Flexible Processing and the Design of Grammar*

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Abstract

We explore the consequences of letting the incremental and integrative nature of language processing inform the design of competence grammar. What emerges is a view of grammar as a system of local monotonic constraints that provide a direct characterization of the signs (the form-meaning correspondences) of a given language. This 'sign-based' conception of grammar has provided precise solutions to the key problems long thought to motivate movement-based analyses, has supported three decades of computational research developing large-scale grammar implementations, and is now beginning to play a role in computational psycholinguistics work that explores the use of underspecification in the incremental computation of partial meanings.

1. Introduction

Language processing involves many sources of information. These include grammatical knowledge, but also knowledge of the discourse context, background world knowledge, gestures and other kinds of visual information, social knowledge, and knowledge of style and genre.

For example, consider the following, from the 1946 movie, *The Big Sleep*:

(1) VIVIAN: You like my father, don't you?
MARLOWE: Mm-hum.
VIVIAN: Why don't you stop?
MARLOWE: Remember I told you I was beginning to like another one of the Sternwoods?
VIVIAN: I wish you show it.

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* Ivan Sag's long battle with cancer kept him from attending the 2012 CUNY conference. He did, however, deliver his invited address via Skype. His illness also kept him from writing up the talk, so he enlisted Tom Wasow's help in turning his slides into a paper. Eva Fernandez provided an audio recording of the talk, which was very helpful in this task. This paper follows the talk slides closely.

The following people were acknowledged in Ivan's talk: Tom Wasow, Emily Bender, Bob Borsley, Bob Carpenter, Herb Clark, Ann Copestake, Penny Eckert, Dan Flickinger, Jerry Hobbs, Ron Kaplan, Martin Kay, Paul Kay, Alex Lascarides, Mark Liberman, John Nerbonne, Fernando Pereira, Dave Rumelhart, Stuart Shieber, Mike Tanenhaus, and Hans Uzskoreit.

MARLOWE: That should be awful easy.
VIVIAN: I like that. I'd like more ____. That's even better.

The audience interprets the underlined occurrence of *that* to denote something like 'the fact that it would be easy for Marlowe to show that he likes another one of the Sternwoods (namely, Vivian)'. And the ellipsis after *more* means something like 'more than just showing you like me'. These interpretations require not just reference to the portion of the dialogue reproduced here, but also knowledge that Vivian's last name is Sternwood, and common-sense knowledge about what plausible meanings could be given to *that* and the ellipsis.

Similarly, in the following from the 1942 movie, *Casablanca*, the name *Paris* is used as shorthand to denote an episode in the lives of the interlocutors, not the geographical location itself.

(2) I wouldn't bring up Paris if I were you...

This interpretation is only possible given a large amount of shared background knowledge.

Visual and gestural information may be crucial in determining the referents of pronouns, as in (3).

(3) I want **you** and **you** to come with me, while **you** stay here with the kids. (Fodor & Sag, 1982, p. 387)

Informal American English even has an expression that must be accompanied by a gesture, namely *yea* as an indicator of size[1], as in (4).

(4) Lin's parents are only yea high, but he's six foot three.

Examples (5)[2] and (6) show that general world knowledge influences how people interpret the referents of pronouns and the meaning of prepositions.

(5) a. The police refused the students permission to demonstrate because they feared violence.
b. The police refused the students permission to demonstrate because they advocated violence.

(6) a. Having found the book on the table, I took steps to make sure I'd always be able to find it again.
b. Having found the book on the fable, I took steps to make sure I'd always be able to find it again.

While *they* in both versions of (5) could, in principle, refer to the police or the students (or some other group not mentioned in the sentences), (5a) biases listeners toward interpreting *they* as referring to the police, and *they* in (5b) tends to get interpreted as referring to the students. In (6a), *on* gets interpreted spatially, whereas in (6b), *on* is understood as roughly synonymous with *about*. In both cases, it is non-linguistic world knowledge that determines the preference.

Staum Casasanto (2008, 2010) has shown that social knowledge can influence language processing, even at the level of speech perception. In one of several experiments, she

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[1] We believe this fact was first noted by Chuck Fillmore.
[2] This example is due to Karen Spärck Jones

presented participants with auditory stimuli containing a potentially ambiguous word that was disambiguated by what followed it. The critical stimuli involved word pairs like *mass* and *mast*, which sound identical when the final [t] of *mast* is deleted, as it often is in speech. Such deletion is known to occur at a higher rate in the speech of African Americans than in the speech of white Americans (Wolfram, 1969). Participants heard a sentence like one of those in (7), while viewing a picture of a face, which they were told was the speaker.

(7) a. The [mæs] probably lasted through the storm.
    b. The [mæs] probably lasted an hour on Sunday.

They were then asked whether the sentence made sense. For examples like (7a), participants responded significantly faster when the accompanying picture was of a black person; and for examples like (7b), they responded significantly faster when the accompanying picture was of a white person. Thus, participants' knowledge of the social fact that African Americans are more likely to delete [t] in this environment influenced the speed with which they processed the spoken stimulus.

Style and genre also affect language processing. A clear example of this is provided by newspaper headlines, which often employ the structure of the canonical garden-path, namely, N-V-PP-VP, in which the V is ambiguous between a past participle and a passive participle. A few examples are given in (8).

(8) a. US tourists seized in Egypt's Sinai released
    b. Peoria man arrested in fatal stabbing is released from jail
    c. Activist detained in Mideast speaks
    d. Baltimore man detained in Guantanamo formally charged
    e. 2 Arrested After Band's Protest at Moscow Cathedral to Remain Jailed

All of these have the same structure as the famously hard-to-parse *The horse raced past the barn fell*, yet readers attuned to the telegraphic style of headlines process them with little difficulty.

In sum, language processing involves many diverse sources of information, including grammatical knowledge, discourse context, gestures and other visual information, general world knowledge, social knowledge, and knowledge of style and genre. Grammar is just one of the resources that a flexible processor (that is, a parser or generator) consults. This raises the following fundamental questions:

- How does integrative processing take place?
- What is the architecture of the processor (or processors)?
- What does processing tell us about the design of grammar?

Our primary focus in this paper is the last of these questions. But it cannot be answered without at least touching on the first two.

2. **Aspects of Language Processing**

Consider the following exchange from *Casablanca*:

(9) Rick: I congratulate you ___.
    Victor: What for___?
    Rick: ___Your work.

Victor: I try___.
Rick: We all try___. You succeed___.

For the interlocutors to understand one another, each must be able to infer the missing parts of the other's utterances, as indicated by the underlined spaces. What sorts of tasks does this involve? First of all, language comprehenders must be able to select among the many alternative possible meanings of linguistic expressions.

There are many kinds of linguistic ambiguity (Wasow, et al, 2005), so language comprehension involves various types of disambiguation. These include lexical disambiguation (10), structural disambiguation (11), and combinations of the two (12):

(10) *bank, can, will, duck, to/two/too,* etc.

(11) a. I found the message in the book.
b. I forgot how good beer tastes.

(12) a. I saw her duck.
b. That creature has two legs and flies.

Comprehenders must also resolve underspecified representations, including those of quantifier scope (Tunstall 1998, Sanford & Sturt 2002) and polysemy (Frazier & Raynor 1990). The two possible scopes of *every* in (13) can resolved by following it with either *The critic was from a major gallery* or *The critics were from a major gallery*.

(13) Kelly showed every photo to a critic last month.

Similarly, the interpretation of *book* as a physical object or a textual object in (14) can be resolved by following it with *Too many pages were torn* or *The reviews were extremely critical*.

(14) Unfortunately, the book didn't sell.

Observations like these have led many people who work on language processing to propose a logic-like division of labor between grammars and processors, along the following lines:

- Grammar provides argument variables (for pronouns, ellipsis, names, etc.). The processor assigns values to variables incrementally.
- Grammar proposes disjunctions in certain cases (e.g., lexical or structural ambiguity). The processor simplifies these disjunctions as quickly as possible.
- Grammar provides underspecified semantic representations (for scope, polysemy, etc.). The processor refines these representations monotonically.

Things are not this simple, however. Consider the following examples, from Bar Hillel (1960):

(15) a. The pen is in the box.
b. The box is in the pen.

The ambiguity of *pen* between a writing implement and a fenced enclosure is resolved by world knowledge in both cases. But there is a crucial difference: listeners or readers of (15a) must entertain both readings of *pen* until the disambiguating word *box* is encountered, whereas the disambiguating information is already available in (15b) when *pen* is encountered. A model in which the grammar provides its full representation before the processor begins to operate cannot capture this intuitive difference.

Our intuitive sense that listeners process utterances incrementally, without needing to hear a whole sentence before starting to construct an interpretation, is borne out by experimental evidence. Much of the psycholinguistic literature over the past two or three decades has shown that comprehenders are remarkably fast at resolving ambiguity and underspecification. Moreover, this resolution proceeds incrementally: comprehenders begin determining the intended interpretations of expressions as soon as they are uttered, without waiting for the grammatical analysis of any subsequent material. The clearest evidence for this comes from work in the visual world paradigm; see Tanenhaus & Trueswell (2006) for a summary. In an earlier paper (Sag & Wasow 2011), we discussed the implications of this work for theories of language processing and summed it up as follows (p. 363): "language comprehension proceeds rapidly and incrementally, with different types of information utilized as they are needed and available," adding, "The same is true of language production."

There is ample evidence that listeners exploit most, if not all, of the various types of information discussed in section 1 of this paper in an incremental fashion to ascertain a speaker's intended meaning as quickly as possible. In the remainder of this paper, we will use this fact to argue for a particular type of grammatical theory.

3. **Realistic Grammar**

We take grammars to be representations of linguistic knowledge that is independent of particular processing applications. That is, we accept Chomsky's imprecise but useful notion of linguistic competence. We also accept what has come to be called the Competence Hypothesis, that is, that a model of language use should incorporate a grammar "that expresses the speaker-hearer's knowledge of the language." (Chomsky, 1965, p. 9). In fact, we adopt the stronger position that facts about processing provide evidence of the form of grammar[3].

Since it is clear that listeners compute partial meanings of expressions while those expressions are being uttered, grammars must allow partial meanings to be computed incrementally. Various design properties of a grammar can facilitate this. In this section we discuss five such properties:

- Constraint-based architecture
- Surface-oriented grammatical analysis
- Sign-based grammar
- Strong lexicalism

[3] This is similar in spirit to the Strong Competence Hypothesis of Bresnan & Kaplan (1982). Bresnan & Kaplan's formulation is somewhat complex, depending on some ancillary definitions. Steedman (1985, p. 361) paraphrases the Strong Competence Hypothesis as follows: "the operations of the processor correspond directly to rules of the grammar." Steedman's formulation seems somewhat dated, given the emergence of what Pullum & Scholz (2001) call "model-theoretic syntactic frameworks". What is important from our perspective is that processing evidence is relevant to grammar design.

- Representational underspecification

3.1 Constraint-based architecture

In order to ensure flexible and incremental computation, a grammar should consist of declarative constraints on linguistic objects (see Sag et al 1986, Fenstad et al 1987, Tanenhaus et al 1995, Jackendoff 2002, inter alia). That is, lexical entries, constructions, and principles of universal grammar are all static well-formedness conditions. Well-formedness is determined by simultaneous constraint satisfaction. Constraints are unordered: the order of application is input-driven, not architecture-driven.

This architecture allows the grammar to be neither comprehension-biased nor production-biased. The same grammatical constraints would be operative for both speaker and listener, but they might be applied in a different order for the two interlocutors.

A constraint-based grammar makes sense of the following famous claim by Fodor, Bever, and Garrett's (1974, p. 368):

> Experimental investigations of the psychological reality of linguistic structural descriptions have, in general, proved quite successful. But experimental investigations of the psychological reality of grammatical rules, derivations, and operations…have generally proved equivocal. This argues against the occurrence of grammatical derivations in the computations involved in sentence recognition…

Instead of concluding as Fodor, et al did that there is no "concrete employment of the grammar by the sentence recognizer", we infer that grammars should be formulated in a process-neutral way. A constraint-based architecture accomplishes this.

3.2 Surface-oriented grammatical analysis

In a grammar without derivations, sentences are licensed directly. No abstract underlying grammatical structures need be posited. This conclusion comports well with the psycholinguistic evidence cited by Fodor, Bever, and Garrett, and it also receives support from more recent experimental work. For example, Pickering and Branigan (2012) argue that priming evidence supports:

> the existence of a single, "shallow" surface syntactic representation, which includes grammatical function information and linear order, together with a single semantic representation that includes information about thematic roles and quantifier scope. The evidence does not support intervening levels of LF, DS, F-structure, or dominance-without-precedence.

Occam's razor favors a theory with only one syntactic level, and experimental evidence from psycholinguistics does, too.

3.3 Sign-based grammar

Linguistic expressions relate forms (sounds or writing) with meanings. They are, then, a species of what Saussure (1916) called "signs". Grammar expresses constraints on the syntax-semantics interface, and signs are the locus of these constraints. Lexical entries express constraints on lexical signs. Grammatical constructions are local constraints on the ways signs combine to form phrasal signs. Thus constructions are similar in crucial ways to phrase structure rules, except that the information they include is far richer. Moreover, they lack the directionality implicit in the arrow notation commonly used for phrase structure rules. Constructions are well-formedness constraints on signs composed of other signs, not instructions to build a structure.

In describing the constraints on signs as local, we mean that they are restricted to mother-daughter pairs. This restriction, taken over from context-free grammar, embodies a substantive empirical claim. In a theory with only local constraints, any apparently non-local dependencies must be decomposable into a set of local dependencies, and there should be evidence to support the existence of the intermediate dependencies. The clearest case of such a situation is with filler-gap dependencies (what are sometimes called long-distance dependencies, or, in the transformational literature, A-bar movement). Research in the 1970s and 1980s discovered phenomena in a variety of languages demonstrating that filler-gap dependencies in those languages need to be analyzed as chains of local dependencies (see Zaenen 1983 and Hukari and Levine 1995 for summaries).

The locality of the constraints maximizes the information available in partial structures and supports a variety of processing regimes (top-down, bottom-up, left-corner, probabilistic, etc.). Hence, this property of our sign-based model of grammar is useful in modeling the incrementality of processing.

3.4 <u>Lexicalist architecture</u>

Words are information-rich. Put another way, knowing a word involves knowing a great deal. Most obviously, words have phonological and orthographic forms and literal meanings. They also have associated subcategorization information – that is, information about what types of expressions they combine with. This can be quite general (e.g., the verb *deny* normally requires a nominal or sentential complement) or very specific (e.g., the verb *crane* normally requires an object that denotes someone's neck or head). Nouns and verbs in English (and other word classes in other languages) have inflectional information associated with them (e.g., that the plural of *goose* is *geese*). Some such information is quite general, covering large sets of words (e.g., that the plural of *dog* is *dogs*) and some is specific to one word or a very small set (e.g., that the plural of *mouse* is *mice*).

The lexicon should represent the groupings of words into categories and subcategories, in terms of what they mean, what they combine with, and their inflectional properties. This has led us to posit a lexicon organized into multiple inheritance hierarchies (see Flickinger, et al 1985, and Pollard and Sag 1987), with individual lexical entries inheriting information from word types, and these types inheriting information from more inclusive types. This allows us to capture both the commonalities and the differences among words.

This architecture permits us to adopt a strong version of lexicalism, namely, that words are syntactic atoms. Thus, we reject the complex pre-lexical derivations proposed by some linguists (e.g. Halle and Marantz 1993).

3.5 Representational underspecification

Comprehenders processing a sentence incrementally construct a meaning for the input in a nearly monotonic fashion. There are of course exceptions: garden-path phenomena have been the subject of an enormous amount of psycholinguistic literature. But the most striking fact about garden-paths is how infrequently they occur outside of the psycholinguistics laboratory. It seems that listeners and readers rarely make commitments to particular analyses or interpretations that they must then abandon, requiring them to backtrack.

Our theory of grammar accommodates this observation by allowing representations in which information is underspecified. That is, we assume that the processor builds partial representations, incorporating the information that is available at each moment, but remaining uncommitted where decisive information is not yet available. There are of course cases in which remaining uncommitted requires a disjunctive representation, and these presumably impose and extra processing cost. But semantic representations can, for the most part, be built up incrementally simply by specifying previously unspecified information.

3.6 Interim summary

The processing literature indicates that language processing involves a system that:

- is situated and discourse-driven;
- is incremental and flexible;
- is semantically and pragmatically modulated;
- is multimodal and cue sensitive;
- is distance-locality sensitive;
- is constrained by frequencies, yet open to priming;
- exhibits similarity-based interference;
- keeps fillers active;
- shows surprisal effects;
- has limited nondeterminism;
- and has appropriate stack resource decay

Taking seriously the idea that a grammar should be a component of a model of language use, we argue that facts about processing should influence the design of grammars. We conclude that realistic competence grammars should meet these criteria:

- Constraint-based architecture
- Surface-oriented grammatical analysis
- Local constraints
- Sign-based analysis
- Strong lexicalism
- Representational underspecification.

Is such realistic grammar possible? Can we design competence grammars that meet these design criteria and also scale up to provide analyses for the rich variety of types of phenomena exhibited by natural languages? We already have!

Over the past thirty years, a number of groups around the world have been developing a variety of constraint-based grammatical theories that satisfy the criteria above. Theories of this type include: Head-driven Phrase Structure Grammar (a descendant of Generalized Phrase Structure Grammar), some varieties of Categorial Grammar[4] (particularly Combinatory Categorial Grammar), Lexical-Functional Grammar, Berkeley Construction Grammar, and Simpler Syntax; see Borsley and Börjars (2011) for a survey. Other theories sharing some of the properties listed above include Word Grammar and Tree Adjoining Grammar.

Most of the remainder of this paper will provide a glimpse of Sign-Based Construction Grammar (SBCG), a theory designed to meet the criteria sketched above. We say "a glimpse" because a detailed presentation of SBCG would have to be book length. We nevertheless would like to convey the flavor of the theory, with pointers to some aspects that we think should make it appealing to psycholinguists.

4. **Sign-Based Construction Grammar**

Sign-Based Construction Grammar is a synthesis of Head-driven Phrase Structure Grammar (HPSG) and Berkeley Construction Grammar. An overview of the theory is provided in the 2012 book, *Sign-Based Construction Grammar*, edited by Hans C. Boas and Ivan A. Sag, published by CSLI Publications, with contributions by Jóhanna Barðdal, Hans Boas, Þórhallur Eyþórsson, Charles Fillmore, Paul Kay, Russell Lee-Goldman, Laura Michaelis, Russell Rhodes, Ivan Sag, and Gert Webelhuth.

SBCG incorporates the properties of a realistic grammar discussed in the preceding section. It has been used in the analysis of a range of different types of phenomena, including lexical classes, complementation patterns, lexical relations, argument-structure constructions, filler-gap dependencies, auxiliary constructions, etc. Like several of the other theories mentioned above, SBCG make use of a uniform representation language of typed feature structures, and it has a simple and well-understood method for combining partial information, namely unification.

Semantics in SBCG draws on the work of Fillmore and colleagues in Frame Semantics (see Fillmore 1976 and Fillmore and Baker 2010, among many other works), as embodied in the FrameNet implementation. The basic idea of this approach is "that the meanings of most words can best be understood on the basis of a **semantic frame:** a description of a type of event, relation, or entity and the participants in it." (https://framenet.icsi.berkeley.edu/fndrupal/about). Frames are modeled as typed feature structures, and lexical meanings are hierarchically organized. The theory is designed to be compatible with ongoing work on dialogue by Ginzburg and others (e.g.

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[4] Among these we would include Stabler's Minimalist Grammars (see Stabler 2013), which, despite their name and some of the rhetoric surrounding them, seem to us to bear a much closer resemblance to categorial grammars than to the informal literature of the Minimalist Program.

Ginzburg 2012). It incorporates the scope underspecification of Minimal Recursion Semantics (Copestake, et al, 2005).

A sample semantic representation in SBCG is given in (16).

(16)

$$\begin{bmatrix} \textit{sem-obj} & \\ \text{LTOP} & l_{0=_q 5} \\ \text{FRAMES} & \left\langle \begin{bmatrix} \textit{some-fr} & \\ \text{LABEL} & l_1 \\ \text{BV} & i \\ \text{RESTR} & l_2 \\ \text{SCOPE} & l_6 \end{bmatrix}, \begin{bmatrix} \textit{student-fr} & \\ \text{LABEL} & l_2 \\ \text{ENTITY} & i \end{bmatrix}, \begin{bmatrix} \textit{every-fr} & \\ \text{LABEL} & l_3 \\ \text{BV} & j \\ \text{RESTR} & l_4 \\ \text{SCOPE} & l_7 \end{bmatrix}, \begin{bmatrix} \textit{answer-fr} & \\ \text{LABEL} & l_4 \\ \text{ENTITY} & j \end{bmatrix}, \begin{bmatrix} \textit{knowing-fr} & \\ \text{LABEL} & l_5 \\ \text{COGNIZER} & i \\ \text{COGNIZED} & j \end{bmatrix} \right\rangle \end{bmatrix}$$

The value of the LTOP feature is a pointer to the sign's fully resolved semantics; in a quantified sentence, this corresponds to the quantifier with the widest scope. The value of the feature FRAMES is the list of predications that together determine the meaning of a sign. The notation '$l_{0=_q 5}$' is used to indicate that this semantic object denotes a knowing situation (l_5 is the label of a 'knowing' frame), and that there may be a quantifier with scope over it. Which of the two quantifiers (the existential in the *some-fr* predication and the universal in the *every-fr* predication) has wider scope is left unspecified in this representation. The two scopings of *Some student knows every answer* can be resolved by different identification of labels. On the interpretation in which the existential has wide scope, $l_0= l_1$ (that is, *some* has the widest scope); $l_3= l_6$ (*some* scopes over *every*); and $l_5= l_7$ (*every* scopes over the 'knowing' predication). On the interpretation in which the universal has wide scope, $l_0= l_3$ (*every* has the widest scope) $l_1= l_7$ (*every* scopes over *some*); and $l_5= l_6$ (*some* scopes over the 'knowing' predication). Thus, (16) is a scope-neutral representation that comports well with experimental results like those of Tunstall (1998).

SBCG similarly provides a method of underspecifying semantic types. For example, the polysemy of *book* as either a physical object or a textual object can be represented by assuming that the semantic frame *book-fr* has two subtypes, *book^{po}-fr and book^{to}-fr*. And the lexical entry for *book* can be something like (17), which is underspecified with respect to these subtypes.

(17)

$$\begin{bmatrix} \textit{cn-lxm} & \\ \text{FORM} & \langle \text{book} \rangle \\ \text{SEM} & \begin{bmatrix} \text{INDEX} & i \\ \text{FRAMES} & \left\langle \begin{bmatrix} \textit{book-fr} & \\ \text{ENTITY} & i \end{bmatrix} \right\rangle \end{bmatrix} \end{bmatrix}$$

Turning now to the licensing of lexemes, what needs to be stipulated for particular lexical items is generally quite minimal: their phonology, their semantic frames, and their lexical types. For example, what we call the listeme for the verb *laugh* would be something like (18).

(18)

$$\begin{bmatrix} \textit{sintrans-v-lxm} \\ \text{FORM } \langle \text{laugh} \rangle \\ \text{SEM } [\text{FRAMES } \langle [\textit{laughing-fr}] \rangle] \end{bmatrix}$$

sintrans-v-lxm is the type of strictly intransitive verb lexemes, which is a subtype of intransitive verb lexemes, which is a subtype of verb lexemes, which is a subtype of lexemes, which is a subtype of lexical signs, which is a subtype of signs. Each of these supertypes of *sintrans-v-lxm* contributes certain constraints, all of which are inherited by the full lexeme for *laugh*, given in (19).

(19)

$$\begin{bmatrix} \textit{sintrans-v-lxm} & \\ \text{FORM} & \langle \text{laugh} \rangle \\ \text{SYN} & \begin{bmatrix} \text{CAT} & \begin{bmatrix} \textit{verb} & \\ \text{XARG} & \boxed{1}\text{NP}_i \\ \text{LID} & \left\langle \begin{bmatrix} \textit{laughing-fr} & \\ \text{SIT} & s \\ \text{S-SRCE} & i \end{bmatrix} \right\rangle \end{bmatrix} \\ \text{MRKG} & \textit{unmk} \\ \text{VAL} & \langle \boxed{1} \rangle \end{bmatrix} \\ \text{SEM} & \begin{bmatrix} \text{IND} & s \\ \text{FRAMES} & \left\langle \begin{bmatrix} \textit{laughing-fr} & \\ \text{SIT} & s \\ \text{S-SRCE} & i \end{bmatrix} \right\rangle \end{bmatrix} \\ \text{CNTXT} & [\text{BCKGRND } \langle\ \rangle] \end{bmatrix}$$

The boxed numerals indicate that the only subcategorized argument of *laugh* is the external argument (that is, the subject), which is a noun phrase whose index shows that it denotes the source in the laughing situation. This information is inherited from supertypes.

Words and phrases can be constructed out of lexemes using constructions, which are another type of sign. (20) shows the preterite construction, which unifies with (19) to license the word *laughed*, presented in tree format in (21).

(20)

$$\begin{bmatrix} \text{MTR} & \begin{bmatrix}\text{FORM} & \langle \mathbf{F}_{pret}(X)\rangle \\ \text{SYN} & \text{V}[\textit{fin}] \\ \text{SEM} & \ldots\end{bmatrix} \\ \text{DTRS} & \left\langle \begin{bmatrix}\text{FORM} & \langle X\rangle \\ \text{SYN} & \text{V} \\ \text{SEM} & \ldots \end{bmatrix}\right\rangle \end{bmatrix}$$

(21)

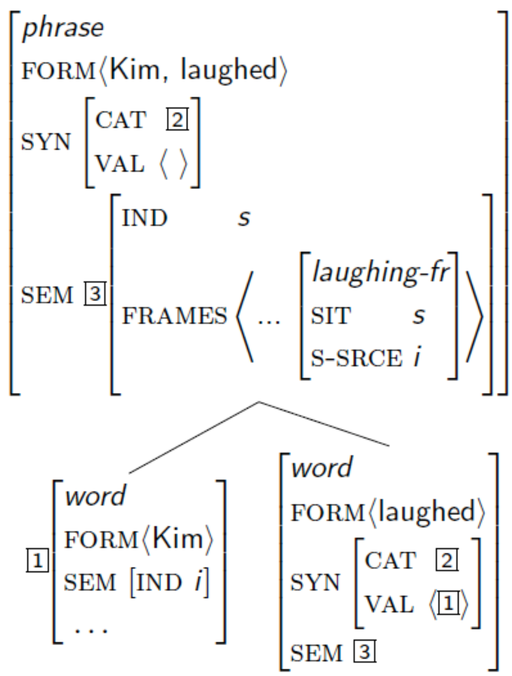
$$\begin{array}{c}
\begin{bmatrix} \textit{word} & \\ \text{FORM}\langle\text{laughed}\rangle & \\ \text{SYN} & \begin{bmatrix}\text{CAT} & \boxed{2} \\ \text{VAL} & \langle\boxed{1}\rangle\end{bmatrix} \\ \text{SEM}\ \boxed{3} & \begin{bmatrix}\text{IND} & s \\ \text{FRAMES} & \left\langle \ldots \begin{bmatrix}\textit{laughing-fr} & \\ \text{SIT} & s \\ \text{S-SRCE} & i\end{bmatrix}\right\rangle\end{bmatrix} \end{bmatrix} \\
| \\
\begin{bmatrix} \textit{sintrans-v-lxm} & \\ \text{FORM}\langle\text{laugh}\rangle & \\ \text{SYN} & \begin{bmatrix}\text{CAT} & \boxed{2} \\ \text{VAL} & \langle\boxed{1}\rangle\end{bmatrix} \\ \text{SEM}\ \boxed{3} & \end{bmatrix}
\end{array}$$

Constructions are also used to license phrases; for example, the Subject-Predicate Construction (22) is used in licensing the phrase *Kim laughed* in (23), also formatted as a tree.

(22)

$$\begin{bmatrix} \text{MTR} & \begin{bmatrix}\text{FORM} & L_1 \oplus L_2\\ \text{SYN} & \mathsf{S}\\ \text{SEM} & \ldots\end{bmatrix}\\ \text{DTRS} & \left\langle X: \begin{bmatrix}\text{FORM} & L_1\\ \text{SYN} & \mathsf{NP}\\ \text{SEM} & \ldots\end{bmatrix}, \begin{bmatrix}\text{FORM} & L_2\\ \text{SYN} & \begin{bmatrix}\text{VF} & \textit{fin}\\ \text{VAL} & \langle X\rangle\end{bmatrix}\\ \text{SEM} & \ldots\end{bmatrix}\right\rangle\end{bmatrix}$$

(23)



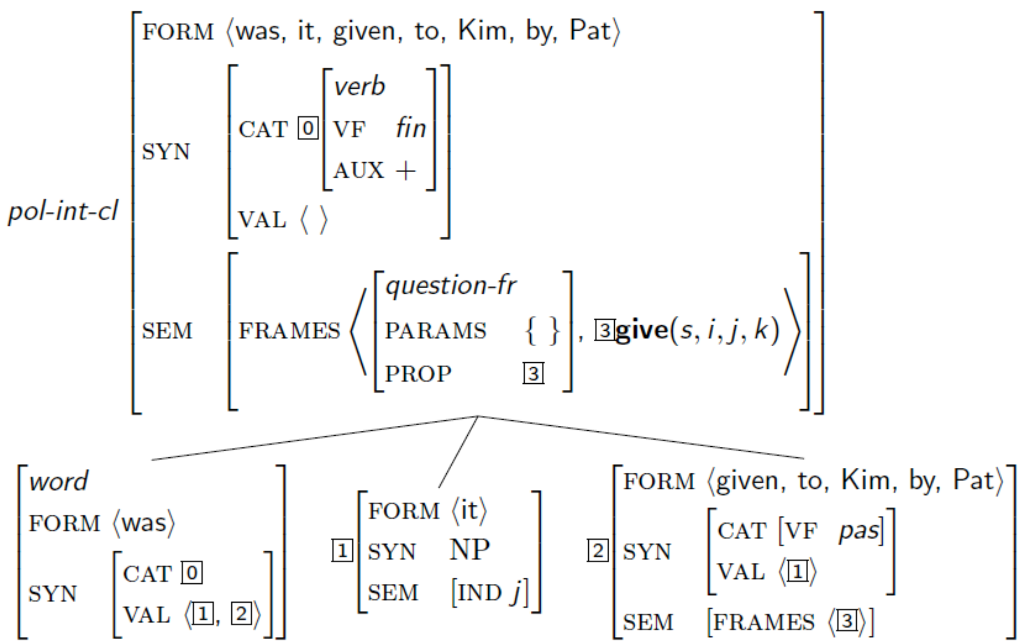
Signs are generated directly via sign recursion. There is no need for movement: no A-movement, no head movement, no A-bar movement, and no other kind of movement. So called "A-dependencies" are purely lexical, handled by simple identity constraints imposed on lexemes. For example, the properties of subject raising follow from the following constraint on the type *intr-sraising-lxm*: [ARG-ST <X, [SYN [VAL <X>]]>]. This says, in effect, that the constraints on the subject of the complement of a subject-raising predicate (like *seem*) are shared by the subject of that predicate. In this way, what are referred to as "A-moved" structures are projected directly from words by the same mechanisms that project "unmoved" structures.

Other "moved" structures are also projected directly from words. The Head Movement Constraint (Travis 1984) is unnecessary. The facts it was posited to explain follow in

SBCG directly from the fact that phrases are projected from their heads, and selection is local.

As an added bonus, the absence of movement simplifies the structures needed, eliminating levels of embedding and empty nodes. For example, (24) shows the top of the SBCG tree for the sentence *Was it given to Kim by Pat?*

(24)



This simple flat structure is directly licensed by the Polar Interrogative Clause construction, which also provides the question frame for the semantics.

The constraint-based architecture of SBCG and the use of underspecification support models of incremental sentence processing. Consider, for example, the utterance (25).

(25) Is the book on the table….

This is ambiguous with respect to the attachment of the prepositional phrase *on the table.* It may be attached low, as modifier of *the book*, in which case another predicate (e.g. *yours*) is required to complete the sentence. Alternatively, it may be attached high, in which case (25) is a complete sentence (though it could be continued, e.g. with *now*). SBCG permits an underspecified semantic representation of this, as in (26).

(26)

$$\left[\begin{array}{ll} \textit{pol-int-cl} & \\ \text{FORM} & \langle \text{is, the, book, on, the, table,...}\rangle \\ \text{SEM} & \left[\begin{array}{ll} \text{FRAMES} & \left\langle \begin{array}{l} \left[\begin{array}{ll} \textit{question-fr} & \\ \text{PARAMS} & \{\ \} \\ \text{PROP} & l_1 \end{array}\right], \left[\begin{array}{ll} \textit{def-fr} & \\ \text{BV} & i \\ \text{RESTR} & \boxed{l_2} \end{array}\right], \left[\begin{array}{ll} \textit{book-fr} & \\ \text{LABEL} & \boxed{l_2} \\ \text{ENTITY} & i \end{array}\right], \\ \left[\begin{array}{ll} \textit{on-fr} & \\ \text{LABEL} & l_4 \\ \text{FIG} & i \\ \text{GROUND} & j \end{array}\right], \left[\begin{array}{ll} \textit{def-fr} & \\ \text{BV} & j \\ \text{RESTR} & \textcircled{l_3} \end{array}\right] \left[\begin{array}{ll} \textit{table-fr} & \\ \text{LABEL} & \textcircled{l_3} \\ \text{ENTITY} & j \end{array}\right] \end{array} \right\rangle \end{array}\right] \end{array}\right]$$

When a listener has heard only (25) and does not yet know whether or how the sentence will be continued, (26) represents the listener's partial interpretation. She already knows that the utterance is a question, because it starts with *is*. This is encoded in SBCG by means of the *pol-int-cl* (for "polar interrogative clause") construction, which combines signs for a finite auxiliary verb, a noun phrase, and something that could serve as a complement to the auxiliary. The resulting sign has among its frames one of type *question-fr*, as in (26).

If the utterance is continued in such a way as to force a low attachment, the interpretation can be further specified by setting l_4 equal to l_2. If the utterance is continued in such a way as to force a high attachment, then the value of PARAMS in the *question-fr* is set to $\{l_4\}$, indicating that what is being questioned is whether the predication in the *on-fr* holds.

This high-vs-low attachment ambiguity is orthogonal to the question of whether *book* is interpreted as a physical or textual object. Both the noun *book* and the preposition *on* are polysemous in this respect; that is, the type *on-fr*, like the type *book-fr* discussed above, has (at least) two subtypes, on^{po}*-fr* and on^{to}*-fr*. The resolution of this polysemy depends on world knowledge and context, and it can take place whenever the necessary information is available to the listener.

In this way, the interpretation of a question beginning with (25) can be built up monotonically. Constraints are imposed by the grammar as well as by other sources of information of the sort discussed in section 1. The order in which they apply in meaning resolution depends on when they become available to the listener, rather than being built into the structure of the grammar or the processor.

5. Concluding remarks

Many of the design properties of SBCG discussed in this paper came from HPSG and were originally motivated, at least in part, by computational considerations. There is now a thirty-year history of implementations of GPSG, HPSG, and SBCG. There are large-scale, adaptable, open-source grammars available for at least English, German, Japanese, and Spanish (see http://www.delph-in.net/) and smaller implementations for many other languages. In addition, Emily Bender's Grammar Matrix (http://www.delph-in.net/matrix/) provides software for rapid prototyping of new grammars – a sort of "universal grammar" for HPSG implementations. A productive and collaborative international community including scholars from US, Germany, Japan, France, UK, Norway, and Korea work on these implementations.

These systems have been used in a number of applications, including database query (Hewlett-Packard), machine translation (Verbmobil), email autoresponse (YY), and grammar error detection and correction. This last deserves special mention, as it is currently in use by the Memphis public school system for the teaching of "language arts", and has been used by some 30,000 students (see Suppes, et al, 2012).

Such systems provide a critical test of the consistency and robustness of the theories that underlie them. They also demonstrate the scalability of the grammar fragments that are provided in theoretical articles. See Pullum (2009) and Sproat and Lappin (2005) for some relevant observations. The existing systems are constantly being refined and augmented. Exploratory work on incremental processing is ongoing.

Because HPSG and SBCG have always nurtured computational applications, they have design properties absent from the movement-based (transformational/GB/Minimalist) tradition. These design properties make SBCG/HPSG grammars ideal candidates for models of human linguistic knowledge. They include

- Architecture based on local constraints
- Surface-oriented, sign-based analyses
- Strong lexicalism
- Representational underspecification

Grammars like these can be used now to investigate psycholinguistically plausible models of comprehension and production. They bring computational modeling together with the results of behavioral and corpus-based experiments. By connecting grammar more tightly with work on processing, we can motivate the high-level design of grammar, draw conclusions about the particulars of individual grammars, provide better sources of explanation for many linguistic phenomena, e.g. many island effects.

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