PARTHA NIYOGI, *The Computational Nature of Language Learning and Evolution.* Cambridge, MA: MIT Press, 2006. xviii + 458 pp.

Reviewed by JOSHUA BOWLES

In his second major book, Professor of Computer Science Partha Niyogi builds mathematically computational models intended to formally capture the intuitive notion that a child individually acquires a language while simultaneously belonging to a population of language learners who may, as a whole, change the paternal language in a principled and consistent fashion. The relation of individual to population in terms of language change is Professor Niyogi's broad concern. The book is organized into five sections with fourteen chapters divided between them. I will review them one by one.

Section I is titled "The Problem" and contains the introduction as chapter one. Here Niyogi sets up his general framework and goals: providing formal models to account for a number of interrelated phenomena including language acquisition, sociolinguistic variation in synchronic and diachronic studies, language change, the role of learning in language change, and the role of evolution. His intended audience, he says, ranges from the linguist, computer scientist, mathematician, evolutionary biologist, anthropologist, and social scientist. In the linguistic domain, Niyogi claims no allegiance to any particular theory within the generative-formalist approach (i.e. Lexical Functional Grammar, Head-driven Phrase Structure Grammar, Tree Adjoining Grammar, Optimality, Minimalist, or Connectionist). But it is clear that whatever grammar may be implemented in his models it must be formal. In an important respect this book is a mathematics book. To understand in detail Niyogi's models one needs at least some level of Calculus. Knowledge of Linear Algebra (i.e. vector spaces, matrices), Probability theory, and Artificial Intelligence would be extremely helpful. Some understanding of algorithm theory could not hurt either. Most linguists don't have this background but may have been introduced to mathematical or symbolic logic in various guises. I would venture that even an introductory understanding of set-theory gleaned from logic should be enough to get the determined reader through the book with a general sense of the author's methods and motivations.

Section II is titled "Language Learning and Acquisition." It contains chapters two, three, and four. Explicit to Niyogi's approach is the linguistic notion that language change in a population over time is reducible to, or at least co-related with, first language acquisition of that population's children members. That is, principled and consistent changes in a population's grammar/language may be explained by minor variations (parameterization) of a principled acquisition device of its members. An explanation for acquisition should result in an explanation for change. Chapter two is subtitled "The Problem of Inductive Inference" in which the author deals with the problems of acquiring knowledge of a grammar by inference over a range of variable primary linguistic data. Specifically, Niyogi gives a class of possible target languages, $Ł$, a class of possible target grammars, G, and a class of possible hypothesis languages constructed during exposure to sample sentences, H, all of which are constructed of various sets and subsets of languages: $L_t \in Ł$; hypotheses: $h \in H$; and sample sentences: $s_i \in L_t$. Thus the technical relation of grammars and languages is expressed as:

Ł = {L_g | g ∈ G }. This is followed by introducing a learning algorithm, A, which is an effective procedure by which L_t are chosen from ℍ by way of s_i (50-52). Using these as his theoretical primitives Niyogi goes on to analyze various theorems of learning such as Gold's theorem (1967) and the Vapnik-Chervonenkis (VC) theorem (1971). He develops a Probably Approximately Correct Model based on the VC theorem. He concludes the second chapter by stating that "successful language acquisition therefore must come about because of the constraints inherent in the interaction of the learning child with its linguistic environment" (82). Not a surprising conclusion but his formal method of reaching it is worth the journey.

In Chapter three the reader is given a linguistic treatment of the above analyses in terms of linguistic theory and psychological learning theory. Much of the chapter is devoted to analyzing the Triggering Learning Algorithm (TLA) within an account of the Principles & Parameters framework. Most interesting is Niyogi's successful use of Markov chain analysis of the TLA, thus giving good reason why the original argument against Markov chains in Chomsky (1957) should not be taken as dogmatic refusal to acknowledge their present value.

Chapter four covers "Memoryless Learning." Capitalizing on the Markov formalization of the TLA, Niyogi develops models that arise from using the TLA as the specifically chosen learning algorithm for A. He shows various results for convergence in the limit of infinity (i.e. convergence to a target grammar, or acquisition of the grammar, dependent on a variable number of sample sentences, s_i) and varieties of algorithms, distributional assumptions about the sample sentences, and possible parameterizations that pose conceptual problems to the logical problem of acquisition. For Niyogi, one of the major goals of this chapter is to investigate the following question: "[H]ow many examples does... the learning algorithm need in order to be able to identify the target grammar with high confidence" (144)? It is not enough to know, states Niyogi, that convergence in the limit can occur. One needs also to know how much time this convergence takes, and this equates to knowing the number of examples, or sample sentences of primary linguistic data, it takes the algorithm to reach identification. The answer to this is neither simple nor direct, but Niyogi provides ample inspiration, research, and reference to the sources of insight and techniques for future directions to the solution of child language acquisition.

While section II dealt with idealized homogenous parent-child interactions with a single grammar and the problem of inferring a language L_t of the target grammar ($g \in G$) based on a finite exposure to a set k of example sentences s_i, Section III, titled "Language Change," extends these notions from language acquisition and learning to language change. It adds substantial formal equipment in order to provide models that are less idealized and more realistic. Section III also provides many conceptual implications for the formal study of historical linguistics and gives multiple diachronic case studies. It contains chapters 5-10, making-up the bulk of the book.

Chapter five is subtitled "A Preliminary Model" and attempts to formally show what David Lightfoot (1979, 1991) informally argues for: "[That]...a model of language change emerges as a logical consequence of language acquisition [models in generative linguistics]" (Niyogi 2006:156). To this end Niyogi incorporates dynamic system approaches of linear and non-linear mathematics. The formal and informal analogy

motivating this direction to a dynamic systems approach is found in the assumed relationship between language change and evolution models: specifically the evolutionary dynamics of population biology. Such an analogy is nothing new, but Niyogi's formal applications certainly bring rigorous tools in which to explore with more precise detail some of the problematic issues of generative historical linguistics and he should be applauded his attempt, whatever the outcome.

In chapter five Niyogi first establishes a maturation rate for convergence to the target grammar based on psycholinguistic evidence of the "critical period" of language acquisition for individuals. Then by way of population dynamics provides models in which the adult population (i.e. the target grammar) is not homogenous. Children receive data from the whole population that reflects the distribution of two competing non-homogenous language populations, $P1$ and $P2$ (= $\{L_1, L_2\} \in Ł$), distributed evenly across the population of adults (164). Thus, the target grammar is evenly split and children receive an equal sample of data from both populations. Given this and a couple of idealized assumptions (such as populations are infinite) Niyogi applies three specific learning algorithms to derive three consequent systems: (i) memoryless learner via the TLA, (ii) batch error-based learner, and (iii) cue-based learner. Three separate models result from the application of (i-iii). He follows this with an attempt to ground the models in an example from the Yiddish change in AUX-V order from the 15th to 19th centuries. He concludes the chapter with two insights: (1) different learning algorithms might have different evolutionary consequences, and (2) "The evolutionary dynamics are typically nonlinear and the bifurcations (phase transitions) associated with them may provide a suitable theoretical construct to explain language change" (181).

Chapter six is an extension of the previous chapters, incorporating multiple languages, n, potentially present in the population at any given time (i.e. L_{n+1}). He includes a set of system states, $\mathcal{S}$, to his theory as well as an update rule that describes how the system-states change from one time-step to the next. Thus, one state, s, at time t, = s_t such that $(s_t \in \mathcal{S})$ and changes by way of a functional mapping, f, to s_{t+1} (189). Through a series of applications and variations on a three-parameter binary system, as well as a short application to Old French word order change with a five-parameter system, Niyogi essentially concludes that such analyses give us a formal view of historical linguistics; and that the class of constrained grammars G with a constrained class of learning algorithms A "can be reduced to a dynamical system whose evolution must be consistent with that of the true evolution of human languages" (230). That is, linguistic theories along with experimental psychological learning algorithms can be analyzed together as dynamical systems and applied and manipulated as models for language change. Such models may be falsified by the empirical data of comparative methods for historical language changes. In other words, theory must be tested against empirical data of conventional, non-formalist, historical linguistics.

Chapters seven and eight are concrete applications of the models developed previously to traditional historical linguistic problems for which non-controversial empirical data exists. In the interest of space I will combine my comments for both chapters. An application to cliticization in European Portuguese from 1800's to present day and an application to Chinese (Wenzhou Province) phonological merger make up the bulk of two the chapters. Both are strictly more mathematical than linguistic and Niyogi

has no illusions of the abstractness and incompleteness of his theory when applied to natural language data. He states, however, that his dynamical non-linear systems approach "allows us to work out the consequences of various assumptions about language and learning and demonstrates the falsifiability of the models constructed" (273). He does well in exemplifying the notion that no matter how sophisticated the mathematical models may be they do us no positive service unless they verify empirical facts (i.e. the empirical facts of comparative historical linguistics). To this end Niyogi does a superb job in showing how incomplete, or empirically unverifiable, models can help us revise formal assumptions about language theory and learnability by falsifying rigorously formulated hypotheses.

Chapter nine treats the individual as an agent within a cultural population. Niyogi continues with a specific model of neutral cultural evolution (Cavalli-Sforza and Feldman 1981) that has a similar mathematical treatment to his own. Cultural "parameters" transmitted from parents to children are given certain probabilities in which the mechanism of transmission is not known. What is known are the probabilities of acquiring only one of several variations of a cultural trait. Models from previous chapters are applied within the cultural model, extending the assumptions for distributions of linguistic data so that "neighborhoods" can be partitioned to reflect a more realistic distribution of adult language data to a "division of children into different classes that are different from each other" (283). The major result is that one is left with non-linear dynamic models as possible tools for explaining language change in terms of cultural transmission of information. However, many simplifying assumptions in these models are clearly falsified by empirical data from historical linguistics. However, the "neighborhoods" he constructs are nonetheless a step in a good direction for useful mathematical models in a formalized historical linguistics. Most importantly, Niyogi shows restraint in overly extending the analogy between linguistics, evolution theory, and culture that many other works on this topic have not.

Chapter ten, "Variations and Case Studies," takes the work of previous chapters 5-9 and synthesizes the major results while eliminating some previous assumptions, applying appropriate variations, and grounding his theory in concrete linguistic data. For a short example, populations of target grammars (adults) and language learners are now treated finitely. As a result, stochastic processes arise: for large or infinite N (where N = a generation of child learners) the proportion of L_1 (target grammar adult) speakers is normally (evenly) distributed. But for small values of N the population "inverts" to result in a skewed distribution, giving at some points in time mostly L_1 speakers and at other points mostly L_2 speakers. Niyogi states that "The general question [of population size] reduces to understanding the relation between the deterministic system (infinite population) and the corresponding stochastic process (finite population)" (313). Other issues he addresses in the chapter include spatial variation and dialect formation (i.e. changing a single or uniform source distribution for one target grammar to a multiple space model with neighborhoods), and multilingual learners (with primary linguistic data coming in a variety of well-formed sources so that competence is a distribution ranging over competing grammatical systems such that a probability measure over the class of possible grammars needs to be stipulated). Niyogi plays with these ideas in a disciplined and interesting fashion giving the reader plenty to think about both philosophically and

technically. His mathematical models and linguistic treatments are inconclusive and incomplete, and Niyogi says as much (337). His intention is clearly to give a possible outline of future research for the linguist by initially developing rigorous tools to aid in the work of historical linguistics. But it is obvious that such techniques cannot supplant more traditional methods in historical linguistics, though the formal tools found here can certainly become very useful.

Section IV, which contains chapters eleven through thirteen, is titled "The Origin of Language." This is the most speculative section of the book and one of the most speculative areas of linguistics and anthropology. The results are highly abstract and probably not applicable directly to historical linguistics. For example, if Niyogi admits that the theoretical models he constructs are generally in need of empirical data, then no such need can be met in this area because there is no empirical data for the origin of natural human languages. Niyogi himself recognizes the difficulty of origin questions because the "empirical facts that pertain to this matter are particularly hard to come by" (341). Nonetheless, he moves forward by developing further methods for measuring communicative efficiency (chapter 11), linguistic coherence (chapters 12, 13), communicative fitness (chapter 12), and social learning (chapter 13). These latter terms relate more to communication systems, information theory, and artificial intelligence than they do to linguistics. The results are intriguing and the mathematics involved. For the linguist, the single most important concept developed in this section has to do with the functional load of items in the lexicon/grammar in terms of communicative efficiency. If Niyogi's premises are correct, then he may have found a formal expression for the intuitive notion motivating much of the minimalist theory: that language is a perfect system, though not perfectly designed for communication purposes. Contra minimalism, functionalist theories operate on the assumption that grammars move towards, or are motivated by, the social need to communicate efficiently. But as Niyogi claims, "there is no significant correlation between functional load and confusability. The lexicon is therefore not optimally adjusted to our perceptual apparatus. The design of the lexicon compromises on its communicative efficiency" (371). Niyogi is claiming here that functionalist theories of grammar may be ill-conceived, but his statement is speculative at best on the singular phonological evidence he bases it on. As a system, a language may opt for an extreme amount of complexity in one particular area, making that aspect inefficient as a communication tool in order to maximize an overall communicative efficiency. These matters are controversial and just beginning to arise, specifically in Optimality Theory. The point here is that Niyogi provides a general theory for a formal system in which to investigate these kinds of questions and if the right kinds of data or evidence were available to us we may have powerful reasons for applying functional or formal approaches to linguistics based on the original communicative design of human language systems. The major result is that computational models of language acquisition may provide evidence for determining some aspects of how such an acquisition system came to evolve in the first place.

Section V contains chapter fourteen, which is the conclusion. Niyogi recaps the major insights of the book including language and learning, the use of dynamic systems approaches to account for language change via acquisition models, emergence of language, and the role of empirical validation of theoretical models. He outlines future areas of research and highlights again the connections to other disciplines.

The book is well written, rigorous, well organized, and methodical. Proofs of theorems are sound, as well as I can tell, and the typeset and symbols used are clear and readable. Overall, Partha Niyogi provides a wonderful and insightful look into the future of formal and computational linguistics, highlighting issues of research that should be around for years to come. He provides invaluable formal tools and his insights and instincts about difficult problems are inspiring and encouraging.

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