard maths without the help of Emmanuel Letellier. Of course any errors or omissions remain my own responsibility (and I have not always taken all the advice I was given).

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