TAKING SCOPE

The Natural Semantics of Quantifiers

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Preface

This book is about the syntax and semantics of quantifier-scope, in interaction with (among other constructions) negation, polarity, coordination, and pronominal binding. It does not consider the ramifications of intensional scope and "opacity," although I hope that the basic apparatus outlined here will be naturally extendable in that direction.

The semantics presented here is "surface-compositional," in the sense that there is a rule-to-rule relation between syntactic types and operations of composition on the one hand, and types and compositions at the level of logical form on the other. In that sense, the semantics is in the "natural logic"–based tradition of Aristotle, Leibniz, Frege, Russell, Carnap, Montague, Geach, Cresswell, Kamp, Karttunen, Partee, Dowty, Kratzer, Heim, Szabolcsi, Jacobson, and others, which seeks to define a psychologically real logic directly reflecting natural language grammar.

As Montague (1970b) points out, translation into a level of logical form is not strictly necessary: the syntax of object languages such as English can in principle be "directly interpreted" in terms of models or possible worlds. The present theory is not directly interpretational or surface-compositional in this strict sense. The level of logical form cannot entirely be dispensed with. In particular, it will become apparent in chapter 6 that the theory allows the language-specific syntactic order of combination of multiple arguments of a lexical head to differ from the presumably universally-determined order in which the corresponding logical arguments combine with the corresponding semantic predicate. It will also become apparent in chapter 7 that an operation of "Skolem term specification" is defined syntactically, at the level of logical form.

These minor departures from the strictest form of direct compositionality greatly simplify the notation, and mean that the theory, like that of Jacobson (1999), is surface-compositional “by construction” (Barker and Jacobson 2007, 9). That is to say that *all projective syntactic rules* above the level governed by lexical heads are strictly direct surface-compositional.

The present approach thus has some affinity to Montague Grammar and the Generative Semantics of the 1970s. However, work in that tradition has generally taken some known logic with a ready-made model theory as its starting point, and has been quite tolerant in practice of the many complications that ensue in mapping natural languages into formulas of such logics (Lakoff 1970a,b; Cresswell 1973; Montague 1973; Seuren 1996, 21–27, and the early papers collected in Seuren 1974). The complications include syntactic rules of very expressive power, leading to very unconstrained theories of the mapping between sound and meaning, with very many degrees of freedom, threatening the explanatory value of the enterprise.

Some linguistic theorists, including those in the generative-transformational tradition initiated by Chomsky, have reacted to this situation by treating the formal syntactic component as entirely autonomous, to be studied in isolation from any semantic influence. Such theories have mainly focused on problems of long-range dependency, exemplified in constructions like relativization and coordination, whose capture seems to demand the greatest formal expressive power. The semantic theories that have subscribed to this approach have generally been forced to introduce further “covert” structural manipulations in order to capture the necessary range of scoped interpretations (May 1977, 1985; Kayne, 1983; Heim and Kratzer, 1998).

Others in the cognitive or construction-based tradition initiated by Fillmore have sought to define a more natural theory of meaning representations, whose primitives are more directly aligned with crosslinguistically recurrent morphological and lexical markers of case, classification, aspect, evidentiality, information structure, and the like, to the exclusion of any sustained concern for the formal nature of the semantics, or the precise nature of the syntactic apparatus that projects such markers onto sentential dependencies, including the long-range dependencies.

Both modern approaches have been immensely productive of linguistic knowledge. The syntactic approach has delivered exquisitely fine observations of crosslinguistic constraints on long-range dependencies that would be unexplained if the syntactic arrangement of words and other meaning-bearing elements in sentences was completely free. The semantic approach has delivered crosslinguistic inventories of semantic primitives that may be assumed to be suggestive of the elements of a universal semantic representation underlying all languages. (Some of the most important work in this vein, including Lakoff's more recent work, exposes the limitations of such inventories in capturing many aspects of meaning, and their crucial interaction with inference and "encyclopedic" knowledge of the world. It follows that some or all of the semantic primitives may not be directly realized syntactically or morphologically in any language. Nevertheless, such a universal semantics of utterance must be accessible if children are to learn language from the context of use.)

This book attempts to reunite these two approaches by standing the problem on its head. Instead of assuming that the underlying meaning representation must resemble some standard form of first-order logic, it seeks to construct a natural logic as directly related as possible to the surface form of language, and to the process of inference and proof that it must support. In particular, it will claim that the semantics of nounphrases and negation is more directly related to surface form than is usually assumed.

Such a natural logic will be nothing if it is not formal. However, it should be allowed to grow organically from a tilth of attested language phenomena, rather than be axiomatized a priori in terms of mathematical principles. To preserve truth to the phenomena that nurture it, the syntax that maps it onto the sentences of the language must eschew all intrinsic use of structure- or type-changing operations in projective syntax and compositional semantics (although we will see that it must allow certain bounded finite-state transductions in the morpholexicon if the syntactic mapping is to be kept direct). It follows that such a theory of syntax must take the form determined by the requirements of surface-compositional interpretation, rather than conforming to syntactic expectations inherited from traditional grammarians or the very different purposes that the artificial languages of standard logic and mathematics were designed for.

This book argues that we need a novel "combinatory" theory of natural language syntax for this purpose, in which the notion of surface-derivational constituency is greatly generalized, so that every component of every construction, however fragmentary it appears in terms of traditional grammar, is a constituent whose syntactic type is transparent to its semantic interpretation, and in which all rules are strictly governed by the constituent condition (Chomsky 1975, 210–211) on their inputs and outputs.

It follows from this approach that the only explanation that can be admitted for any constraints we observe on attested scoped interpretations is one based on the combinatorics of surface syntactic projection from the lexicon of the language in question.

It will be objected that any logic developed for surface-compositional interpretation of a particular language will inevitably embody language-specific features, and thereby fail to qualify as a truly natural logic. It will certainly be apparent that the logical language developed below remains quite close to traditional first-order logic, and conspicuously fails to include intensional elements such as evidentials, aspectuals, and causatives, natural-kind markers such as classifiers, and many other elements that are needed for surface composition in non-European languages. The logic presented here is nowhere close to a universal language of thought, embodying the prelinguistic Old Weird Cognition, most of which we share to a greater or lesser extent with our vertebrate animal cousins, and which the child uses as an armature when it learns its first languages, but to which we seem to lose access once that process is complete.

My only defense to this charge is that it is probably only by looking at language-specific surface-compositional semantics for as many languages of as different ancestry as possible that we will ever come to understand the nature of that lost language of thought. (The alternative approach that expects a universal semantics to emerge from machine learning in sensory-motorically "grounded" robots does not seem to have had much success, probably because what we are talking about is mainly the result of over five hundred million years of chordate evolution.)

Despite taking a primarily linguistic approach to this problem, a central concern throughout the book is the application of natural semantic interpretations to practical natural language processing tasks, such as automated question answering and information retrieval. Such applications call for simplicity and monotonicity in representation, and for the elimination of any tendency toward model-theoretically spurious ambiguity, or proliferating semantically equivalent logical forms. For this reason, there is an emphasis throughout the book on eliminating traditional quantifiers from the semantic formalism in favor of devices such as Skolem terms, and on structure sharing across representations in the processing component.

Acknowledgments

The research described in this book began when I taught at the University of Pennsylvania, in conversations with Jong Park, whose doctoral dissertation (1996) represented the first attempt on this problem in a CCG framework and provided a catalyst to the present work. Some of the ideas presented here (including the use of generalized Skolem terms) were first advanced in embryonic form in Steedman, 1999 and Steedman, 2000b, 70–85. The present work completely revises and supersedes the latter accounts, providing a model theory and extensions to a large number of new phenomena, including negation and some aspects of anaphora. Early drafts were presented in 1999 to audiences at Brown University, New York University, Univerzita Karlova in Prague, the Formal Grammar Conference in Utrecht, and the Twelfth Amsterdam Colloquium, under the title "Syntactic Constraints on Quantifier-scope Alternation;" to the 14th SALT Conference at Northwestern University, June 2004, the Conference on Strategies of Quantification, University of York, July 2004, and the conference on Formal Grammar and Mathematics of Language, Edinburgh, August 2005, under the title "Scope Alternation and the Syntax-Semantics Interface," as well as in talks at Ohio State University and the X-TAG seminar at the University of Pennsylvania in 2006–2007 under the title "Surface-Compositional Semantics of Scope Alternation."

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Chapter 1
Prologue

An effective silencer must be fitted to every vehicle.
—UK vehicle regulations

Like many other phenomena whose importance might seem to a linguist to be self-evident, the formal semantics of quantification is nowadays largely ignored by the computational linguists and psycholinguists most concerned with the practicalities of building devices that retrieve information from text on the web, and explaining human language performance. For such purposes, it often seems not to matter what the precise scope relations of natural language quantifiers are.

For example, if a human user wants to know if they need a television license in the United Kingdom, then a machine might detect that the statement *Every household with the intention to receive broadcast television in the United Kingdom must hold a valid UK television license* entails a positive answer to the query, without bothering to resolve the ambiguity inherent in that text as to whether the world is such that everybody in question has to hold the *same* license, or whether each needs a different license from everyone else. Somehow, the answer to that question just seems to come out in the pragmatic wash, because the questioner has already resolved that question in their own mind, and in the majority of cases, the corresponding sentences in the texts will reflect the *same* bias as the user, one way or the other. (While all sentences are hugely ambiguous syntactically and even semantically, very few sentences are ambiguous once pragmatics and world knowledge, perhaps approximated for computational purposes using a statistical model, are taken into account.)

We should therefore begin by assuring ourselves that quantifiers and other scoping elements actually do matter for practical human and computational natural language processing purposes.

1.1 Why Quantifiers Matter

It is hard to escape the conclusion that the meaning of sentences like (1a) involves universal quantification over some set of dogs, rather than mere predication over an individual with a property *every*, as (1b) is a predication over an individual dog with the property *old*:

(1) a. Every dog has his day.
    b. Old Fido has had his day.

Whereas the pronoun in (1b) does refer to an individual Fido, so that it means something like *Old Fido has had Old Fido's day*, (1a) does not mean anything like *Every dog has every dog's day*.

Quantifiers and negation are also important because, along with other categories that space and time will prevent us from considering here, such as modality, tense, and aspect, they support inference and entailment. Thus, if we need to decide whether to board the next train to arrive, the statement *All trains go via Camden Town* together with some knowledge of the relevant transport system, may help us to decide. The statement that *Congress shall make no law respecting an establishment of religion* may similarly inform our expectations in another direction. The study of logic has its origins in the desire to render such inference systematic and understandable.

The same long-standing tradition in the study of logic has always assumed that natural language is very close to the logic of everyday reasoning, with variation across languages amounting to nothing more than the legitimate ways of ordering and lumping together the primitive elements of commonsense thinking to produce irrefutable argument. Two research strategies suggest themselves. One, the more ancient, seeks to identify a "natural" logic by studying the detailed form of natural language and reasoning. Such a tradition is essentially proof-theoretic, and places an emphasis on relations of entailment and correct reasoning. The Aristotelian syllogistic and subsequent work reviewed by Geach (1962) is one example. So is the program of Leibniz, Frege, and Russell. More recently, this approach has been taken in rather different directions by Sommers (1982), Hobbs (1985), and (in part) van Benthem (1986, 1991).

A second strategy, of more recent origin, seeks to extend known logics, especially those with nice mathematical properties such as completeness, to cover a more languagelike range of phenomena. Such logics tend to claim minimal diversity in ontology and rules of inference as a virtue (Quine 1953). So-called tense logics (which typically have a tenuous relation to any linguistic notion of tense) are an example (see Goldblatt 1992 for a review). This tradition is essentially model-theoretic, building on the work of Skolem and Tarski.

Of course, proof theory and model theory are closely related, and much work in logic involves elements of both. Nevertheless, most modern work in linguistic semantics has followed Montague 1970a in emphasizing the second, model-theoretic approach (see Portner and Partee 2002 for a representative collection).

To some extent, this is as it should be. In order to show that a deductive system is sound, every proof theory eventually needs a model theory. A model theory for the present proposal is duly delivered in chapter 5. However, natural language and commonsense reasoning are sufficiently different from deduction in standard logics that it may be premature to worry too much about such niceties, rather than first working out what sort of logic we are actually dealing with.

To take a simple example that will be discussed in greater detail in chapter 5, a standard and widely accepted tradition in classical logic treats the conditional *if P, then Q* as "material implication," model-theoretically equivalent to *either not P, or Q*, as in the following:

(2) a. If the switch is down, then the light is on.
    b. Either the switch isn't down, or the light is on.

The reason for assuming material implication is that it yields a family of logics with delightfully simple proof theories and model theories. Naturally, this has a certain appeal.

However, generations of students have indignantly objected to the "implicational paradoxes" that ensue, such as that the mere fact of the light being on implies the truth of (2a). They point out that material implication manifestly fails to correspond to natural logic and the use of the natural language conditional.

The students seem to have a point. The mere fact that I live in Scotland seems insufficient to make the following sentence true:

(3) If I live in London, I live in Scotland.

Moreover, the following sentences (adapted from Abbott 2004) do not seem to mean the same thing—in fact the disjunctive (b) seems unacceptable:

(4) a. If Alice comes, then Bob will come too.
    b. #Either Alice won't come, or Bill will come too.

Such examples are typical of the paradoxical nature of negation in natural logic. This problem shows up in many forms. For example, the logic must be such as to predict the sensitivity to contextual negation of the direction of entailment toward the more general or the more particular, as in examples like the following:

(5) a. A woman won the election.
b. $\models$ Somebody won the election; A woman won some event; etc.
c. $\not\models$ A good woman won the election; A woman won the election easily; etc.

(6) a. No woman won the election.
b. $\not\models$ Nobody won the election; No woman won any event; etc.
c. $\models$ No good woman won the election; No woman won the election easily; etc.

If we fail to get this right, such effects can combine in disconcerting ways. Huet (2006) reminds us that if we reason carelessly with the innocuous-seeming rule *If P, then P*, where *P*= "Any number is odd," we may find ourselves concluding that the existence of the odd number 1 implies that 2 is odd:[1]

(7) If any number is odd, then any number is odd.

Of course, the first occurrence of *any* in (7) is the "negative polarity item" that seems to mean much the same as *some*, while the second is the "free-choice" *any* that seems to mean something more like *every*. In that sense, one might assume it to be an accident of English that (7) appears to have the form *If P, then P*—in fact (7) is false. But one might ask what it is about the natural equivalent of quantification that makes it possible for English *any* to carry such apparently diametrically opposed meanings, without inducing undesirably cynical attitudes on the part of our children, when faced with the task of acquiring English.

If we *can* capture natural logic in this sense, upward- and downward-monotone entailments such as those in (5) and (6) are likely to be very useful for practical natural language processing by machine, since they can be computed directly from something very close to the surface form of the original sentences. MacCartney and Manning (2007) and Bobrow, Condoravdi, de Paiva, Karttunen, King, Nairn, Price, and Zaenen (2006) have applied this insight to the "textual entailment" task, with encouraging results. The book will explore this possibility further below.

1. I am grateful to Stephen Isard for drawing this example to my attention.

It follows that, while it is as well for proof-theoretic approaches to keep a weather-eye open for deductive paradox (Russell 1902), discovering just which logic it is that lies behind such examples, and what ontology it applies over, may be a higher priority than ease of developing a model theory.[2]

The present work pursues this alternative program with fanatical enthusiasm. It assumes that natural language sentences—even those like (7)—are entirely transparent to natural logic, in the sense that, for any given reading Λ and corresponding syntactic derivation Σ of a sentence Φ, there is a one-to-one mapping from terms in its natural logical form Λ and elements of that syntactic derivation Σ.

Of course, that does not mean there is a one-to-one mapping between *sentences* and logical forms. There may be, and generally are, several distinct readings of each element of syntactic form. Moreover, the terms of the logical form need not be simple, and in general they are not, even at the lexical level. It follows that different languages may pair different sets of semantic objects with different syntactic forms, including lexical items. For example, English freely lexicalizes resultative concepts like *run (across the grass)* where French treats them more analytically (*traverser (le gazon) (en courant)*, 'cross the grass by running'). Such discrepancies present a widely recognized challenge for machine translation.

The entire task for the child acquiring the grammar of its native language is to decide what those lexical pairings are. The extreme ambiguity that natural languages exhibit, together with the very large size of their grammars, means that statistical models are probably as central to natural language processing by the child as they are for the machine.

In investigating these questions, it will often be important to look at sentences involving multiple quantifiers, which often have multiple readings, like the one in the epigraph to this chapter, found on the web in a page of UK vehicle regulations, and repeated here:[3]

(8) An effective silencer must be fitted to every vehicle.

Such text entails an affirmative answer to questions like *Does my motorcyle need a muffler?* The availability of the narrow-scope reading in particular is important if we are not to infer anomalous answers to the follow-up question *Where can I find a muffler?*, such as *Fitted to every vehicle*.

2. This was in fact the program of Relevance Logic (Ackermann 1956; Anderson and Belnap, 1975, especially chap. 1 and "Appendix: Grammatical Propædeutic"). Relevance Logic had a proof theory for which a model theory was remarkably hard to find at all; see Fine 1992).

3. Silencer is British English for the U.S. English muffler.

It is often pointed out that sentences including such multiple quantifiers are comparatively rare. For example, Higgins and Sadock (2003) found that just under 1,000 of the 40,000 sentences in the Penn Wall Street Journal treebank had two or more quantifiers, of which only around 350 had those quantifiers standing in a dominance relation, as they do in (8). Koller, Pinkal, and Thater (2007), who looked at a much wider range of scope-bearing elements including modal and intensional verbs in a smaller corpus of 322 sentences, found that over a third of those sentences involved two or more such elements in a dominance relation. However, both groups report that these various scope relations are hard to annotate reliably and/or to train classifiers for. In particular, Koller and colleagues note the importance of world knowledge in deciding these relations.

Moreover, like almost all phenomena in natural language, the interpretations of multiply quantified sentences are vastly skewed in their distribution. "Inverting" readings like the one preferred for (8), where the object takes scope over the subject, with the reading that every vehicle must have a *different* silencer, are much rarer than noninverting "surface" readings, for reasons relating to focus and information structure (Hajičová, Partee, and Sgall 1998; Kennelly 2004). For sentences on the pattern of (3) in the next chapter, inverting readings are exceedingly rare. Such practical applications of natural language processing as closed- or open-domain question answering make strikingly little use of quantified expressions in either questions or answers (Woods, Kaplan, and Nash-Webber 1972; Voorhees 2001).

Nevertheless, the rarity of inverting readings should not be taken as meaning that they can be ignored for practical purposes. Zipf's law (Zipf 1936) says that almost everything in natural language obeys a power law, according to which the frequency of any event, such as the word *the* (the most frequent word in the *Wall Street Journal* corpus if punctuation is ignored), is roughly twice that of the next most frequent event of that kind (in this case, *of*).

The involvement of a power law means that we can often capture 80 to 90 percent of the data by just looking at the few most frequent events, ignoring the "long tail" of double-exponentially rarer ones. Often we can make such approximations automatically and on a vast scale, using machine learning. Such approximations account for much of the amazing progress we experience in such applications as automatic speech recognition and statistical machine translation. Their robustness in comparison to hand-built methods explains the fact that many computational linguists have given up linguistics for machine learning.

However, Zipf's law is double-edged. It also means that the information needed to capture the remaining 10 to 20 percent of the data is in the long tail, in rare events. Collectively speaking, rare events are very common. For example, while a few words are very common, around half of the words in any corpus occur just once.

Linguists know this very well. Almost everything they consider interesting and informative about the nature of the system, such as long-range dependency or quantifer scope inversion, is in the long tail. Unfortunately, machine learning is very bad at learning systems for which the crucial information is in rare events.[4]

Nevertheless, rare events happen all the time, and they may matter to users of applications, to a degree that is out of all proportion to their frequency. (For example, if my question answerer does too well with its grammar-free bag-of-words approach to entailment (Jijkoun and de Rijke 2005; de Salvo Braz, Girju, Punyakanok, Roth, and Sammons 2005), and has lulled me into a false sense of security when it answers the question *What do frogs eat?* with *Herons*, I am unlikely to trust that technology ever again.)

Thus, to understand why we should care about quantifier-scope, we should briefly consider both how rare events reveal the nature of the system, and where quantifers might actually be practically useful.

1.2 Quantifiers and Question Answering

Questions themselves provide few opportunities to deploy quantifiers, other than simple definites and indefinites, as in *Do you own a car?* and *How did you like the movie?* The following are unnatural as questions, and give the impression that the inquirer knows more than they are letting on:

(9) a. #Will at least three senators abstain?
    b. #Are most vegetarians teetotal?
    c. #Do exactly six samples contain plagioclase?

Questions are usually more open-ended, deploying indefinites and *wh*-items:

(10) a. Will any senators abstain?
     b. What proportion of vegetarians are teetotal?
     c. How many samples contain plagioclase?

4. The use of statistical priors based on skewed distributions such as Dirichlet mitigates the problem but does not eliminate it.

Quantifiers come into their own in *answers* and other statements like the following:

(11) a. At least three senators will abstain.
b. Most vegetarians are teetotal.
c. Exactly six samples contain plagioclase.

Such quantifiers convey subtle implicatures about the completeness or otherwise of the speaker's knowledge. For example, (11a) is appropriate in a situation where the speaker does not have information about all senators, whereas (11b,c) requires knowledge about all relevant individuals. Such distinctions are extremely important—for example in generating summaries to queries of the kind found in corpora like the UK National Library of Health question answering service, such as the following.[5]

(12) Is there any evidence that statins can prevent or delay the onset of senile dementia?

Their semantics is also relevant to the task of data mining such summaries for purposes of information extraction. The kind of machine summarization that is directed at summarizing evidence (rather than merely eliminating textual redundancy) is also a prospective area of application for a rich range of quantifiers. Entailments of the kind illustrated in (5) and (6) are likely to be useful for such tasks.

Applications of natural language generation, summarization, and information extraction currently lag behind the more elementary capabilities of recognition, parsing, and interpretation, and as of this writing, no language generation program is capable of deploying them with even the modest degree of subtlety illustrated in the above examples. However, as computational discourse is brought under better control—in particular, once it becomes possible to plan relevant utterances in "mixed-initiative" human-machine dialog more effectively—quantifiers will come into their own.[6]

Multiply quantified sentences will remain rare, and the inverting readings considered in the next chapter will remain rarer still. Nevertheless, they are out there, particularly in pages of rules and regulations like the one (8) was found in, and they will catch us out, even though on occasion we can get away with answering questions such as the earlier *Does my motorcycle need a muffler?* without actually resolving the ambiguity. To better keep in focus their real rel-

5. `http://www.clinicalanswers.nhs.uk/`.
6. The main obstacle to progress in this area seems to be representing the knowledge required for effective discourse planning in the face of uncertainty about the state of the discourse.

evance to natural language processing by people and machines, the epigraphs to the present chapters mainly consist of attested wild examples of most of the phenomena discussed in this book, of a kind easily captured with the aid of various search engines and a little salt on the long tail of the World Wide Web.

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