On Comparing Dynamic and Underspecified Semantics for LFG

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1 Introduction

Lexical Functional Grammar [Kaplan and Bresnan, 1982; Dalrymple *et al.*, 1995a] has enjoyed a rich variety of semantic interpretation components including [Halvorsen, 1983; Frey and Reyle, 1983; Frey *et al.*, 1983; Reyle, 1985; Wada and Asher, 1986; Fenstad *et al.*, 1987; Reyle, 1988; Halvorsen and Kaplan, 1988; Asher and Wada, 1988; Wedekind and Kaplan, 1993; Dalrymple *et al.*, 1996; Muskens, 1995]. With the exception of [Muskens, 1995], these approaches concentrate on providing schemas for relating (or translating) f-structures (in)to (sets of) *disambiguated* semantic representations. Typically, the semantics employed provide interpretations for isolated sentences and their constituents (exceptions are the DRT inspired [Frey and Reyle, 1983; Frey *et al.*, 1983; Reyle, 1985; Wada and Asher, 1986; Asher and Wada, 1988]). More recently, a number of papers have outlined alternative ways of providing LFGs with both *underspecified* and *dynamic* interpretation components. These approaches can be classified into a *mapping*-approach, a *"dynamic" meaning representation language* approach and a *linear logic context management* approach. The *mapping* approach [Genabith and Crouch, 1996a; Genabith and Crouch, 1996b; Genabith and Crouch, 1997b] is based on structural similarities between syntactic LFG f-structure and semantic Quasi-Logical Form (QLF) [Alshawi and Crouch, 1992] and Underspecified Discourse Representation Structure (UDRS) [Reyle, 1993; Reyle, 1995] representations. It establishes one-to-one correspondences between (subsets of) these representation formalisms and reads (i.e. interprets) an f-structure as its corresponding QLF or UDRS. The *"dynamic" meaning representation language* approach [Genabith and Crouch, 1997a] is based on [Dalrymple *et al.*, 1996] and imports dynamic meaning representation expressions [Muskens, 1996] into the meaning representation slots in the original glue language semantics. The *linear logic context management* approach [Crouch and Genabith, 1996] exploits the properties of the linear logic glue language to directly model context update and interpretation in context in the glue language derivations without the need of importing a dynamic meaning representation language. Both the *linear logic context management* and the *"dynamic" meaning representation language* approach can be combined with a fine-grained approach to operator and quantifier scope underspecification developed in [Crouch and Genabith, 1996] and a set of linear logic premises thus obtained can be given a QLF- or UDRT-style underspecified interpretation. The three approaches are developed independently and discussed at length elsewhere. In the present paper, we give brief and informal presentations of the dynamic and underspecified approaches and then compare them against each other and with some of the alternatives discussed in the literature.

2 LFG and Semantics

Early proposals for combining LFG and formal semantics are [Halvorsen, 1983; Frey and Reyle, 1983; Frey *et al.*, 1983; Reyle, 1985]. Halvorsen assumes five levels of representation: c-structure, f-structure, s-structure (semantic structure), IL (Montague's intensional logic) and models. f-structures are translated into s-structure by means of translation rules triggered by f-structure templates (in the LFG literature this is referred to as a *description by analysis* approach). The translation assigns quantifier scope. The scope of adjuncts, tense, negation and modal operators is decided by translation rules mapping s-structure to IL. IL formulas are then interpreted model theoretically. [Frey and Reyle, 1983; Frey *et al.*, 1983; Reyle, 1985] explore a number of ways of combining a DRT-based semantics with LFG grammars in a computational setting. Some of these approaches provide algorithms for translating (semantically annotated) f-structures into disambiguated DRSs, others early instances of what is now usually referred to as *co-description* based approaches. These proposals have been developed further by [Wada and Asher, 1986;

Asher and Wada, 1988]. A co-description based approach for relating syntactic and semantic representations is developed in [Halvorsen and Kaplan, 1988] where quantifier scopes are explicated at s-structure with QP quantifier scope points. Scope constraints are formulated lexically in terms of inside-out functional uncertainty equations. [Fenstad *et al.*, 1987] develop a sign based approach (c.f. [Pollard and Sag, 1994]) to integrating phonological, syntactic and semantic information. The semantic representations are inspired by Situation Theoretic approaches [Barwise and Perry, 1983]. They underspecify quantifier scope but are not given a direct interpretation. Instead they require disambiguation in terms of externally provided QMODE specifications resulting in fully disambiguated interpretable representations. [Wedekind and Kaplan, 1993] develop type-driven algorithms involving a restriction operator for computing (sets of) disambiguated type-theory based representations from semantically annotated f-structures. A deductive linear logic glue language based approach to assembly of meaning representation expressions in LFG is developed in a series of papers including [Dalrymple *et al.*, 1993b; Dalrymple *et al.*, 1995b; Dalrymple *et al.*, 1996]. Despite the many differences in approach and orientation the proposals share two properties: first, they require disambiguated semantic representations for the purposes of model-theoretic interpretation (this is even true for [Fenstad *et al.*, 1987]) and second, with the exception of [Frey and Reyle, 1983; Frey *et al.*, 1983; Reyle, 1985] (and the subsequent elaborations) the semantics is sentence based (i.e. not dynamic). An underspecified and dynamic approach is provided by [Muskens, 1995]. In addition to f-structure annotations c-structure rules are annotated with what are called l-descriptions and s-descriptions. l-descriptions determine the structure of logical form expressions and allow to partially determine scope possibilities (in terms of dominance constraints) while s-descriptions determine the composition of semantic representations in the generalized l-trees. f-, l- and s-descriptions are stated as sets of simultaneous constraints (specifications of dominance relations and equality statements) on the various representations and a good representation is a solution to those constraints.

Ambiguity is all pervasive in natural language, so much so that a simple *generate and test* strategy is plainly infeasible in NLP. Two responses are possible. The first is historically the initial approach. It kind of "ignores" ambiguity and picks a single, fully disambiguated, most likely, default interpretation. If the particular choice turns out to be wrong one has to undo the choice (and everything that depends on it) and consider alternatives, computationally not a very attractive task. The second approach, one that has been developed formally largely in the 90's, is to underspecify analyses. The basic idea is to represent just as much information as one has evidence for. This is done in such a way that the representations can be enriched (i.e. further specified) monotonically with information yet to be encountered. The representations are capable of covering the whole spectrum of complete and partial underspecification to complete specification. Ideally underspecified representations are fully interpreted (i.e. come equipped with a logic with semantic and syntactic consequence relations). Underspecification is computationally attractive because it avoids the generate and test approach by simply accumulating information into a single data-structure. Quasi-Logical form (QLF) [Alshawi and Crouch, 1992] and Underspecified Discourse Representation Theory [Reyle, 1993; Reyle, 1995] are probably the most prominent approaches along these lines developed so far.

Context update and interpretation in context are the hallmarks of dynamic semantics (as opposed to traditional sentence based semantics). Both QLF and UDRT are dynamic in this general sense. UDRT inherits its dynamics from the DRT [Kamp and Reyle, 1993] approach. The QLF dynamics is based on E-type analyses and AI inspired approaches [Alshawi, 1990; Alshawi, 1992] to context modeling. Thus, both QLF and UDRT combine underspecification and dynamics.

It is interesting to note that several of the developers of earlier LFG semantics have commented on the fact that in a sense f-structures are flat (scopally etc. underspecified) representations and that this creates tensions with respect to mapping them to fully disambiguated semantic representations.

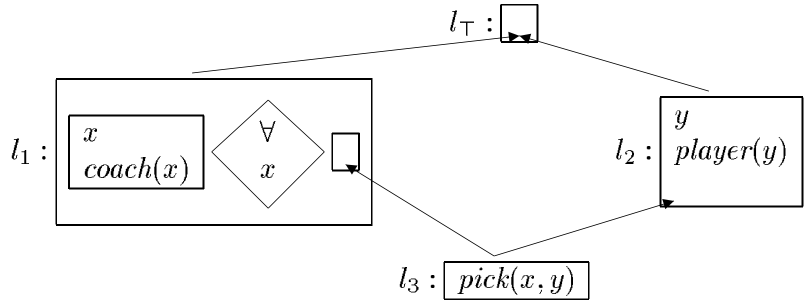
The reason is that traditional syntax/semantics interfaces tend to require strongly hierarchical syntactic structures (e.g. trees) to drive semantic composition. The approaches presented below turn what from the point of view of traditional approaches tends to look like a disadvantage into an advantage: that is they relate *underspecified syntactic* to *underspecified semantic* representations. All of this is, of course, facilitated by the fact that on the one hand we can draw on the earlier static and fully disambiguated LFG semantics and on the other hand the emergence of underspecified and dynamic formal semantics like QLF and UDRT. Part of the aim of the paper is therefore to trace to what extent the "new" approaches are inspired by their predecessors and where they differ.

3 F-Structure, QLF and UDRS Return Trips

LFG f-structures are abstract flat syntactic representations. Quasi Logical Forms (QLFs) [Alshawi and Crouch, 1992] and Underspecified Discourse Representation Structures (UDRSs) [Reyle, 1993; Reyle, 1995] are underspecified semantic representations. A number of papers [Genabith and Crouch, 1996a; Genabith and Crouch, 1997b] have proposed to "read" (i.e. interpret) f-structures as QLFs or UDRSs. In each case the approach is prompted by striking structural similarities between f-structure, QLF and UDRT representations. Consider, for example, (simplified) f-structure, QLF and UDRS representations associated with the sentence *every coach picked a player*:

$$\left[\begin{array}{ll} \text{SUBJ} & \left[\begin{array}{ll}\text{PRED} & \text{`COACH'}\\ \text{NUM} & \text{SG}\\ \text{SPEC} & \text{EVERY}\end{array}\right]\boxed{1} \\ \text{PRED} & \text{`PICK}\,\langle\uparrow\text{SUBJ},\uparrow\text{OBJ}\rangle\text{'} \\ \text{OBJ} & \left[\begin{array}{ll}\text{PRED} & \text{`PLAYER'}\\ \text{NUM} & \text{SG}\\ \text{SPEC} & \text{A}\end{array}\right]\boxed{2} \end{array}\right]\boxed{3}$$

```
?Scope:pick(+3,term(+1,<num=sg,spec=every>,
                    coach,?Q,?X),
          term(+2,<num=sg,spec=a>,
                    player,?P,?R))
```



Notice that the syntactic and the two semantic representations underspecify the scope of the quantificational NPs.[1] Notice further that the syntactic representation provides basic semantic, predicate-argument information in the form of the values of PRED features as well as quantificational information in terms of the values of SPEC features. While there certainly is difference in approach and emphasis unresolved QLFs, UDRSs and f-structures bear a striking similarity and it

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[1] Of course, the QLF or UDRT representations need not underspecify scope.

is easy to see how to get from the syntactic to either of the semantic representations and back.[2] To give an example, the core of a mapping τ_q taking us from f-structures to QLFs places the values of subcategorizable grammatical functions into their argument positions in the governing semantic form and recurses on those arguments.

$$\tau_q(\left[\begin{array}{ll} \Gamma_1 & \gamma_1 \\ \ldots & \\ \textsc{pred} & \Pi\langle\uparrow\Gamma_1,\ldots,\uparrow\Gamma_n\rangle \\ \ldots & \\ \Gamma_n & \gamma_n \end{array}\right]\boxed{\scriptstyle i}) := \texttt{?Scope}:\Pi(\texttt{i},\tau_q(\gamma_1),\ldots,\tau_q(\gamma_n))$$

$$\tau_q(\left[\begin{array}{ll} \alpha_1 & v_1 \\ \ldots & \\ \textsc{pred} & \Pi\langle\rangle \\ \ldots & \\ \alpha_n & v_n \end{array}\right]\boxed{\scriptstyle i}) := \texttt{term(i,<}\alpha_1 = v_1,\ldots,\alpha_n = v_n\texttt{>,}\Pi\texttt{,?Q,?R)}$$

From this rather general perspective the difference between f-structures and QLF is one of information packaging rather than anything else. Similarly, the core of a translation τ_u from f-structures into UDRSs can be defined as

$$\tau_u(\left[\begin{array}{ll} \Gamma_1 & \gamma_1 \\ \ldots & \\ \textsc{pred} & \Pi\langle\uparrow\Gamma_1,\ldots,\uparrow\Gamma_n\rangle \\ \ldots & \\ \Gamma_n & \gamma_n \end{array}\right]\boxed{\scriptstyle i}) := \tau_u(\mathrm{i}:\Pi\langle\uparrow\Gamma_1,\ldots,\uparrow\Gamma_n\rangle) \cup \tau_u(\gamma_1) \cup \ldots \cup \tau_u(\gamma_n)$$

where the translation of an f-structure is simply the union of the translation of its component parts. The translation functions τ_q and τ_u enable us to interpret f-structures as their translation images. An f-structure and its component parts inherit the underspecified semantics associated with its translation. τ_q and τ_u are simple and good natured. In fact they are homomorphic embeddings. Instead of an f-structure indirectly inheriting the semantics of its translation image we can eliminate the mapping and interpret f-structures directly. [Genabith and Crouch, 1996a] do this by adapting a QLF semantics to f-structure representations obtaining a direct and underspecified interpretation for f-structures. The UDRS mapping τ_u, on the other hand, allows us to exploit the UDRT deduction components [Reyle, 1993; Reyle, 1995; König and Reyle, 1996] with the translation images. UDRT deduction differs from other deduction systems in that as far as possible deductions are defined directly on the underspecified representations without the need to consider cases (i.e. without the need for disambiguations and then separate deductions on each of the disambiguations). [Genabith and Crouch, 1997b] discuss UDRS deduction on translation images and [König and Reyle, 1996] consider direct deductions on f-structures.

The translation functions τ_q and τ_u can be complemented with inverse functions τ_q^{-1} and τ_u^{-1} taking us from QLFs and UDRSs back to f-structures. It can be shown that for f-structures φ in a set of well-formed f-structures *wff-s*

$$\tau_q^{-1}(\tau_q(\varphi)) = \varphi$$

$$\tau_u^{-1}(\tau_u(\varphi)) = \varphi$$

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[2] Or, indeed, from any one of the semantic formalisms to the other.

The reverse, however, is not true: we cannot expect to translate any arbitrary QLF or UDRS into a corresponding f-structure. The reason is that currently f-structures do not explicitly encode fine-grained scope constraints (as available in QLF and UDRT). What the mappings do is establish one-to-one correspondences between subsets of the LFG, QLF and UDRS formalisms. It is possible to extend the correspondence by adding a scope constraint mechanism to the original f-structure formalism. Here we sketch how a QLF-style scope constraint mechanism could be implemented. Add list valued scope points SCP to f-structure representations as in

$$\left[\begin{array}{ll}
\text{SCP} & \left[\begin{array}{ll}\text{FST} & \boxed{2}\\ \text{RST} & \left[\begin{array}{ll}\text{FST} & \boxed{1}\\ \text{RST} & [\,]\end{array}\right]\end{array}\right]\\
\text{SUBJ} & \left[\begin{array}{ll}\text{PRED} & \text{`COACH'}\\ \text{NUM} & \text{SG}\\ \text{SPEC} & \text{EVERY}\end{array}\right]\boxed{1}\\
\text{PRED} & \text{`PICK}\ \langle\uparrow\text{SUBJ},\uparrow\text{OBJ}\rangle\text{'}\\
\text{OBJ} & \left[\begin{array}{ll}\text{PRED} & \text{`PLAYER'}\\ \text{NUM} & \text{SG}\\ \text{SPEC} & \text{A}\end{array}\right]\boxed{2}
\end{array}\right]$$

which represents the wide scope reading of the indefinite object NP. Scope constraints are then expressed in terms of inside-out functional uncertainty constraints (cf. [Halvorsen and Kaplan, 1988; Dalrymple, 1993]) of e.g. the form

$$(\text{GF}^{*}\uparrow)\ \text{SCP}\ \text{RST}^{*}\ \text{FST} = \downarrow$$

This constraint is associated with elements that are allowed to take arbitrarily wide scope (as e.g. claimed for indefinites in DRT). It says "go up any number of grammatical functions GF until you find a scope point SCP and assign scope".[3]

Mappings such as τ_q and τ_u are useful only if they are correct. A correctness criterion can be defined as preservation of truth with respect to an independent semantics. Both τ_q and τ_u can be shown to be correct with respect to e.g. the linear logic based glue language semantics in [Dalrymple *et al.*, 1996]. Because this semantics is neither underspecified nor dynamic correctness is with respect to sets of disambiguations and truth. Given an f-structure φ, the underspecified semantics of $\tau_q(\varphi)$ and $\tau_u(\varphi)$ is defined in terms of sets of disambiguations. Abstracting away from particular wrinkles of the QLF and UDRS disambiguation operations[4] Δ_Q and Δ_U we get

$$\tau_q(\varphi) \xrightarrow{\Delta_Q} \{\varrho^q_1, \ldots, \varrho^q_n\}$$

$$\tau_u(\varphi) \xrightarrow{\Delta_U} \{\varrho^u_1, \ldots, \varrho^u_n\}$$

Furthermore, for $\sigma_{ll}(\varphi)$ (where $\sigma_{ll}(\varphi)$ is the set of meaning constructors in the linear logic glue language semantics obtained from the σ projection of φ) we get

$$\{\varrho^l_i | \sigma_{ll}(\varphi) \vdash_{ll} \varrho^l_i\}$$

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[3] This is a sketch only. The full theory would have to ensure that the constraint would not construct arbitrary scope points and infinite scope lists etc. In addition one would also need to ensure that during analysis not all possible scopes are constructed - this would defeat the role of f-structures as underspecified representations. An underspecified f-structure is an f-structure plus *satisfiable* (sets of) scope constraints.

[4] Such as for example the clause boundedness of genuinely quantificational NPs in UDRT etc.

where $\vdash_{ll}$ is the linear logic syntactic consequence relation. Switching off QLF contextual resolution, disregarding the UDRT dynamics and restricting ourselves to simple truth-conditions (everything else being equal)[5] we have a one-to-one correspondence between the sets of disambiguations obtained from $\sigma_{ll}(\varphi)$, $\tau_q(\varphi)$ and $\tau_u(\varphi)$ defined by

$$[\![\varrho_i^q]\!]^Q = [\![\varrho_i^u]\!]^U = [\![\varrho_i^l]\!]^L$$

where $[\![\cdot]\!]^Q, [\![\cdot]\!]^U$ and $[\![\cdot]\!]^L$ are the thus restricted QLF, UDRT and the [Dalrymple *et al.*, 1996] type theory with generalized quantifiers interpretations. Notice that this does *not* imply that the underspecified semantics (even if restricted as outlined above) associated with $\tau_q(\varphi)$ and $\tau_u(\varphi)$ coincide. This point is discussed further in [Genabith and Crouch, 1997b] and in section 4 below.

4 Dynamic Meaning Representation Expressions and Glue

As an alternative to the mapping approach we can obtain a dynamic and underspecified semantics for LFG by modifying one of the current LFG semantics. This approach has been explored in [Genabith and Crouch, 1997a] which builds on and extends the glue language semantics developed in [Dalrymple *et al.*, 1996]. The basic idea is twofold: first, replace the static type theoretic meaning representation expressions by "*dynamic*" expressions and second, interpret sets of linear logic premises (sets of meaning constructors – or the corresponding f-structures) as underspecified representations. In order to achieve a fine-grained approach to underspecification as in QLF and UDRT (which allow complete underspecification, complete disambiguation and partial (under)specification) sets of linear logic premises need to be complemented with a flexible scope constraint mechanism. It turns out that the mechanism developed in [Crouch and Genabith, 1996] and discussed in section 5 below carries over unchanged.
The new meaning representation language is Muskens' CDRT (Compositional DRT) [Muskens, 1996]. This choice is motivated by the fact that CDTR is expressed in a three-sorted variant TY_3 of standard type theory. In addition to types e for individuals and t for truth values we have a type π for registers and a type s for states (sequences of registers). The basic idea in CDRT is to internalize states and assignments into the language so as to be able to talk *in the language* about updates (i.e. the object of prime concern in dynamic semantics) as transitions between states. Given a suitable axiomatisation of states it can be shown that one does not need to take recourse to special purpose dynamic logics to describe systems like DRT but can stay within the confines of a simple sorted variant of standard type theory. For our purposes this proximity to standard type theory means that transplanting CDRT into the meaning representation slots in [Dalrymple *et al.*, 1996] does not cause allergic reactions in the host whose meaning representation slots were occupied by expressions in standard type theory, after all. To be sure, the underlying logic of CDRT is static; the CDRT expressions modeling DRT expressions, however, capture the desired dynamic effects. This is why we quote the *dynamic* as in "*dynamic*" meaning representation language. The approach described in [Genabith and Crouch, 1997a] is of a general nature and could also be applied to porting what from the point of view of CDRT look like more special purpose languages such as λ-DRT [Kohlhase *et al.*, 1996; Bos *et al.*, 1994; Asher, 1993], Dynamic Montague Grammar [Groenendijk and Stokhof, 1990], Dynamic Type Theory [Chierchia, 1991] or the compositional version of DRT due to [Eijck and Kamp, 1997]. Without going into any great detail the modified meaning constructors (instantiated to (the σ projection of) the f-structure associated with *Every coach picked a player*) are:

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[5] Generalized quantifiers rather then the un-selective $\Rightarrow$ DRT-conditional etc.

$$
\begin{array}{rl}
\text{every}^1: & \forall \mathit{Scope}, R, S(\forall x.\mathit{subj.var} \rightsquigarrow x \multimap \mathit{subj.restr} \rightsquigarrow R(x)) \otimes \\
 & \qquad\qquad (\forall x.\mathit{subj} \rightsquigarrow x \multimap \mathit{Scope} \rightsquigarrow S(x)) \\
 & \quad\multimap \mathit{Scope} \rightsquigarrow [|([u_1|]; R(u_1)) \Rightarrow S(u_1)] \\
\text{a}^2: & \forall \mathit{Scope}, R, S(\forall x.\mathit{obj.var} \rightsquigarrow x \multimap \mathit{obj.restr} \rightsquigarrow R(x)) \otimes \\
 & \qquad\qquad (\forall x.\mathit{obj} \rightsquigarrow x \multimap \mathit{Scope} \rightsquigarrow S(x)) \\
 & \quad\multimap \mathit{Scope} \rightsquigarrow [u_2|]; R(u_2); S(u_2) \\
\text{picked}: & \forall X, Y(\mathit{subj} \rightsquigarrow X \otimes \mathit{obj} \rightsquigarrow Y) \multimap s \rightsquigarrow [|\mathit{pick}(X, Y)] \\
\text{coach}: & \forall X(\mathit{subj.var} \rightsquigarrow X \multimap \mathit{subj.restr} \rightsquigarrow [|\mathit{coach}(X)]) \\
\text{player}: & \forall X(\mathit{obj.var} \rightsquigarrow X \multimap \mathit{obj.restr} \rightsquigarrow [|\mathit{player}(X)])
\end{array}
$$

The type system in TY_3 is very basic (it is flat, does not have polymorphism). Provided term unification respects type assignment in TY_3, the higher order term matching task reduces to the one in described in [Dalrymple *et al.*, 1995b][6] and both the $\forall\exists$ and the $\exists\forall$ readings are obtained:

$$s \rightsquigarrow [|([u_1|\mathit{coach}(u_1)]) \Rightarrow [u_2|\mathit{player}(u_2)\ \mathit{pick}(u_1, u_2)]]$$

$$s \rightsquigarrow [u_2|\mathit{player}(u_2), [u_1|\mathit{coach}(u_1)] \Rightarrow [|\mathit{pick}(u_1, u_2)]]$$

In [Genabith and Crouch, 1997a] sets of meaning constructors (plus possible scope constraints) are interpreted as underspecified representations. We return to the scope constraint mechanism in section 5 below. If a set of linear logic premises is regarded as an underspecified representation then the linear logic deductions mapping this set into fully specified (i.e. disambiguated) meaning representations do in fact (part of) the job of the *interpretation* clauses in QLF and the *disambiguation operation* in UDRT. In other words the linear logic deductions are instrumental in *defining* the *semantics* of an underspecified representation (construed as a set of linear logic premises - or even the f-structures that give rise to them) rather than being *executed* during the construction of an (unambiguous) semantic representation representing a reading of some phrase under consideration as before. Note that this does not yet commit the resulting semantics to a QLF or a UDRT style semantics. Indeed, a QLF style [Alshawi and Crouch, 1992] supervaluation semantics for a set of linear logic premisses Δ is obtained as follows:

$$
[\![\Delta]\!] = \begin{cases} 1 \text{ iff for } \mathit{all}\ c \text{ such that } \Delta \vdash_{ll} c,\ [\![c]\!] = 1 \\ 0 \text{ iff for } \mathit{all}\ c \text{ such that } \Delta \vdash_{ll} c,\ [\![c]\!] = 0 \\ \mathit{undefined} \text{ otherwise} \end{cases}
$$

where $\vdash_{ll}$ is the linear logic consequence relation. The different UDRT semantics [Reyle, 1993; Reyle, 1995], on the other hand, are defined classically and take their cue from the definition of the UDRS consequence relations.[7] The most recent version [Reyle, 1995] is

$$\forall\delta(\Gamma^{\delta^I} \models_{95} \gamma^{\delta^I})$$

which requires pairwise (in the case of coindexed elements - synchronized) disambiguations. The definition implies that a goal UDRS γ is interpreted conjunctively, i.e. $[\![\gamma]\!] = 1$ iff for all disambiguations δ: $[\![\gamma^\delta]\!] = 1$, $[\![\gamma]\!] = 0$ otherwise. In the world of sets of linear logic premises Δ, this translates as

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[6] In particular matching is still decidable: p.c. Fernando Pereira.

[7] We will write $\models_{95}$ for the consequence relation in [Reyle, 1995] and $\models_{93}$ for the original UDRS consequence relation in [Reyle, 1993].

$$[\![\Delta]\!] = \begin{cases} 1 & \text{iff for } \textit{all} \;\; c \;\; \text{such that} \;\; \Delta \vdash_{ll} c,\; [\![c]\!] = 1 \\ 0 & \text{otherwise} \end{cases}$$

The original semantics in [Reyle, 1993] took its cue from

$$\forall\delta\exists\delta'(\Gamma^{\delta} \models_{93} \gamma^{\delta'})$$

which results in a disjunctive interpretation of a goal UDRS. Applying this to a set of linear logic premises Δ, we get

$$[\![\Delta]\!] = \begin{cases} 1 & \text{iff there } \textit{exists} \text{ a} \;\; c \;\; \text{such that} \;\; \Delta \vdash_{ll} c,\; [\![c]\!] = 1 \\ 0 & \text{otherwise} \end{cases}$$

Plugging two different semantics into the same system facilitates comparison. Notice that the original UDRT semantics [Reyle, 1993] and the more recent [Reyle, 1995] each cover two different corners of the QLF semantics (either *definite falsity* or *definite truth*).

5 Dynamic and Underspecified Glue

Linear logic is a logic of change. It is therefore natural to explore how linear logic itself can be used to model both interpretation in context and context update (i.e. without a dynamic meaning representation language). This approach is pursued in [Crouch and Genabith, 1996]. Change and update are already present in the account of meaning representation assembly in the original glue language semantics. To give a simple example, suppose that the meaning of a particular constituent σ is 'John slept'

$$\sigma \rightsquigarrow \mathit{sleep(john)}$$

Suppose further that we have a sentential modifier whose meaning constructor is

$$\forall\phi.\; \sigma \rightsquigarrow \phi \multimap \sigma \rightsquigarrow \mathit{probably}(\phi)$$

The two meaning constructors can be combined through modus ponens to derive an updated meaning assignment for the constituent σ

$$\sigma \rightsquigarrow \mathit{probably}(\mathit{sleep}(\mathit{john}))$$

Since the two original premises are consumed in the application of modus ponens we can't conclude that both $\sigma \rightsquigarrow \mathit{sleep}(\mathit{john})$ and $\sigma \rightsquigarrow \mathit{probably}(\mathit{sleep}(\mathit{john}))$. The original meaning of σ has been updated, and is no longer available. In order to model interpretation in context and context update, context assignments, $\hookrightarrow$, analogous to the meaning assignments, $\rightsquigarrow$, are introduced. Constituents may be associated with both a meaning and a context assignment. The meanings and/or contextual contributions of some nodes may depend on the meanings and/or contextual contributions of other nodes; and the meaning/context constructors may also update these assignments by means of the linear implication, $\multimap$. In the original glue language semantics we needed to establish conclusions of the form

$$\Gamma \vdash s \rightsquigarrow M$$

where Γ was the entire set of lexical premises, and a single meaning assignment occurred on the right hand side. This guarantees that each lexical premise is used *exactly once* and that *all* of the lexically induced premises are consumed and contribute to the final meaning assignment. Context assignments differ from meaning assignments in that some of them may be used repeatedly while others are not used at all. Furthermore, each reuse is liable to update a context contribution. It is for this reason that it is inappropriate to make use of linear logic's 'of course' modality, !, to allow zero or repeated use of context assignments. Use of the modality would undo the effects of updates. Instead we modify the form of the desired results of glue language derivations to allow any number of context assignments to occur on the right hand side of the turnstile. These output context assignments may either be passed on directly from the input assignments Δ, or may be updated versions of assignments in Δ, or context assignments to entirely new constituents. The output assignments $\delta_0, \ldots, \delta_n$ form the input assignments Δ for the next sentence to be interpreted.

$$\Gamma, \Delta \vdash s \leadsto M \otimes \delta_0 \otimes \ldots \otimes \delta_n$$

We illustrate the use of context assignments in terms of an example involving a (simplified) E-type analysis of the pronoun *he* in the mini-discourse:

A man walked. He whistled.

For the first sentence, *A man walked*, we have the following meaning constructors:

$$\begin{array}{ll}
\text{a}: & \forall \mathit{Scope}, R, S (\forall x. \mathit{subj1.var} \leadsto x \multimap \mathit{subj1.restr} \leadsto R(x)) \otimes \\
& \qquad\qquad (\forall x. \mathit{obj} \leadsto x \multimap \mathit{Scope} \leadsto S(x)) \\
& \qquad \multimap (\mathit{Scope} \leadsto \mathit{exists}(R, S) \otimes \mathit{subj1} \hookrightarrow \lambda y. R(y) \wedge S(y)) \\
\text{walked}: & \forall X \ \mathit{subj1} \leadsto X \multimap \mathit{s1} \leadsto \mathit{walk}(X) \\
\text{man}: & \forall X \ \mathit{subj1.var} \leadsto X \multimap \mathit{subj1.restr} \leadsto \mathit{man}(X)
\end{array}$$

Starting with the empty context we derive

$$\text{a, man, walked} \vdash \mathit{s1} \leadsto \mathit{exists}(\mathit{man}, \mathit{walk}) \otimes \mathit{subj1} \hookrightarrow \lambda y. \mathit{man}(y) \wedge \mathit{walk}(y)$$

where the contextual assignment associated with *subj1* is the property of being a man that walks. For the second sentence, *He whistled*, we have the constructors

$$\begin{array}{ll}
\text{he}: & \forall \mathit{Scope}, \mathit{Ante}, P, S (\forall x. \mathit{subj2} \leadsto x \multimap \mathit{Scope} \leadsto S(x)) \otimes (\mathit{Ante} \hookrightarrow P) \\
& \qquad \multimap \mathit{Scope} \leadsto \mathit{exists}(P, S) \otimes \mathit{subj2} \hookrightarrow \lambda y. P(y) \wedge S(y)) \otimes \\
& \qquad\quad \forall Q. \mathit{subj2} \hookrightarrow Q \multimap (\mathit{subj2} \hookrightarrow Q \otimes \mathit{Ante} \hookrightarrow Q) \\
\text{whistled}: & \forall X \ \mathit{subj1} \leadsto X \multimap \mathit{s1} \leadsto \mathit{whistle}(X)
\end{array}$$

The meaning constructor for *he* is a simple extension of NP-type meaning constructors. Its antecedent contains an additional conjunct $(\mathit{Ante} \hookrightarrow P)$ which picks up the contextual property assigned to some linguistic antecedent. The consequent existentially quantifies this property over the chosen scope (i.e. it interprets the pronoun in the context set up by some antecedent), sets up a context assignment for the pronoun and updates the original context assignment to the antecedent (context update). Thus we can interpret the second sentence in the context set up by the first as

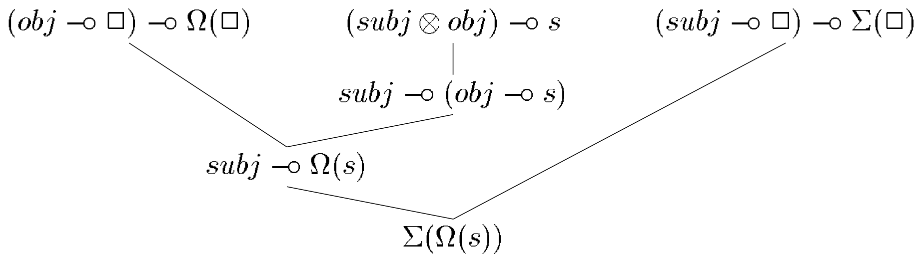
$$\begin{array}{c}
\text{he, whistled}, \mathit{subj1} \hookrightarrow \lambda y. \mathit{man}(y) \wedge \mathit{walk}(y) \vdash \\
\mathit{s2} \leadsto \mathit{exists}(\lambda x. \mathit{man}(x) \wedge \mathit{walk}(x), \mathit{whistle}(x)) \\
\otimes \mathit{subj1} \hookrightarrow \lambda y. \mathit{man}(y) \wedge \mathit{walk}(y) \wedge \mathit{whistle}(y) \\
\otimes \mathit{subj2} \hookrightarrow \lambda y. \mathit{man}(y) \wedge \mathit{walk}(y) \wedge \mathit{whistle}(y)
\end{array}$$

The meaning for the second sentence entails the meaning of the first and is truth-conditionally equivalent to the DPL formula [Groenendijk and Stokhof, 1991] and the DRS [Kamp and Reyle, 1993] for the entire discourse

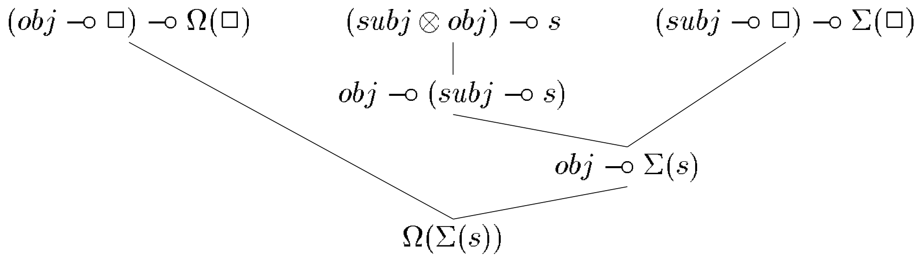
$$\exists x(man(x) \wedge walk(x)) \wedge whistle(x) \qquad \begin{array}{|c|} \hline x\ y \\ \hline man(x) \\ walk(x) \\ whistle(y) \\ x = y \\ \hline \end{array}$$

Notice that in the glue language semantics, much like in standard DRT, the dynamics resides in the composition of meaning rather then in the semantics of the meaning representations as in DPL. The example given above is deliberately simplified to introduce the idea of interpretation in context and context update with minimal clutter. [Crouch and Genabith, 1996] extends the approach to bound variable anaphora, interactions of context assignments with scope, and underspecification to which we turn now.

In glue language semantics, underspecification is manifest in semantic compositions where either (a) the meanings of certain constituents are not fully specified, or (b) the way in which they are combined is not fully specified. In glue language terms, this amounts to (a) having a choice about which contextual assignments to make use of in a derivation (i.e. choice of antecedents), and (b) a choice about the order in which certain steps in the derivation are carried out. In the case of sentences involving quantifiers, several different proofs resulting in distinct meaning assignments may be possible. In this sense, a set of glue language premises can be seen as describing a set of ways in which the meaning of the sentence can be constructed, i.e. it can be viewed as an underspecified representation. What the original glue language account lacked was a way of refining these descriptions so as to allow partial specification of scope (rather than just complete underspecification). Different scopings arise from different derivations from the same premises. If we had some way of constraining derivations, we would also have a way of constraining scope. It turns out that the required constraints can be formulated in terms of an ordering over the nodes in the semantic projections referred to by the glue language premises. Each node is a 'channel' controlling how certain semantic elements combine to form meanings, and where each channel term of the form $Channel \rightsquigarrow Meaning$ acts as either a consumer or producer on the specified channel [Dalrymple *et al.*, 1993a]. A successful glue language derivation is one that matches up consumers and producers on all channels, except for one remaining producer on the channel corresponding to the sentence as a whole. The lexical meaning constructors ensure that there are normally only a few orderings of production and consumption on the various channels that meet the requirements. By imposing further ordering constraints on the nodes, one can monotonically eliminate possible derivations. Scoping a noun phrase matches a consumer with a producer on the NP channel. In terms of the derivations sketched above, this means that the channel term for the NP disappears from the rest of the derivation. By constraining the order in which NP channel terms disappear, both relative to each other and to those for other nodes, we constrain the range of derivations and hence the possible scopings. In [Crouch and Genabith, 1996] this is unpacked in terms of constraints on the tree topology of *normalized* proofs in a natural deduction style formulation of a linear logic fragment obtained from [Troelstra, 1992]. Here we illustrate the basic idea. The constraint $subj \succ obj$ assigns wide scope to the semantic contribution provided by the subject with respect to the object contribution. In the proof world this means that the *subj* channel "survives" longer in the proof tree towards the conclusion (the root of the proof tree) than its *obj* counterpart. Schematically this corresponds to the following sub-tree in a proof:



Similarly, the constraint *obj* ≻ *subj* enforces a proof where the *obj* channel survives longer than the *subj* channel:



The fine-grained approach to scope underspecification in terms of node ordering constraints can be integrated with the original glue language semantics [Dalrymple *et al.*, 1996], the dynamic meaning representation language approach [Genabith and Crouch, 1997a] and the dynamic glue approach [Crouch and Genabith, 1996]. The resulting systems can be given QLF- or UDRT-style underspecified interpretations.

6 Conclusions and further work

Briefly, the *mapping* approach [Genabith and Crouch, 1996a; Genabith and Crouch, 1996b; Genabith and Crouch, 1997b] is probably the most direct approach to associate LFG grammars with an underspecified and dynamic semantics. Its formulation is reminiscent of the translation principle templates in [Halvorsen, 1983] and an approach by [Reyle, 1988]. In theory at least, interfacing LFG f-structures with QLFs and UDRSs makes available extensive computational work both on contextual resolution in QLF [Alshawi, 1990; Alshawi, 1992; Alshawi *et al.*, 1992] and UDRT deduction components [Reyle, 1993; Reyle, 1995; König and Reyle, 1996] to LFG grammars. However, it may well turn out to be the case that f-structures do not provide the most suitable representation format for semantic phenomena in all cases. By contrast, the glue language approach in [Dalrymple *et al.*, 1996] involves an independent and proper construction of semantic representations which are, however, neither underspecified nor dynamic. In the modified glue approach in [Genabith and Crouch, 1997a] dynamic meaning representation expressions are imported into the meaning representation slots in the glue language premises. Sets of linear logic premises associated with (the semantic projection of) an f-structure are given QLF- or UDRT-style underspecified interpretations where the linear logic deductions are instrumental in the interpretation rather than the construction of a semantic representation. The approach can (in fact in contrast to "standard" DRT [Kamp and Reyle, 1993] the dynamic meaning representation expressions employed requires it to be) intergrated with syntactic approaches to anaphora as in [Dalrymple, 1993]. In turn the approach provides a way of relating deductive approaches to quantifier scope to dynamic semantics. In many respects the approach is remiscent of a number of recent flat UDRT inspired semantics as in MRS and Verbmobil [Copestake *et al.*, 1995; Bos *et al.*, 1996]. In our approach the labels are provided by the nodes in the semantic projections. What is lost in most of these approaches is some of the filter function that the "proper" construction of a disambiguated semantic representation may have during a parsing process. Furthermore one cannot *directly* plug in sets of linear logic premises into a "semantic" deduction component (as opposed to the linear logic reasoning component) in order to compute consequence realtions between underspecified representations (as e.g. in UDRT). In some respects our approach is remiscent of [Muskens, 1995]. In the latter case, meanings are constrained by both the level of "logical form"-like generalized tree (l-structure) and the semantic meaning representation (s-structure) dominance and equality constraints. In our approach, as in the original glue language semantics, combination possibilities are determined by the (semantic projection) nodes in and the form of glue language premises (plus the additional scope constraint mechanism in [Crouch and Genabith, 1996]). The *linear logic context management* approach does not involve a dynamic meaning representation language. Instead, context update and interpretation in context are modeled in the glue language derivations. The resulting system provides an E-type treatment of anaphora and thus contrasts with the DRT-style dynamics available in the *mapping* and the *"dynamic" meaning representation language* glue based approach. Our treatment of scope constraints in terms of constraints on the form of glue language derivations [Crouch and Genabith, 1996] can be integrated with the original [Dalrymple *et al.*, 1996] and the modified glue language based approaches [Crouch and Genabith, 1996; Genabith and Crouch, 1997a] discussed. It treats proofs as first class citizens, a move further supported by work on ellipsis and glue languages [Crouch, 1997].

Much of what has been discussed in the previous pages is no more than exploratory exercises in blending results in recent formal and computational semantics (underspecification, interpretation in context and context update) with LFG. Of course, we have exhausted neither the comparison dimensions between the different approaches nor the types of approaches possible. In particular, there is no reason why a considerable number of the orginal LFG semantics could not be made both dynamic and underspecified. Hopefully this study has provided a small contribution to charting such approaches.

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