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Glue Semantics

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Abstract

Glue Semantics (Glue) is a general framework for semantic composition and the syntax–semantics interface. The framework grew out of an interdisciplinary collaboration at the intersection of formal linguistics, formal logic, and computer science. Glue assumes a separate level of syntax; this can be any syntactic framework in which syntactic structures have heads. Glue uses a fragment of linear logic for semantic composition. General linear logic terms in Glue meaning constructors are instantiated relative to a syntactic parse. The separation of the logic of composition from structural syntax distinguishes Glue from other theories of semantic composition and the syntax–semantics interface. It allows Glue to capture semantic ambiguity, such as quantifier scope ambiguity, without necessarily positing an ambiguity in the syntactic structure. Glue is introduced here in relation to four of its key properties, which are used as organizing themes: resource-sensitive composition, flexible composition, autonomy of syntax, and syntax/semantics non-isomorphism.

1. INTRODUCTION

Glue Semantics (Glue) is a general framework for semantic composition and the syntax–semantics interface that grew out of a collaboration at the intersection of formal linguistics, formal logic, and computer science. It was first conceived and developed by Mary Dalrymple, John Lamping, and Vijay Saraswat, who were then all colleagues at Xerox PARC. They were joined for some of the key early developments by Vineet Gupta, also at Xerox PARC at the time, and Fernando Pereira, who was then at AT&T Bell Laboratories. The first papers in the framework were published in the mid-1990s (Dalrymple et al. 1993, 1995b, 1997a,b). The initial major publications on Glue, including revised versions of most of these papers, appeared in a collection edited by Dalrymple (1999).

Glue assumes a commutative logic for semantic composition (i.e., order does not matter). This means that Glue needs to be paired with some independent syntactic framework. Glue has been closely associated with Lexical-Functional Grammar (LFG) (Kaplan & Bresnan 1982, Bresnan et al. 2016, Dalrymple et al. 2019), but the syntax does not necessarily have to be LFG. The only aspect of syntax that Glue presupposes is a notion of headedness, which is universal across formal syntactic theories, even if specifics vary. Glue thus offers a highly flexible and adaptable approach to semantic composition and the syntax–semantics interface, and Glue has been defined for a variety of syntactic frameworks, such as Lexicalized Tree-Adjoining Grammar (Frank & van Genabith 2001), Head-Driven Phrase Structure Grammar (HPSG) (Asudeh & Crouch 2002b), Minimalism (Gotham 2018), and Universal Dependencies (Gotham & Haug 2018).

The primary early motivation for the development of Glue was to provide a semantics for LFG that would fit developments in the ethos of the theory perhaps better than the original semantics for LFG developed by Halvorsen (1983). In particular, Halvorsen's semantics for LFG was a kind of interpretive theory whereby a f(unctional)-structure—LFG's representation of grammatical functions and syntactic features, like case and agreement, and local and unbounded dependencies—was the input to a semantic process of interpretation. This is similar in spirit to Logical Form semantics (Heim & Kratzer 1998), although the formal properties of the input syntactic structures are different. In LFG parlance this is called description by analysis (Halvorsen & Kaplan 1988, Kaplan 1995): One structure/representation (syntactic) is systematically analyzed to yield a description that defines another structure/representation (semantic). Although the execution is different, description by analysis is comparable to the Logical Form semantics approach, in which the interpretation function applies to an entire syntactic structure for the sentence or phrase.

Partly in reaction to Halvorsen's (1983) work, LFG's original bipartite syntactic architecture—which consisted of c(onstituent)-structure and f-structure—was generalized to a highly modular Correspondence Architecture (Kaplan 1987, 1995). In the Correspondence Architecture, c-structure and f-structure are part of a larger mapping between form and meaning, with modules related by correspondence functions (see also Asudeh 2006; 2012, chap. 3). In this understanding of the theory, the predominant view of interfaces between modules is codescription: A lexical entry specifies its c-structural category, which captures its syntactic distribution, and specifies through a set of simultaneous constraints how it contributes information to other grammatical modules, including not only f-structure but also s(emantic)-structure and others [e.g., m(orphological)-structure, p(rosodic)-structure, i(nformation)-structure] (see Asudeh 2012, chap. 3, for a basic introduction to one version of the Correspondence Architecture). Thus, a syntactic formative in this view simultaneously codescribes its contributions to semantic interpretation. A first step in this direction was taken by Halvorsen & Kaplan (1988), who adapted the description-by-analysis approach of Halvorsen (1983) to a codescription analysis. Glue provides a further generalization and logical systematization of this idea. Unlike description by analysis, codescriptive semantics is in the spirit of the syntax–semantics interface tradition that grew out of what Bach (1976) called the rule-by-rule approach of Montague (1973). This tradition is standardly exemplified by Categorial Grammar (CG) (for a basic overview and foundational references, see Wood 1993). Indeed, Dalrymple et al. (1999a) discuss how Glue is strongly related to CG in the type-logical tradition (for overviews and further references, see, e.g., Morrill 1994, 2011; Carpenter 1997; Moortgat 1997).

The main high-level distinction between Glue and CG is that Glue assumes a looser relation between the syntax of word order and compositional semantics than CG does (for discussion and further references on this aspect of CG, see Steedman 2014). Although Glue does not have to be paired with LFG, it is perhaps useful to think about this in terms of LFG's claims about Universal Grammar (Bresnan et al. 2016, chap. 4). LFG assumes that c-structure, which represents word order, is highly variable cross-linguistically, whereas f-structure, which represents syntactic features and dependencies, is largely invariant cross-linguistically. This is reflected in the fact that although embedding is significant at the level of f-structure, order among features in the same f-structure is not (these are general properties of attribute-value matrices):

(1) $\begin{bmatrix}\textsc{att1} & \begin{bmatrix}\textsc{att2} & \textsc{val}\end{bmatrix}\end{bmatrix} \neq \begin{bmatrix}\textsc{att2} & \textsc{val}\end{bmatrix}$

(2) $\begin{bmatrix}\textsc{att1} & \textsc{val1}\\ \textsc{att2} & \textsc{val2}\end{bmatrix} = \begin{bmatrix}\textsc{att2} & \textsc{val2}\\ \textsc{att1} & \textsc{val1}\end{bmatrix}$

Thus, a language with relatively free word order, like Warlpiri, has quite different c-structures compared to a language with relatively fixed word order, like English, but the two languages have similar f-structures, which predicts that they are syntactically similar with respect to syntactic features and dependencies (Bresnan et al. 2016, chap. 1). It would be antithetical to the theory for compositional semantics to be defined by word order, since the cross-linguistically relevant information for semantics is captured in the unordered f-structure. So Glue uses a commutative logic for composition, which turns out to yield insights beyond those that originally motivated Glue. This is explored more carefully below, from a higher-level perspective.

This review highlights four properties of Glue, which will be used as organizing themes. These are:

1. Resource-sensitive composition. The logic of composition in Glue is resource sensitive: All and only the premises instantiated from the syntax are used in semantic composition, as a matter of the underlying logic of composition.
2. Flexible composition. The logic of composition in Glue is commutative: Semantic composition is systematically related to and constrained by syntax, but it is not determined by syntactic word order and is tightly restricted by resource-sensitive composition.
3. Autonomy of syntax. The logical assumptions of Glue yield a truly autonomous syntax, as a corollary of flexible composition. Semantic composition is commutative, but syntax is not. Therefore, syntax is subject to word order constraints that do not apply to semantic composition.
4. Syntax/semantics non-isomorphism. Grammatical formatives, e.g., lexical items, may contribute multiple Glue terms that are all contributed to the semantic proof or no Glue terms at all, as a corollary of autonomy of syntax. There is no requirement that a formative must make exactly one contribution to interpretation.

These themes are discussed more explicitly and demonstrated below, with a focus on the intuition behind each theme rather than its purely formal implementation. The review is organized as follows. Section 2 provides a general overview of Glue as a theory of semantic composition, without emphasis on the syntax–semantics interface. A reader who wishes only to get a very general sense of Glue could read just this section. Section 3 is a discussion of the Glue logic, expanding on the resource-sensitive composition and flexible composition themes. Section 4 turns to the relationship between Glue and syntax, expanding on flexible composition and bringing into play the autonomy of syntax and syntax/semantics non-isomorphism themes. Section 4.1 demonstrates how flexible composition and non-isomorphism allow tightly corresponding analyses of superficially quite distinct languages (Finnish and English). Section 4.2 presents a basic overview of quantifier scope in Glue, highlighting autonomy of syntax and further demonstrating flexible composition. Section 5 concludes and provides a bibliographic overview of Glue work of the last two decades or so, listed by topic.

2. GENERAL GLUE SEMANTICS

Linguistic meanings in Glue are encoded in meaning constructors, which are pairs of terms from two logics (the colon is just an uninterpreted pairing symbol):

(3) $\mathcal{M} : G$

$\mathcal{M}$ is an expression of the meaning language—that is, anything that supports the lambda calculus.[1] G is an expression of linear logic (Girard 1987), which specifies semantic composition based on a syntactic parse that instantiates the general terms in G to a specific syntactic structure. The meaning constructors thus serve as premises in a linear logic proof of the compositional semantics.

The fundamental compositional rules are those for the linear implication connective, $\multimap$. They are presented here in natural deduction style:

(4) Functional application:
Implication elimination — Modus ponens

$$\frac{\beta : A \multimap B \qquad \alpha : A}{\beta(\alpha) : B}\multimap_{\mathcal{E}}$$

(5) Functional abstraction:
Implication introduction — Hypothetical reasoning

$$\frac{\begin{array}{c}[\alpha : A]^{1}\\ \vdots\\ \beta : B\end{array}}{\lambda\alpha.\beta : A \multimap B}\multimap_{\mathcal{I},1}$$

The term on the left is a term from $\mathcal{M}$; the term on the right is a term from G. The correspondence between the left and right sides is determined by the Curry-Howard Isomorphism (Curry & Feys 1958, Howard 1980), which puts logical formulas in correspondence with computational types. In

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[1] For example, van Genabith & Crouch (1999), Bary & Haug (2011), and Lowe (2015b) use Muskens's (1996) Compositional Discourse Representation Theory (CDRT), and Dalrymple et al. (2019, chap. 14) use Haug's (2014) partialized version, Partial Compositional DRT (PCDRT).

this case, the correspondence is between linear logic formulas and types in the lambda calculus.[2] Note that A, B are schematics for possibly complex formulas, and therefore α, β may be complex terms. The rule for linear implication elimination corresponds to functional application. The rule for linear implication introduction corresponds to functional abstraction.

The implication elimination rule is standard modus ponens. The implication introduction rule is hypothetical reasoning: A hypothesis is uniquely flagged and is indicated by square brackets. Given the hypothesis, if a conclusion can be derived through some series of proof steps, indicated by the vertical ellipsis, then the hypothesis is discharged as the antecedent of an implication with the conclusion as the consequent, and its flag is withdrawn. On the left side of the colon, this corresponds to abstraction over the variable introduced in the left side of the hypothesis.

Given some head h and some arguments of the head $a_1, \ldots, a_n$, the implicational term associated with the head would be $a_1 \multimap \cdots \multimap a_n \multimap h$. For example, let us assume the following meaning constructor for the verb *likes* in the sentence *Alex likes Blake*:[3]

(6) $\lambda y.\lambda x.\mathbf{like}(y)(x) : b \multimap a \multimap l$

On the Glue side, l is mnemonic for *likes*, a for *Alex*, and b for *Blake*. The meaning constructor for *likes* would in fact be specified in some general form but instantiated relative to a particular syntactic structure. Let us assume that some instantiation has given us the meaning constructor in example 6.

Assuming that the lexical entries for *Alex* and *Blake* contribute meaning constructors that are instantiated to $\mathbf{alex} : a$ and $\mathbf{blake} : b$, we can construct the following proof, given example 6 (note that $\Rightarrow_\beta$ indicates β-reduction of a lambda term):

(7)
$$\dfrac{\mathbf{alex} : a \qquad \dfrac{\lambda y.\lambda x.\mathbf{like}(y)(x) : b \multimap a \multimap l \qquad \mathbf{blake} : b}{\lambda x.\mathbf{like}(\mathbf{blake})(x) : a \multimap l}\ {\multimap_{\mathcal{E}}}, \Rightarrow_\beta}{\mathbf{like}(\mathbf{blake})(\mathbf{alex}) : l}\ {\multimap_{\mathcal{E}}}, \Rightarrow_\beta$$

In fact this is only one of four ways to write down the single abstract normal form proof (Prawitz 1965), given that writing the proof down imposes an order.[4] Because the Glue logic is commutative (see Section 3 for further details), all four representations of the proof are equivalent.

Given the commutativity of the Glue logic, the arguments of the function can be freely reordered (recurried), as in example 8 below, but still yield the appropriate meaning:

(8) $\lambda x.\lambda y.\mathbf{like}(y)(x) : a \multimap b \multimap l$

Here is a schematic demonstration of how this argument reordering works in a proof, abstracting away from the particular **like** function. This also shows the implication rules in action:

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[2] Some early papers in Glue (Dalrymple et al. 1993, 1995b, 1997b; Crouch & van Genabith 1999; Fry 1999; Kehler et al. 1999; van Genabith & Crouch 1999) used a more ad-hoc method of relating the meaning terms to the Glue logic, but Dalrymple et al. (1997a, 1999a) introduced the Curry-Howard approach to Glue, which is now standard. Kokkonidis (2008) introduced an alternant called First-Order Glue that has also proven influential in subsequent Glue literature (e.g., Bary & Haug 2011, Lowe 2014, Gotham 2018, Gotham & Haug 2018, Findlay 2019; see also Andrews 2010 for a related proposal).

[3] The lambda term $\lambda y.\lambda x.\mathbf{like}(y)(x)$ is equivalent to the function **like** that it is built around (this is η-equivalence/reduction in the lambda calculus), but it is useful for the subsequent exposition to present it in non-η-reduced form.

[4] The *Blake* meaning constructor/premise must be written either to the right or to the left of the function, and similarly for the *Alex* meaning constructor/premise.

(9)
$$\dfrac{\dfrac{\dfrac{\dfrac{\dfrac{\lambda y.\lambda x.f(y)(x) : a \multimap b \multimap c \qquad [v : a]^1}{\lambda x.f(v)(x) : b \multimap c}\multimap_{\mathcal{E}} \qquad [u : b]^2}{f(v)(u) : c}\multimap_{\mathcal{E}}}{\lambda v.f(v)(u) : a \multimap c}\multimap_{\mathcal{I},1}}{\lambda u.\lambda v.f(v)(u) : b \multimap a \multimap c}\multimap_{\mathcal{I},2}}{\lambda x.\lambda y.f(y)(x) : b \multimap a \multimap c}\Rightarrow_{\alpha}, \Rightarrow_{\alpha}$$

The result is the original term in reordered form but without any change in meaning. The α-equivalences (where variables are renamed) are not strictly necessary but have been added for exposition. In general, given n arguments in the order $a_1 \dots a_n$, a reverse order $a_n \dots a_1$ can be obtained by a series of hypotheses on the arguments that are discharged in the order they were made. More generally, the arguments can be reordered in any order by mixing the order of hypothesis assumption and discharge.

3. THE GLUE LOGIC

The Glue logic is a fragment of linear logic (Girard 1987), a logic of resources.[5] Each premise in a linear logic proof must be used exactly once. This can be usefully understood from the perspective of substructural logics, which "focus on the behavior and presence—or more suggestively, the *absence*—of structural rules. These are particular rules in a logic which govern the behavior of collections of information" (Restall 2000, pp. 1–2; emphasis in the original). The key intuition is that manipulation of structural rules allows a precise logical characterization of some system of information. Language can be construed as information, whether from a cognitive (e.g., Chomsky 1986) or logical (e.g., van Benthem 1991) perspective.

Three structural rules of particular linguistic interest are weakening, contraction, and commutativity:

(10) Weakening — Intuition: A premise can be freely added

$$\dfrac{\Gamma \vdash B}{\Gamma, A \vdash B}$$

(11) Contraction — Intuition: Any additional occurrence of a premise can be freely discarded

$$\dfrac{\Gamma, A, A \vdash B}{\Gamma, A \vdash B}$$

(12) Commutativity — Intuition: Premises can be freely reordered

$$\dfrac{\Gamma, A, B \vdash C}{\Gamma, B, A \vdash C}$$

---

[5] Girard (1987) defines two modal operators for linear logic, ! (*Of course!*) and ? (*Why not?*), which can prefix particular premises (e.g., $!A$ or $?A$), allowing resource accounting to be turned off for the premise. Some early work in Glue used the ! modal in the analysis of coordination (Kehler et al. 1995, 1999), but Asudeh (2004, 2005a) argued for a stricter notion of resource sensitivity resulting from a simpler modality-free fragment of linear logic. Asudeh & Crouch (2002a) presented a polymorphic Glue analysis of coordination (Steedman 1985; Emms 1990, 1992) that does not require the modality (see also Dalrymple et al. 2019, chap. 16).

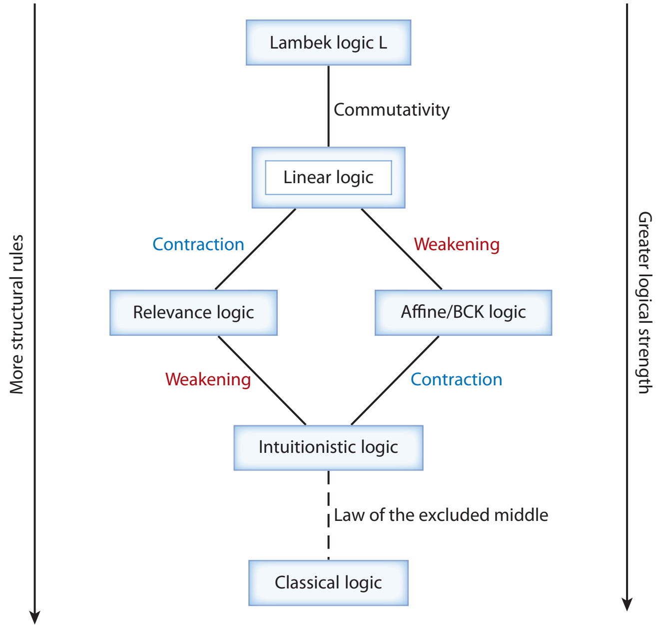


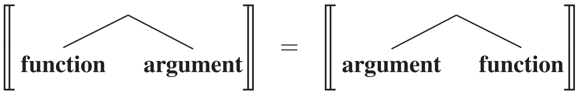
Figure 1

Hierarchy of logics related by structural rules (*solid lines*). The main logic of interest, linear logic, is indicated by the double box. Related logics are shown in single boxes. Classical logic is related to intuitionistic logic by the addition of the law of the excluded middle, which is not strictly a substructural rule, as indicated by the dashed line. Figure adapted with permission from Asudeh (2012, p. 103).

If the rules of weakening and contraction are missing from a logic, premises cannot be added or discarded: The logic is a resource logic. A resource logic can be commutative or noncommutative. Linear logic is a commutative resource logic, whereas the Lambek logic L (Lambek 1958) is noncommutative. L is the fundamental logic of the Lambek calculus, the basis for the type-logical approach to CG (see, e.g., van Benthem 1991, Moortgat 1997). The diagram in **Figure 1** situates linear logic, the logic that serves as the Glue logic, in a space of related substructural logics. (A caveat is that the relation between intuitionistic logic and classical logic is characterized by the addition of the law of the excluded middle, but this is not strictly a structural rule, and hence the dashed line.)

Semantics is most directly modeled by a commutative resource logic, because semantic composition is resource sensitive but does not show evidence of order sensitivity in its own right (Asudeh 2012, chap. 5). Given some binary structure to be interpreted, if one branch denotes a function and the other denotes an argument, the function applies to the argument, whether the function is on the left or the right:

(13)



It is not the order of the function and the argument that determines their composition, but rather their semantic types (Klein & Sag 1985). This is saliently exemplified by the rule of functional application in the widely familiar system of Heim & Kratzer (1998, pp. 44, 95). It is also exemplified by the equivalent interpretations of the forward and backward slash rules of

Combinatory Categorial Grammar (see, e.g., Steedman 1987, p. 406; Steedman & Baldridge 2011, p. 186).

But how is semantics resource sensitive? Klein & Sag (1985, p. 172) note:

> Translation rules in Montague semantics have the property that the translation of each component of a complex expression occurs exactly once in the translation of the whole.... That is to say, we do not want the set S [of semantic interpretations of a phrase] to contain all meaningful expressions of IL [Intensional Logic] which can be built up from the elements of S, but only those which use each element exactly once.

In other words, Montague's translation rules are resource sensitive, but this is coincidental as far as his translation process is concerned. In their generalization of the Montagovian system, Klein & Sag (1985, p. 174) need to define an operation of bounded closure, which ensures that the meaning of each semantic element is indeed used "exactly once."

In contrast, if we adopt a resource logic for semantic composition, we get this result in a more general way. First, a set of linear logic premises is a multiset (a.k.a. a bag), since the lack of contraction means that the number of occurrences of a premise matters. Second, the lack of weakening means that the bag must be emptied in constructing a valid proof. In short, "each element" must be used "exactly once." Thus, Klein & Sag's bounded closure is effectively an attempt to capture the logical resource sensitivity of linear logic or L. In turn, logical resource sensitivity forms the basis for linguistic resource sensitivity just by placing a linguistically motivated goal condition on the Glue logic proof (Asudeh 2012, chap. 4); for example, we can require that the proof of a sentence terminate in a single meaning constructor of type *t* (Dalrymple et al. 1999a). Resource-sensitive composition not only directly captures bounded closure but arguably also captures a disparate set of principles across a variety of frameworks, such as Completeness and Coherence (Kaplan & Bresnan 1982), the Theta Criterion (Chomsky 1981), the Projection Principle (Chomsky 1981, 1982, 1986), No Vacuous Quantification (Chomsky 1982, 1995; Kratzer 1995; Kennedy 1997; Heim & Kratzer 1998; Fox 2000), the Principle of Full Interpretation (Chomsky 1986, 1995), and the Inclusiveness Condition (Chomsky 1995).

In fact, it seems phonology and syntax can be equally considered resource sensitive; that is, they lack weakening and contraction from a logical perspective, as sketched by Asudeh (2012, pp. 98–99). This allows a deeper generalization about natural language as computation (Steedman 2007): Natural language is resource sensitive. The claim is enshrined in the Resource Sensitivity Hypothesis (Asudeh 2012, p. 95). Where phonology and syntax contrast with semantics is not with respect to weakening and contraction, but rather with respect to commutativity: Phonology is strictly noncommutative, whereas syntax shows commutativity in certain circumstances of free word order. The partial commutativity of syntax can be captured by separating syntax and semantics, by treating syntax autonomously as in Glue, or by not separating them and introducing a mechanism to the syntax–semantics interface that relaxes commutativity in an otherwise noncommutative system, such as the categorial modalities of Baldridge (2002).

4. GLUE AND THE SYNTAX–SEMANTICS INTERFACE

Glue makes the following assumptions about the syntax–semantics interface:

1. The logical syntax of semantic composition (Fenstad et al. 1987), captured through the syntax of linear logic proofs, is distinct from the structural syntax of categorially determined distribution, word order, constituency, and local and unbounded dependencies (i.e., syntax in the standard sense).
2. Structural syntax is systematically related to logical syntax through the instantiation of Glue meaning constructors.

These assumptions make Glue a semantic theory of a third kind, related to but also ultimately distinct both from interpretive theories of semantic composition—such as Logical Form semantics (e.g., Heim & Kratzer 1998) or description-by-analysis semantics for LFG (Halvorsen 1983)—and from parallel theories of semantic composition—such as Combinatory or Type-Logical Categorial Grammar (e.g., Carpenter 1997, Steedman & Baldridge 2011).[6] Like Logical Form semantics, Glue posits a separate level of structural syntax; but unlike Logical Form semantics, the syntactic structure in its entirety is not the input to semantic interpretation. Like CG, Glue assumes that the fundamental compositional operation, functional application, is directly paired with complex categories in terms that are defined implicationally;[7] but unlike CG, Glue does not assume that these conditional categories are responsible for word order, but rather that there is a syntactic representation that is separate (though parallel, at least in constraint-based theories of syntax).

These assumptions bring forth a strong notion of syntactic autonomy. The very strong assumptions about the relationship between syntax and semantics in CG semantics entail that any semantic distinction must be reflected by a syntactic distinction. Similarly, in Logical Form semantics, any interpretive difference must be due to an underlying syntactic difference. Moreover, in an interpretive theory like Logical Form semantics, the needs of semantics perforce result in things in the syntax that are not obviously syntactic in nature. The predicate abstraction/numerical nodes in Heim & Kratzer (1998, p. 186), which require the effective addition of lambda operators to the object language, are an example.

The themes of flexible composition and autonomy of syntax in Glue will be demonstrated by the analysis of quantifier scope ambiguity in Section 4.2. Consider the following standard example:

(14) Everybody loves somebody

The Glue logic computes two readings for this sentence, but without any corresponding syntactic distinction. This contrasts with both Logical Form semantics and CG semantics, which both require the sentence to be somehow syntactically ambiguous.

In order to demonstrate Glue at the syntax–semantics interface, we need to pair it with some syntactic framework. The natural framework to pair it with is LFG, since this is the syntax that most Glue work has assumed, but readers are referred to Section 1 for a list of other syntactic frameworks that have been paired with Glue.

4.1. Glue Semantics for Lexical-Functional Grammar

The pairing of Glue with LFG, often called LFG+Glue, also allows us to demonstrate flexible composition and syntax/semantics non-isomorphism. Consider the parallel Finnish/English example in **Figure 2**.[8,9] The distinct simple c-structures capture the variation in syntactic realization between the two languages—in particular, that Finnish allows null subjects, unlike English—whereas the common f-structure shows that these distinct realizations encode identical syntactic

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[6] This kind of theory was historically called rule-by-rule composition (Bach 1976) and is sometimes still referred to as such, but the term is deprecated now, since it originates in the paired syntactic/semantic rules approach of Montague (1973), which is no longer practiced in that form. This kind of theory is also sometimes referred to as direct compositionality (Barker & Jacobson 2007, Jacobson 2014), but this raises the further question of direct relative to what (Asudeh 2006).

[7] Slashes are just directed implications (since the logic of categories is noncommutative; see Section 3). For example, X/Y states that one can conclude a category X conditional on there being a category Y to the right; in other words, Y → X yields X so long as Y is on the right.

[8] Note that all pronouns in LFG have the PRED value 'pro.'

[9] LFG's theory of phrase structure allows the Finnish verb to be absent in VP and to be base-generated in I (Bresnan et al. 2016, chaps. 6–7).

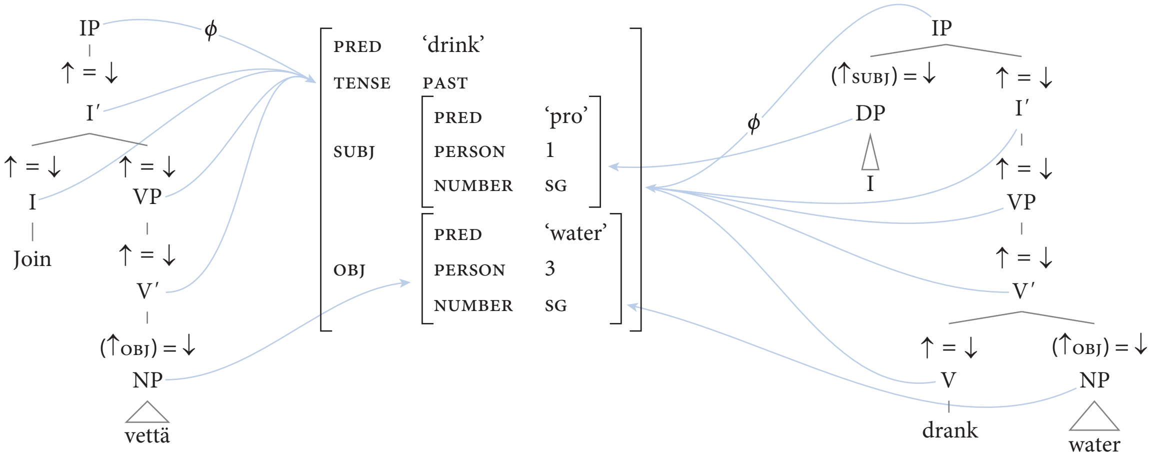

Figure 2

Finnish and English examples demonstrating variability at c-structure (trees) and universality at f-structure (attribute-value matrix) in Lexical-Functional Grammar. The up and down arrows indicate the mapping from c-structure to f-structure: ↑ means 'my parent's f-structure'; ↓ means 'my f-structure.' Figure adapted with permission from Asudeh & Toivonen (2015, p. 398).

features and dependencies. An up arrow in c-structure, ↑, refers to the f-structure of a node's mother, and a down arrow, ↓, refers to the f-structure of the node itself. The up and down arrows are called metavariables in LFG (Kaplan & Bresnan 1982), because they are variables over f-structure labels, which are themselves variables. The annotation ↑ = ↓ is thus the mechanism for equating the f-structure content of a head with that of its projections, and it is also what is ultimately responsible for the functional category I and the lexical category V cocontributing to the verbal spine. The ϕ correspondence function maps from c-structure to f-structure; only one of the ϕ-mappings from each c-structure has been labeled with the ϕ function to reduce clutter. **Figure 3** shows the same structures with the arrows resolved. One way to solve the equations is

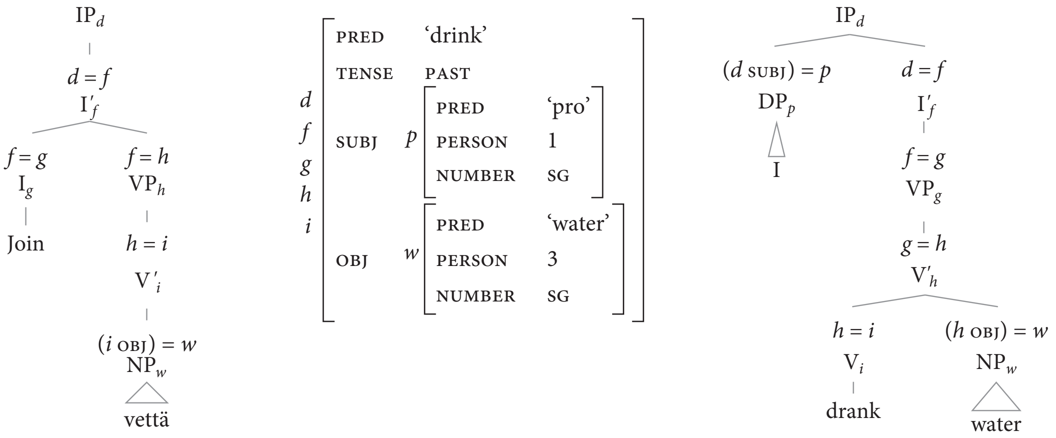

Figure 3

Lexical-Functional Grammar: Finnish and English c-structures (trees) and f-structure (attribute-value matrix) with ↑ and ↓ metavariables resolved in c-structures to their correspondents in the f-structure.

Table 1 Lexicons: Finnish and English

Finnish			English		
join	I	$(\uparrow \textsc{pred}) = \text{‘drink’}$ $(\uparrow \textsc{tense}) = \textsc{past}$ $(\uparrow \textsc{subj pred}) = \text{‘pro’}$ $(\uparrow \textsc{subj person}) = 1$ $(\uparrow \textsc{subj number}) = \textsc{sg}$ $\textbf{speaker} : (\uparrow \textsc{subj})_\sigma$ $\textbf{drink} :$ $(\uparrow \textsc{obj})_\sigma \multimap (\uparrow \textsc{subj})_\sigma \multimap \uparrow_\sigma$	I	D	$(\uparrow \textsc{pred}) = \text{‘pro’}$ $(\uparrow \textsc{person}) = 1$ $(\uparrow \textsc{number}) = \textsc{sg}$ $\textbf{speaker} : \uparrow_\sigma$
			drank	V	$(\uparrow \textsc{pred}) = \text{‘drink’}$ $(\uparrow \textsc{tense}) = \textsc{past}$ $\textbf{drink} :$ $(\uparrow \textsc{obj})_\sigma \multimap (\uparrow \textsc{subj})_\sigma \multimap \uparrow_\sigma$
vettä	N	$(\uparrow \textsc{pred}) = \text{‘water’}$ $(\uparrow (\textsc{person}) = 3$ $(\uparrow \textsc{number}) = \textsc{sg}$ $^*\textbf{water} : \uparrow_\sigma$	*water*	N	$(\uparrow \textsc{pred}) = \text{‘water’}$ $(\uparrow \textsc{person}) = 3$ $(\uparrow \textsc{number}) = \textsc{sg}$ $^*\textbf{water} : \uparrow_\sigma$

to label all c-structure nodes that bear a down arrow with an f-structure variable. Instantiation of the metavariables ↑ and ↓ is arbitrary, barring accidental identity, and resolves the equalities (Bresnan et al. 2016, pp. 54–58). Thus, the variables on the f-structure in **Figure 3** correspond to the f-structure variables that adorn the c-structure nodes; e.g., d is the f-structure of the root IP node, the main f-structure. For a brief introduction to LFG and the c-structure/f-structure mapping, readers are referred to Börjars (2020).

The mapping to the OBJ(ECT) grammatical function in both languages is contributed structurally by the annotation $(\uparrow \textsc{obj}) = \downarrow$. In contrast, the mapping to the SUBJ grammatical function is also contributed structurally in English but is instead contributed morphologically in Finnish. This is captured in the lexical entries in **Table 1**, which describe the mappings to f-structure that are encoded lexically and also contain Glue meaning constructors that define the mappings to s-structure and encode the composition for the head as linear implications.[10,11] The annotation σ on the arrows in the Glue meaning constructors indicates that these are the s-structure correspondents of the relevant f-structures; the σ correspondence function maps from f-structure to s-structure.[12]

The up arrows in the lexical entries in **Table 1** are instantiated to the f-structure of the relevant preterminal node: g (Finnish *join*), w (Finnish *vettä*), p (English *I*), i (English *drank*), and w (English *water*).[13] However, because we know from **Figure 3** that $g = i = d$, we can just use the mnemonic label d in all relevant cases. And because we know that $(d\ \textsc{subj}) = p$, we can also

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[10] Note that the asterisk in the term for *vettä*/*water* is the cumulativity operator of Link (1983), which indicates that **water** is a mass term.

[11] Tense is set aside here for simplicity, but it is straightforward to adapt standard analyses of tense to the Glue context (Haug 2008, Bary & Haug 2011, Lowe 2015b). Grønn & von Stechow (2016) provide a recent overview of core literature on tense and some analytical options.

[12] LFG's use of the term "s-structure" for semantic-structure is not to be confused with the use of "S-structure" in Government and Binding Theory (Chomsky 1981). The ϕ correspondence is not shown explicitly, because it is already part of the definition of the up and down arrows (see, e.g., Dalrymple et al. 2019, p. 169).

[13] In the case of the abbreviated (triangle) structures, there would be intervening nodes, so this is a slight fudge, but in this case each word is the head of its phrase and there would be a chain of $\uparrow = \downarrow$ annotations between the word and the phrase it heads, so it is a harmless fudge.

take advantage of that equality. We therefore get the following collection of identical instantiated meaning constructors for each language:[14]

(15) $\Gamma = \{\textbf{speaker} : p_\sigma, \textbf{drink} : w_\sigma \multimap p_\sigma \multimap d_\sigma, \textbf{*water} : w_\sigma\}$

This yields a single normal form proof (i.e., minimal proof; Prawitz 1965) for the corresponding Finnish and English sentences, which can be presented in natural deduction format as follows (recall that order of premises on a proof line does not matter, since the Glue logic is commutative):

(16)

$$\dfrac{\textbf{speaker} : p_\sigma \qquad \dfrac{\textbf{drink} : w_\sigma \multimap p_\sigma \multimap d_\sigma \qquad \textbf{*water} : w_\sigma}{\textbf{drink}(\textbf{*water}) : p_\sigma \multimap d_\sigma}\multimap_{\mathcal{E}}}{\textbf{drink}(\textbf{*water})(\textbf{speaker}) : d_\sigma}\multimap_{\mathcal{E}}$$

This concludes the demonstration of the basics of Glue at the syntax–semantics interface, using LFG as the syntactic framework.

Notice how the themes of autonomy of syntax and syntax/semantics non-isomorphism came into play. The Glue meaning constructors are related to the syntax and require instantiation by a syntactic structure (an f-structure), but they neither interpret the structure, as in Logical Form semantics, nor assume that structural/categorial syntax is the logical syntax, as in CG semantics. Glue's autonomous syntax thus distinguishes Glue from both Logical Form semantics and CG semantics. With respect to the theme of non-isomorphism, we have seen how Glue can directly capture the parallelism between morphosyntactically quite distinct languages, such as Finnish and English, by attributing the same set of meaning constructors to both languages but allowing them to distribute distinctly in the morphosyntax. It is noteworthy that Glue can achieve non-isomorphism and capture distributed semantics even when paired with a lexicalist theory such as LFG in which syntactic terminals are complete words.[15] This again showcases autonomy of syntax, because it shows that there can be a mismatch between syntax and semantics. Next I turn to quantifier scope, which further expands on the themes of autonomy of syntax and flexible composition.

4.2. Quantifier Scope

Let us return to the standard quantifier scope example above, repeated here:

(14) Everybody loves somebody

As we have seen, Glue derives a strong notion of autonomy of syntax and an attendant notion of flexible composition. This allows Glue to treat example 14 as syntactically unambiguous but nevertheless semantically ambiguous.

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[14] Note that Γ is a multiset, not a set, due to the Glue logic's lack of contraction, and that the only valid proof empties this multiset, due to the Glue logic's lack of weakening (see Section 3).

[15] It is possible to pair Glue with a model of morphosyntax in which syntactic terminal nodes are not words, as in Distributed Morphology (Halle & Marantz 1993). This is part of the Lexical-Realizational Functional Grammar (L_RFG) project, which seeks to marry the realizational morpheme-based assumptions of Distributed Morphology to a nonlexicalist version of LFG (Melchin et al. 2020, Asudeh et al. 2021). However, this would be a weaker demonstration of non-isomorphism, since it is not surprising that a model that breaks syntax up into minimal meaningful units can capture the meaning fragmentation/distributed semantics offered by Glue's syntax/semantics non-isomorphism; there is no mismatch in that case.

I will not show the c-structure here, but it would be equivalent to the c-structure for English in **Figures 2** and **3** above, with the DP *everybody* in the position that maps to SUBJ, the DP *somebody* in the position that maps to OBJ, and the verb suitably replaced. The single f-structure for the sentence is shown here, with mnemonic labels:

(17)

$$l\left[\begin{array}{ll} \text{PRED} & \text{‘love’} \\ \text{TENSE} & \text{PRES} \\ \text{SUBJ} & e\left[\begin{array}{ll} \text{PRED} & \text{‘everybody’} \\ \text{PERSON} & 3 \\ \text{NUMBER} & \text{SG} \end{array}\right] \\ \text{OBJ} & s\left[\begin{array}{ll} \text{PRED} & \text{‘somebody’} \\ \text{PERSON} & 3 \\ \text{NUMBER} & \text{SG} \end{array}\right] \end{array}\right]$$

The Glue meaning constructors in the lexical entries are as follows, again setting tense aside:[16]

(18) *everybody* D $\lambda Q.\mathbf{every}(\mathbf{person}, Q) : \forall S.(\uparrow_\sigma \multimap S) \multimap S$
somebody D $\lambda Q.\mathbf{some}(\mathbf{person}, Q) : \forall S.(\uparrow_\sigma \multimap S) \multimap S$
loves V $\lambda y.\lambda x.\mathbf{love}(y)(x) : (\uparrow \text{OBJ})_\sigma \multimap (\uparrow \text{SUBJ})_\sigma \multimap \uparrow_\sigma$

Instantiating these relative to the f-structure in example 17, we get:

(19) $\Gamma = \{\, \lambda y.\lambda x.\mathbf{love}(y)(x) : s \multimap e \multimap l,$
$\lambda Q.\mathbf{every}(\mathbf{person}, Q) : \forall S.(e \multimap S) \multimap S,$
$\lambda Q.\mathbf{some}(\mathbf{person}, Q) : \forall S.(s \multimap S) \multimap S \,\}$

The functions **every** and **some** are standard type $\langle\langle e,t\rangle, \langle\langle e,t\rangle, t\rangle\rangle$ quantificational determiners from generalized quantifier theory (Montague 1973, Barwise & Cooper 1981, Keenan & Faltz 1985). They are defined respectively as $\lambda P.\lambda Q.P \subseteq Q$ and $\lambda P.\lambda Q.P \cap Q \neq \varnothing$, where P is the set of entities that is the determiner's restriction, and Q is the set of entities that is its scope. The quantifier $\lambda Q.\mathbf{every}(\mathbf{person}, Q)$ therefore returns true if the set of people is a subset of its scope set, and the quantifier $\lambda Q.\mathbf{some}(\mathbf{person}, Q)$ returns true if the intersection of the set of people and its scope set is not empty.

The universal quantification symbol $\forall$ in the Glue logic terms for the quantifiers ranges over terms in the Glue logic. It allows the quantifier to take as its scope any Glue logic dependency on the semantic correspondent of the quantifier. Readers are referred to Asudeh (2005b, pp. 393–94) for some discussion of the interpretation of $\forall$ in linear logic; in short, the basic intuition is that, given the resource sensitivity of linear logic, the universal means “any one,” not “all.” Importantly, the linear universal defines scope points—where quantifiers can take scope—and its interpretation is not related to the quantificational force in the meaning language: In fact, **every** and **some** are equivalently associated with these linear universal scope terms, even though **some** has existential force.

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[16] It is again useful for expository purposes to present the meaning term for *loves* in non-η-reduced form.

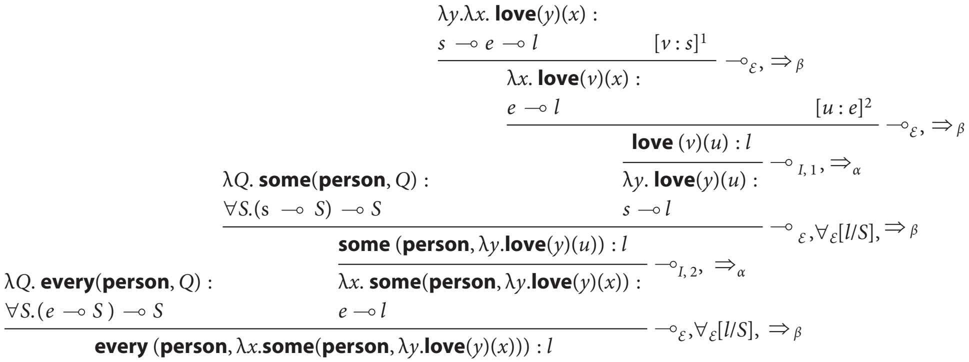

Figure 4

Surface scope interpretation of *Everybody loves somebody*. Symbols and conventions: $\multimap$ is linear implication; bold indicates a function; I indicates natural deduction introduction; ε indicates natural deduction elimination; $\Rightarrow$ indicates α/β conversion in the lambda calculus; square brackets in a premise indicate a hypothesis/assumption; square brackets beside a rule indicate a variable substitution.

The meaning constructors in example 19 yield exactly two normal form/minimal proofs, which can be represented as in **Figures 4** and **5**.[17] In other theories, this necessitates either a syntactic operation such as Quantifier Raising in Logical Form semantics (May 1977, 1985; Heim & Kratzer 1998), an interpretive theory of composition, or a type shifting operation and corresponding categorial modification of some kind in parallel composition approaches, as in Combinatory or Type-Logical Categorial Grammar semantics (Partee & Rooth 1983, Hendriks 1993; see Jacobson 2014, chap. 14, for a textbook comparison of the Logical Form and CG approaches). Flexible composition in Glue is related to its strong notion of autonomy of syntax. The fact that Glue assumes an independent level of syntax allows composition to be flexible, which in turn allows the theory to derive the two distinct scope readings without positing a syntactic ambiguity or type shift.

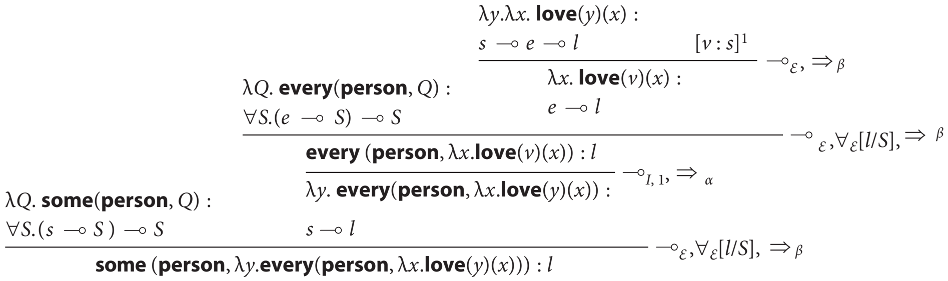

Figure 5

Inverse scope interpretation of *Everybody loves somebody*. Symbols and conventions: $\multimap$ is linear implication; bold indicates a function; I indicates natural deduction introduction; ε indicates natural deduction elimination; $\Rightarrow$ indicates α/β conversion in the lambda calculus; square brackets in a premise indicate a hypothesis/assumption; square brackets beside a rule indicate a variable substitution.

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[17] The universal linear instantiation step is straightforward, as in classical/intuitionistic logic, so I have not shown it explicitly.

5. CONCLUSION

Glue Semantics is a general framework for semantic composition and the syntax–semantics interface. Semantic theories can be built around this framework by developing some of its key properties. Four key properties were identified and used as themes throughout this article: resource-sensitive composition, flexible composition, autonomy of syntax, and syntax/semantics non-isomorphism. Resource-sensitive composition means that analyses in Glue are highly constrained by the logic of composition, that is, linear logic. For example, resource sensitivity highlights problems of shared arguments in phenomena like control and raising, unbounded dependencies, coordination, resumptive pronouns, and their interactions. Resource-sensitive composition allows semantic composition to be constrained but nevertheless commutative, which in turn yields the property of flexible composition, such that the logical syntax of composition is not identical to the structural syntax, although the two are related in a well-defined way. This yields the property of autonomy of syntax, according to which syntax and semantics are separate levels, and semantic concerns do not trump syntactic ones or vice versa. Lastly, the autonomy of syntax in turn yields the property of non-isomorphism, whereby syntactic formatives may make multiple or no contributions to semantic composition. It is then an independent theoretical choice whether to capture the meaning constructors in syntactic terminals that represent words or to distribute them in some other way in the syntactic structure.

It would be impossible in a review of this scope to do full justice to the work that has been carried out in Glue over the last nearly three decades. Instead, I here present a representative sample of that work, listed alphabetically by the descriptive terms I have chosen for the phenomena:[18] anaphora (Dalrymple et al. 1999c; Asudeh 2005b, 2012; Bary & Haug 2011; Belyaev & Haug 2014; Dalrymple et al. 2019, chap. 14); argument structure and argument realization (Asudeh & Giorgolo 2012; Arnold & Sadler 2012; Asudeh et al. 2014; Findlay 2014, 2016, 2020; Lowe 2015a, 2019; Przepiórkowski 2017; Lowe & Birahimani 2019; Lovestrand 2020; Asudeh 2021); category theory for natural language semantics (Giorgolo & Asudeh 2012a,b, 2014a,b; Asudeh & Giorgolo 2016, 2020); complex predicates (Andrews 2007, 2018; Lowe 2015a, 2019; Lowe & Birahimani 2019; Lovestrand 2020); computational applications (Crouch et al. 2001, Lev 2007, Meßmer & Zymla 2018, Dalrymple et al. 2020); constructions (Asudeh et al. 2008, 2013; Asudeh & Toivonen 2014); control/equi and raising (Asudeh 2005a; Haug 2013; Dalrymple et al. 2019, chap. 15); conventional implicature (Asudeh 2004; Potts 2005; Arnold & Sadler 2010, 2011; Giorgolo & Asudeh 2012a, chap. 4); coordination (Kehler et al. 1999; Asudeh & Crouch 2002a; Dalrymple et al. 2019, chap. 16); copy raising (Asudeh 2004, 2012; Asudeh & Toivonen 2007, 2012); distance distributivity (Przepiórkowski 2014a,b, 2015); dynamic semantics (Crouch & van Genabith 1999; van Genabith & Crouch 1999; Dalrymple et al. 2019, chap. 14); event semantics (Fry 1999; Asudeh & Giorgolo 2012; Asudeh & Toivonen 2012; Asudeh et al. 2013, 2014); evidentiality (Asudeh & Toivonen 2017); formal foundations (Dalrymple et al. 1999a,b,c; Asudeh 2004, 2012, chap. 5; Kokkonidis 2008; Andrews 2008, 2010; Findlay 2021); idioms and multiword expressions (Findlay 2019); incorporation (Asudeh 2007, Baker et al. 2010); information structure (Mycock 2006, Dalrymple & Nikolaeva 2011, Morrison 2017); intensionality (Dalrymple et al. 1999c, Asudeh & Toivonen 2012); interpretation of concomitance (Haug 2009); interpretation of fragments (Asudeh 2012, chap. 11); interpretation of split nominals (Kuhn 2001); interpretation of unbounded dependencies (Asudeh 2012; Dalrymple et al. 2019, chap. 17); modification (Dalrymple et al. 1993, 1999b; Dalrymple 2001; Asudeh & Crouch 2002b; Andrews 2018;

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[18] Other terms and orderings are available.

Dalrymple et al. 2019, chap. 13); negative polarity items (Fry 1999); perception verbs (Asudeh & Toivonen 2007, 2012; Asudeh 2012; Camilleri et al. 2014); predication (Dalrymple 2001; Asudeh & Crouch 2002b; Dalrymple et al. 2019, chap. 13); quantification and scope (Dalrymple et al. 1999c; Dalrymple et al. 2019, chap. 8); relational nouns (Asudeh 2005b); resumptive pronouns (Asudeh 2004, 2005b, 2011, 2012; Camilleri & Sadler 2011); and tense and aspect (Haug 2008; Bary & Haug 2011; Lowe 2014, 2015b; Belyaev 2020). Also relevant is the rich set of open source tools developed by Zymla (2021a,b,c) for computational implementation and testing of Glue analyses.[19] The initial paper describing these tools is by Dalrymple et al. (2020).

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[19] Zymla's (2021c) tool is in particular for use with the XLE tools for computational implementation and testing of LFG grammars (Crouch et al. 2011).

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