CONSTRAINT-BASED GRAMMAR FORMALISMS

PARSING AND TYPE INFERENCE FOR NATURAL AND COMPUTER LANGUAGES

STUART M. SHIEBER

Constraint-Based Grammar Formalisms

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To Linda Ann Sarnoff (1959–1988)

Strength. Wisdom. Beauty.

Contents

Preface

A wise man once said, "Fine words butter no parsnips." I didn't make this up; you can check in Bartlett's. I don't pretend to know what that means, but I have a sneaking suspicion that it applies to this document. Worse, I fear, as all writers of technical material must, that people will have the same quizzical reaction to this book that I have to the proverb. In any case, insofar as the ideas presented herein have any currency and consequence—butter any parsnips, I suppose—I owe a debt to a great many people.

The present volume is a revised version of a Ph.D. dissertation submitted in March, 1989 to the Computer Science Department at Stanford University. It has endured a long gestation period since Stan Rosenschein first introduced me to the design of natural-language grammar formalisms. Thereafter, an increasingly large number of individuals and institutions have participated in its etiology.

Barbara Grosz persuaded me, against my better judgment at the time, to return to school; Stan Rosenschein and Fernando Pereira applied significant pressure as well. At that point, the die was cast.

SRI International allowed me to undertake the responsibilities of a student while maintaining my job; Artificial Intelligence Center directors Nils Nilsson, Stan Rosenschein, and Ray Perrault have been primarily responsible for this enlightened policy. The Center for the Study of Language and Information, under the thoughtful guidance of, variously, John Perry, Jon Barwise, Tom Wasow, and Stanley Peters, made facilities of various sorts—including computers, office space, and time—available to me. These two institutions have provided a work environment unparalleled with respect to quantity and quality of resources and ideas, academic freedom, personal camaraderie, and good humor.

The most important enabling force, however, has been the minds I have had the privilege of working with over the years. From the original work on PATR with Stan Rosenschein to the brainstorming sessions designing PATR-II with the early PATR group (comprising at various times John Bear, Lauri Karttunen, Fernando Pereira, Jane Robinson, Stan Rosenschein, Susan Stucky, Mabry Tyson, and Hans Uszkoreit) to the later consolidation of results through the aegis of the Foundations of

Grammar group at CSLI (Mark Johnson, Ron Kaplan, Lauri Karttunen, Bob Kasper, Martin Kay, Fernando Pereira, Carl Pollard, Bill Rounds, Ivan Sag, Annie Zaenen, and numerous others), many people have directly influenced my ideas on the topic of this dissertation and have kept the study of the area exciting and fast-paced.

I have also benefited from the many insights of the members of the natural-language group in the AIC (Susan Hirsh, Jerry Hobbs, Paul Martin, Bob Moore, Barney Pell, and Martha Pollack, in addition to those mentioned elsewhere in the preface) and the users of early and recent PATR versions, including Jane Robinson, Kent Wittenburg, and Mary Dalrymple. Others who deserve thanks, though they may not realize why, include Leslie Kaelbling, Dikran Karagueuzian, Peter Ludlow, Stan Reifel, Hilary Sachs, Brian Smith, Sandy Wells, and the host and frequenters of Richard Waldinger's coffees.

However, the single person with the foremost impact on this dissertation, technically and otherwise, must be Fernando Pereira, who has throughout the ordeal acted as technical source, adviser, and friend. His invaluable guidance through innumerable well-placed suggestions and comments was a determining factor in any coherence this work enjoys, and his friendship allowed me to keep the effort in its proper perspective.

I am also obliged to all of my reading committee members, Terry Winograd, Fernando Pereira, Vaughan Pratt, and Gordon Plotkin, for seeing me through draft after draft with a minimum of angst. Their comments were much appreciated and gratefully incorporated. Terry Winograd, my principal advisor, made good on that designation through his counsel on the proper negotiation of departmental and university rules and practices. Fernando Pereira spent an extraordinary amount of time assiduously examining all of the proofs, thereby maintaining my integrity at a level far above its natural station. A debt of thanks is also owed the additional members of my oral-defense committee: Nils Nilsson and Stanley Peters, committee chair.

Savel Kliachko must, once again, be thanked for exemplary editing of the final version of the thesis. He agreed (none too reluctantly) to be dragged from his bucolic retirement to perform this one last editing task for me. My heartfelt appreciation goes to him.

The research reported herein was supported in part under contract with the Nippon Telegraph and Telephone Company and in part by a grant from the System Development Foundation to the Center for the

Study of Language and Information. I am indebted to the principal investigators of these two projects—Phil Cohen and Doug Appelt for the former, David Israel for the latter—for making these funds available. Final editing of the manuscript was supported in part by a Presidential Young Investigator award IRI-9157996 from the National Science Foundation.

The genesis of a dissertation reveals to the author the deep influences in his life. I am profoundly grateful to my family—to my parents for instilling in me an appreciation of the beauty of science, the power and limits of rational thought, and the importance of competence in all undertakings; to my brothers for providing exemplars thereof.

The predominant influence on my life over the seven-year genesis of this work as a Ph.D. dissertation, and for many years before, was Linda Sarnoff. After her tragic death in 1989, I was doubtful that the present work would ever be completed. The memory of her strength in the face of incomparable adversities provided the inspiration to finish. I will love her always.

1 Introduction

Over the last few years a new subfield of computational linguistics has emerged, as subfields do, spontaneously and with surprising speed. The rapidity with which work progresses in the initial stages of a field often leaves little time for careful foundational research. Such is the case with the approaches to computational linguistics that have been referred to as unification-based, information-based, or constraint-based.

Grammar formalisms from within this general approach have been proposed independently in linguistics, computational linguistics, and artificial-intelligence research as alternatives to previous formalisms in use in the respective areas. By utilizing declarative constructs that emphasize the modularization of information and its manipulation in the face of partiality, many technical problems in language description and computer manipulation of language can be solved.[1]

Intuition suggests that these various efforts from a broad range of disciplines form a natural methodological class; still, there is no general foundation on which to ground this impression. This book comprises an attempt to build some of the foundational understanding of this class of formalisms—from both a mathematical and a computational perspective. We address the following questions:

1. What are constraint-based grammar formalisms? How are they alike and how do they differ from other formalisms?
2. What are their general properties, computational and mathematical?
3. How can they be applied to the task of describing aspects of natural and computer languages? What do they tell us about the similarities and differences between the two language classes?

We characterize the class of formalisms by focusing on their particular use of *information* and *constraints* thereon as an organizing basis. (The formalisms are thus more aptly referred to as information- or constraint-based rather than unification-based, and we will do so here.) We define the underlying conception of information implicit in previous work by examining its desired properties. Primary among these are modularity, partiality, and equationality; these are codified in a class of logics of information, each of which bears syntactic reflexes of the important

[1] An overview of these results can be found in earlier work (Shieber, 1985b).

semantic intuitions. A specific instance of this class of logics, $\mathcal{L}_{L,C}$, is described.

In order to provide a concrete grounding for such logics, we consider appropriate semantics. By defining a set of properties of logical systems (that is, logic plus class of models together with an appropriate relation of satisfaction), we can compare the advantages and disadvantages of various choices of models, both existing and new. These properties have not only logical but also computational ramifications. The development of the logics including $\mathcal{L}_{L,C}$ and an examination of the properties of appropriate classes of models comprise Chapter 2.

Given a logical system with the requisite properties, we can define a grammar formalism based on logical constraints over information associated with phrases. The definition is quite abstract: any logical system of sufficient expressiveness satisfying the properties outlined in Chapter 2 will serve to define a formalism. It is this abstraction that justifies considering these methods as characterizing constraint-based formalisms in general, rather than an individual formalism.

Furthermore, so long as the models of the logic have some further quite strong computational properties, a general algorithm can be defined for parsing phrases with respect to a grammar in the constraint-based formalism. The construction of the algorithm and a proof of its correctness are given independently of the details of the logic upon which the formalism is based. A further abstraction in the definition of the algorithm makes the algorithm and its correctness proof independent of the control regime employed. Thus, at one stroke, a wide range of parsing algorithms are proved correct for any constraint-based formalism. Particular instances of the algorithm, including an incarnation as an extended Earley's algorithm and a simulation of LR parsing, are discussed. The latter is especially important because of its ties to psycholinguistic effects. The definition of grammar formalisms and their parsing algorithms takes up Chapter 3.

In Chapter 4 we return to the topic of appropriate classes of models for the constraint logics, and develop a series of possible classes of models for the logic $\mathcal{L}_{L,C}$, with an eye toward their utility for logical and computational purposes.

Finally, we turn to a more speculative topic: the relation between these techniques and those devised for characterizing computer languages. In so doing, we attempt to bring out more clearly the similarities and differences between the two classes of languages.

As a concrete example of the techniques described in Chapters 2 and 3, and as an application of those techniques to both natural and computer languages, we define a more expressive logic than $\mathcal{L}_{L,C}$, extending the equational constraints of $\mathcal{L}_{L,C}$ to encompass inequations; we provide a class of models for the logic and algorithms for computing with the models on the basis of the foundations built up in Chapter 4. The existence of the logic and its model structure with appropriate properties immediately gives rise to algorithms for interpreting grammars in the formalism constructed around the logic. Chapter 5 discusses the connections to computer languages and the inequality logic.

This work can be seen as an attempt to characterize the abstract notion of a constraint-based grammar formalism. The abstraction occurs along several dimensions. First, the constraint types on which such formalisms are built are characterized generally, as logics satisfying certain properties. Second, the models for the logics are characterized by their properties rather than by direct construction. Finally, the algorithms for manipulating phrases according to a grammar are characterized independently of the specifics of the formalism and of the choice of control regime. This abstract view of constraint-based grammar formalisms engenders a rigorous understanding not just of one attempt to characterize a particular natural language from a particular perspective, but rather of a broad class of techniques applicable to both natural and computer languages from both mathematical and computational perspectives.

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