Economical Discourse Representation Theory

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1 Introduction

First-order logic (FOL) is undecidable — that is, no algorithm exists that can decide whether a formula of FOL is valid or not. However, there are various fragments of FOL that are known to be decidable. FO^2, the two-variable fragment of FOL, is one of such languages [1,2]. FO^2 is a first-order language where formulas have maximally two variables, no function symbols, but possibly do have equality. FO^2 has the finite model property [1], which means that if a formula of FO^2 is satisfiable, it is satisfiable in a finite model.

In this paper we propose a controlled fragment of Discourse Representation Theory (DRT, [3]) with a semantics formalised on the basis of the two-variable fragment with equality. DRT encapsulates the idea of text interpretation that "one and the same structure serves simultaneously as content and context" [4], where *content* refers to the semantic interpretation of sentences already processed, and *context* serves in aiding the interpretation of anaphoric expressions (such as pronouns) in subsequent sentences.

However, providing a two-variable natural language fragment is, in itself, not a new idea. In fact, the framework presented here is very much inspired by Ian Pratt-Hartmann's language E2V [5]. But as Pratt-Hartmann himself notes, E2V is "certainly not proposed as a practically useful controlled language". Our aim is to try to find out how useful a controlled language based on the two-variable fragment actually can be, mostly from a computational linguistic point of view. We will do this by:

– defining a transparant translation from the DRT fragment to FO^2;
– including events, thematic roles, and pronouns in the fragment;
– specifying a syntax-semantics interface.

The syntax-semantic interface of our choice will be based on combinatory categorial grammar (CCG, [6]), rather than, say, a simple definite clause grammar. Because of its type transparency principle, CCG will enable us to set up a clean interface, where each syntactic category uniformly corresponds to a semantic type. CCG gives us further means for incremental processing [6], and large databases of texts annotated with CCG-derivations are available [7], which might aid us in enlarging the lexicon for practical applications.

This article is organised as follows. First we briefly revise Discourse Representation Theory (Section 2). Then we introduce our decidable fragment of DRT, Economical DRT (Section 3), including the syntax and semantics of the

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meaning representation language. In Section 4 we show how a neo-Davidsonian analysis of events combines well with the main ideas of Economical DRT. We show how a syntax-semantics interface based on CCG can be realised for EDRT in Section 5. Finally, in Section 6, we discuss the interpretation of pronouns in multi-sentential texts.

2 Discourse Representation Theory (DRT)

DRT is a theory of natural language meaning, and was originally designed by Kamp to study the relationship between indefinite noun phrases and anaphoric pronouns as well as temporal relations [8]. Since its publication in the early 1980s, DRT has grown in depth and coverage, establishing itself as a well-documented formal theory of meaning, dealing with a large number of semantic phenomena ranging from pronouns, abstract anaphora, presupposition, tense and aspect, propositional attitudes, ellipsis, to plurals [3,9,10,11,4,12,13].

A key idea of DRT is that a DRS (Discourse Representation Structure) plays both the role of content (giving a precise model-theoretic interpretation of the text processed so far) and context (assisting in interpreting anaphoric expression occurring in subsequent text). Viewed from a distance, DRT can be seen as a theory with three components:

1. A formal language of DRS, the meaning representations for texts;
2. the syntax-semantics interface, mapping text into DRS;
3. A component that deals with the semantic interpretation of DRSs.

A DRS consists of a set of discourse referents and a set of DRS-conditions. DRS-conditions can either be basic, storing information about the discouse referents or relations between them, or complex, containing embedded DRSs. Hence DRSs are recursively defined, and the way they are nested predicts which discourse referents are accessible for future anaphoric reference and which are not. An example DRS is shown in Fig. 1, presented in the familiar box notation known from DRT.

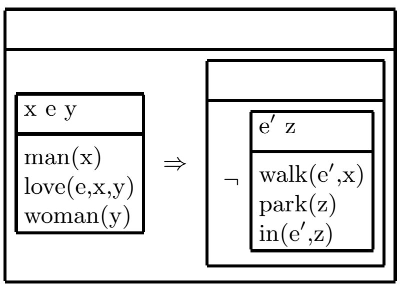

Fig. 1. DRS for *No man who loves a woman walks in a park*

DRSs can be given a direct model-theoretic interpretation [8,3,4]. Alternatively, the standard DRS language can be translated into first-order logic [14,15,16]. For instance, the DRS in Fig. 1 can be loosely paraphrased in first-order logic as *for all x, y and e, if x is a man, y is a woman, and x and y are part of a love event e, then it is not the case that there is a z and e′ such that z is a park and x is involved in a walking event e′ located in z.* We will make use of a translation function when mapping our proposed DRS language into the two-variable fragment of first-order logic.

3 Economical DRT

The standard DRS language of DRT is not decidable, because it has the same expressive power as first-order logic. The fragment of DRT that we introduce here, Economical DRT, is decidable, because we can show that the meaning representations of EDRT can be translated into FO^2. Let's first define the syntax of the meaning representation called EDRS (Economical Discourse Representation Structure):

Definition 1 (Syntax of EDRSs).

1. *If* $\{c_1 \cdots c_n\}$ *is a non-empty set of EDRS-conditions, then* $< \emptyset, \{c_1 \cdots c_n\} >$ *is an EDRS;*
2. *If u is a discourse referent, and* $\{c_1 \cdots c_n\}$ *is a non-empty set of EDRS-conditions, then* $< \{u\}, \{c_1 \cdots c_n\} >$ *is an EDRS;*
3. *Nothing else is an EDRS.*

Clause 1 says that an EDRS can have an empty domain. Clause 2 states that an EDRS has at most one discourse referent in its domain (unlike standard DRT). As we can see from this defnition, EDRSs are mutually recursively defined with EDRS-conditions. So let's now consider the syntax of EDRS-conditions, where we use the variable B (possibly indexed) ranging over EDRSs:

Definition 2 (Syntax of EDRS-conditions).

1. *If P is a one-place predicate symbol, and u is a discourse referent, then P(u) is an EDRS-condition;*
2. *If R is a two-place predicate symbol, and u and u′ are discourse referents, then R(u,u′) is an EDRS-condition;*
3. *If B is an EDRS, then* $+B$ *and* $-B$ *are EDRS-conditions;*
4. *If* B_1 *and* B_2 *are EDRSs, then* $B_1 \Rightarrow B_2$ *and* $B_1 \vee B_2$ *are EDRS-conditions;*
5. *Nothing else is an EDRS-condition.*

Clause 1 and 2 define one-place and two-place relations, respectively. Unlike standard DRT, we don't need ternary or relations of higher arity. We come back to this issue when discussing events and thematic roles in the next section. Clause 3 defines complex conditions to record positive and negative information. Clause 4 defines implicational and disjunctive conditions, respectively. Most of these EDRS-conditions resemble those of standard DRT, with two exceptions: $-$B marks negative information, and $+$B marks positive information.

Note that the language of EDRT hosts only two discourse referents, named "1" and "2". This restriction doesn't mean that we can only name two different discourse referent in an EDRS — we may re-use discourse referents as often as we like, nested in sub-EDRSs. Examples below will illustrate this technique, such as the EDRS in Fig. 3.

Now that we know what the syntax of EDRSs looks like, let's consider its semantics. The EDRS language is interpreted by translation to FO^2 with the aid of the function $[.]^{fo2}$. This function is defined for discourse referents, EDRS-conditions, and EDRSs. The full translation is shown in Fig. 2. It always produces a formula of FO^2, simply because it only yields at most two different variables (namely x and y).

Recall that in DRT, discourse representation structure serves as both the content and context. We have shown, with the help of the translation function in Fig. 2, how EDRT interprets *content*. With respect to *context*, we borrow some terminology of standard DRT to clarify the concepts *subordination*, *accessibility*, and introduce a new concept of *insertability*. Let's first consider subordination of EDRSs (where we mean by c is a condition of B that B is a DRS $< D, C >$ and c is a member of C).

Definition 3 (EDRS Subordination). *Given an EDRS B, an EDRS B_1 subordinates an EDRS B_2 iff:*

1. $+B_2$ *is an EDRS-condition of* B_1,
2. $-B_2$ *is an EDRS-condition of* B_1,
3. $B{\vee}B_2$ *is an EDRS-condition of* B_1,
4. $B_2{\vee}B$ *is an EDRS-condition of* B_1,
5. $B_2{\Rightarrow}B$ *is an EDRS-condition of* B_1,
6. $B_1{\Rightarrow}B_2$ *is an EDRS-condition of B, or*
7. B_1 *subordinates B, and B subordinates* B_2.

Hence, subordination is recursively defined over EDRSs. We use it to define two more relations that play a crucial role for processing anaphoric pronouns in EDRT, which will be discussed in Section 6. The first is accessibility, which follows the definition from standard DRT. The second, new relation, is insertability.

$$
\begin{aligned}
[< \emptyset, \{c_1, \ldots, c_n\} >]^{fo2} &= ([c_1]^{fo2} \wedge \ldots \wedge [c_n]^{fo2})\\
[< \{\mathrm{u}\}, \{c_1, \ldots, c_n\} >]^{fo2} &= \exists[\mathrm{u}]^{fo2}([c_1]^{fo2} \wedge \ldots \wedge [c_n]^{fo2})\\
[< \emptyset, \{c_1, \ldots, c_n\} >\Rightarrow\mathrm{B}]^{fo2} &= ([c_1]^{fo2} \wedge \ldots \wedge [c_n]^{fo2}) \rightarrow [\mathrm{B}]^{fo2})\\
[< \{\mathrm{u}\}, \{c_1, \ldots, c_n\} >\Rightarrow\mathrm{B}]^{fo2} &= \forall[\mathrm{u}]^{fol2}([c_1]^{fo2} \wedge \ldots \wedge [c_n]^{fo2}) \rightarrow [\mathrm{B}]^{fo2})\\
[\mathrm{B}_1{\vee}\mathrm{B}_2]^{fo2} &= ([\mathrm{B}_1]^{fo2} \vee [\mathrm{B}_2]^{fo2})\\
[+\mathrm{B}]^{fo2} &= [\mathrm{B}]^{fo2}\\
[-\mathrm{B}]^{fo2} &= \neg[\mathrm{B}]^{fo2}\\
[\mathrm{R}(\mathrm{u},\mathrm{u}')]^{fo2} &= \mathrm{R}([\mathrm{u}]^{fo2},[\mathrm{u}']^{fo2})\\
[\mathrm{P}(\mathrm{u})]^{fo2} &= \mathrm{P}([\mathrm{u}]^{fo2})\\
[1]^{fo2} &= \mathrm{x}\\
[2]^{fo2} &= \mathrm{y}
\end{aligned}
$$

Fig. 2. Translation from EDRS to the two-variable fragment of First-Order Logic

Definition 4 (Accessibility). *A discourse referent in an EDRS B is accessible from an EDRS B′ iff:*

1. *B subordinates B′, or*
2. *B equals B′.*

Definition 5 (Insertability). *An EDRS can be inserted into another EDRS B (B is insertable) iff:*

1. *There is no EDRS B′ such that B′ subordinates B, or*
2. *+B is an EDRS-condition of B′ and B′ is insertable.*

Accessibility is an important notion in DRT for establishing anaphoric links. Our EDRS language inherits the nice properties of accessibility of antecedents of pronouns, but also controls the use of pronouns by adding further restrictions on the structure of discourse. Insertability is the EDRT concept for conjoining sentences. It basically states at which level of discourse we can insert information coming from subsequent sentences. In the next section, which demonstrates the modelling of events and thematic roles in the EDRS language, we will illustrate this mechanism with various examples.

4 Events and Thematic Roles

Davidson suggested that sentences quantify over events and that adverbs and adjuncts essentially can be seen as modifiers of events, at least from a semantic point of view [17]. This is attractive from a modelling perspective, because the meaning of sentences with events can be captured by a simple first-order language, rather than a more complicated language based on higher-order logic. Davidson's view of "events introducing individuals", is adopted by standard DRT [3], shown by the DRS in Fig. 1.

Parsons, in turn, proposed a modification of Davidson's analysis [18]. He stipulated that not only modifiers but also the arguments of verbs should be viewed as predicates of events. The resulting framework is what is usually referred to as the *neo-Davidsonian* system [19]. It has two interesting consequences: (1) we can uniformly introduce *thematic roles* as relations between events and individuals; (2) verbs with optional arguments can be covered with a simpler signature of predicates.

Unlike standard DRT, we adopt the neo-Davidsonian representation of events. Thematic roles are modelled as two-place relations between events and other entities. We use the inventory of VerbNet to assign thematic roles to verbal arguments [20], such as *agent*, *patient* and *theme*. The neo-Davidsonian representation is central to our technique of re-using discourse referents in EDRT.

A first example illustrating this technique is shown in Fig. 3. Even though we only use two different discourse referents, five different entities are introduced. The nesting of the positive EDRS-conditions allows us to reuse discourse referents of what essentially would be a "flat" DRS in ordinary DRT. The use of a

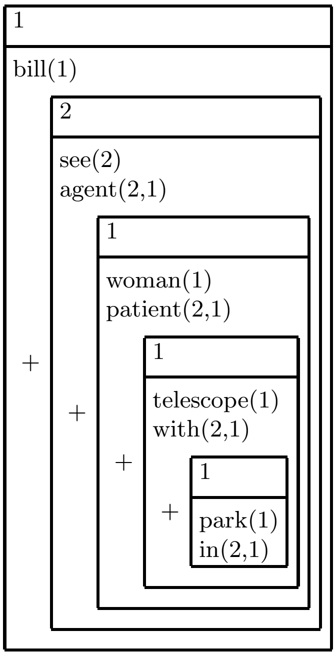

Fig. 3. EDRS for *Bill saw a woman with a telescope in the park*

neo-Davidsonian approach with thematic roles relating an event with a participating entity, rather than Davidson's original proposal, ensures we don't need more than two variables to analyse events. As a second example, consider again the DRS of standard DRT in Fig. 1 for *No man who loves a woman walks in a park*. In EDRT, this DRS is represented as shown in Fig. 4.

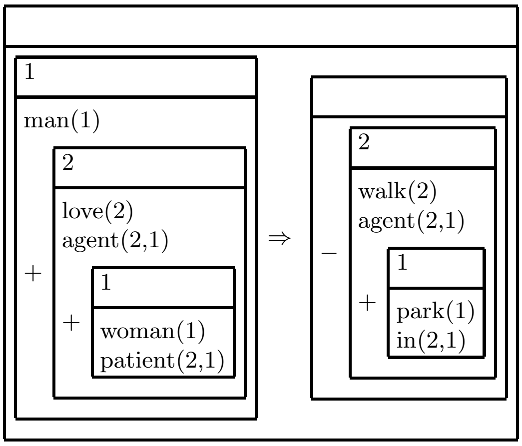

Fig. 4. EDRS for *No man who loves a woman walks in a park*

Perhaps these examples suggest that we can chain any number of arguments and modifiers within this neo-Davidsonian framework employing only two discourse referents, using one discourse referent denoting an event, and re-using another repeatedly to represent each of the participants. This is not the case. To ensure an adequate meaning representation, at most one quantifying noun phrase can be involved in each event in EDRT. This is because any quantified noun phrase needs to outscope the discourse referent introduced for the event — otherwise it wouldn't predict the correct truth conditions. Hence, we need to impose grammar constraints on the use of quantifiers in any fragment of English that is built on the basis of EDRT. One way to do this is by setting up the syntax-semantic interface in such a way that quantified noun phrase can only occur in subject position.

But what exactly do we mean by quantified noun phrases? Put simply, these are all noun phrases that introduce a universal quantifier when translated into first-order logic, or in DRT terms, those noun phrases that introduce an implicational DRS condition. Among these are noun phrases such as *everyone* and *nobody*, and those headed by the determiners *every*, *all*, and *no*. The non-quantifying noun phrases comprise indefinite and definite noun phrases, which all introduce discourse referents interpreted as existential quantifiers.

5 Building Economical DRSs

To obtain a syntactic structure for a natural language expression we employ a categorial grammar with basic categories n (noun), np (noun phrase), s (sentence), pp (prepositional phrase), and t (text). The notation of slashes follows CCG, hence a functor category α/β is subcategorising for a category β on its right yielding a category α, and a functor category $\alpha\backslash\beta$ is subcategorising for a category β on its left to produce a category α.

Each category corresponds to a (typed) partial EDRS. Because we only have two different discourse referents and no constant terms, β-conversion with renaming of variables to overcome accidental capture of free variables is not needed — instead it is safe to use unification for substitution. We will do so with a two-place operator (A·B), simulating to λ-abstraction [21], where B is always an EDRS, and A a discourse referent or another dot operation. Partial EDRSs can also only contain at most two distinct discourse referents.

In this version of EDRT we only use four combinatory rules: forward application (>), backward application (<), forward composition (**B**>), and backward composition (**B**<). They are defined in Fig. 5.

$$\frac{\alpha/\beta\text{: (X}\cdot\text{Y)} \qquad \beta\text{: X}}{\alpha\text{: Y}}\,> \qquad\qquad \frac{\beta\text{: X} \qquad \alpha\backslash\beta\text{: (X}\cdot\text{Y)}}{\alpha\text{: Y}}\,<$$

$$\frac{\alpha/\beta\text{: (X}\cdot\text{Y)} \qquad \beta/\gamma\text{: (Z}\cdot\text{X)}}{\alpha/\gamma\text{: (Z}\cdot\text{Y)}}\,>\mathbf{B} \qquad\qquad \frac{\beta\backslash\gamma\text{: (Z}\cdot\text{X)} \qquad \alpha\backslash\beta\text{: (X}\cdot\text{Y)}}{\alpha\backslash\gamma\text{: (Z}\cdot\text{Y)}}\,<\mathbf{B}$$

Fig. 5. Combinatory rules (α, β and γ range over CCG categories)

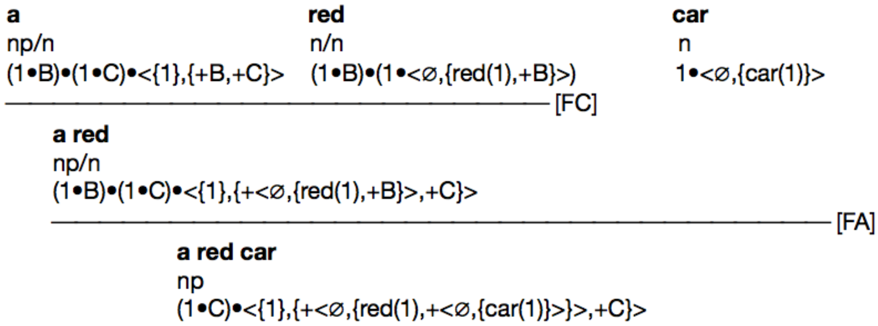

Fig. 6. CCG derivation for the noun phrase *a red car*, decorated with partial EDRSs

In Fig. 6 a CCG derivation, including EDRSs, for a simple noun phrase is shown, illustrating the combinatory rules forward composition and forward application. Fig. 7 shows several examples of lexical entries. Note that quantified determiners and pronouns are type-raised in the lexicon. This ensures that they only can occur in subject position, conform the discussion in Section 5. The entries for verbs in Fig. 7 illustrate how modifiers are dealt within the framework of a neo-Davidsonian event semantics.

6 Processing Pronouns

In this section we illustrate how the concept of insertability, introduced earlier in Section 3, determines the interpretation of pronouns. Pronouns introduce a free discourse referent "1". Their interpretation depends on where they are inserted in the EDRS. Furthermore, the structure of an EDRS constrains insertability possibilities, and thereby correctly predicts the possibility and impossibility of certain anaphoric links, as in standard DRT.

Let's first exemplify insertability. Consider the two EDRSs in Fig. 8. Recall the definition of insertability given in Section 3. This implies that the DRS for *Mia saw a woman* has three insertable DRSs (the outermost DRS, and the two embedded DRSs prefixed by the + operator), and the DRS for *Mia didn't see a woman* has only one insertable DRS (the outermost DRS, the embedded DRS prefixed by + is blocked because it is not part of an insertable EDRS).

These insertability constraints predict that the third-person pronoun in the subsequent sentence *She smiled* can refer to either Mia or the woman she saw in the first case, but only to Mia in the second case. These possibilities are summarised as follows (where ∗ marks an uninterpretable sentence):

(1a) Mia^i saw a^j woman. She$_i$ smiled.
(1b) Mia^i saw a^j woman. She$_j$ smiled.
(2a) Mia^i didn't see a^j woman. She$_i$ smiled.
(2b) Mia^i didn't see a^j woman. ∗ She$_j$ smiled.

Cat	Partial EDRS	Entry
n	(1· [| car(1)])	car
n/n	((1·B)·(1· [| big(1) +B]))	big
np	((1·B)· [1 | person(1) +B])	someone
s/(s\np)	((1·B)· [| female(1) +B] ·C)·C	she
np/n	(1·C)·(1·B)· [1 | +C +B]	a
(s/(s\np))/n	(1·C)·(((1·B)· [| [1 | +C] ⇒ B] ·D)·D)	every
s\np	((1· [2 | walk(2) theme(2,1) +B])·C)·((2·B)·C)	walks
(s\np)/np	((1· [| theme(2,1) +D])·B)·(((1· [2 | see(2) agent(2,1) +B])·C)·((2·D)·C))	saw
pp	(2· [1 | london(1) to(2,1)])	to London
t\s	(((2· [| event(2)])·B)·B)	.

Fig. 7. Mapping of CCG categories to EDRSs

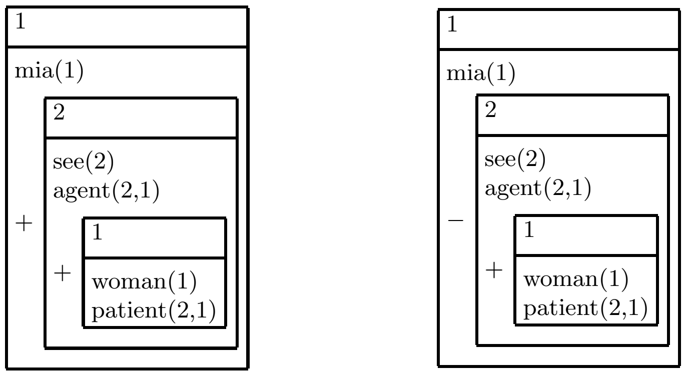

Fig. 8. EDRSs for *Mia saw a woman* (left) and *Mia didn't see a woman* (right)

These examples show how different insertability possibilities allow a pronoun to have several possible antecedents in EDRT. For instance, in Example (1a) above, the DRS for the second sentence "She smiled" can be inserted in the outermost DRS, resulting in an interpretation where the pronoun refers to Mia. Alternatively, the DRS containing the pronoun can be inserted in the deepest embedded +DRS, thereby establishing an anaphoric link between the third-person pronoun and "a woman". Both possibilities are shown in Fig. 9.

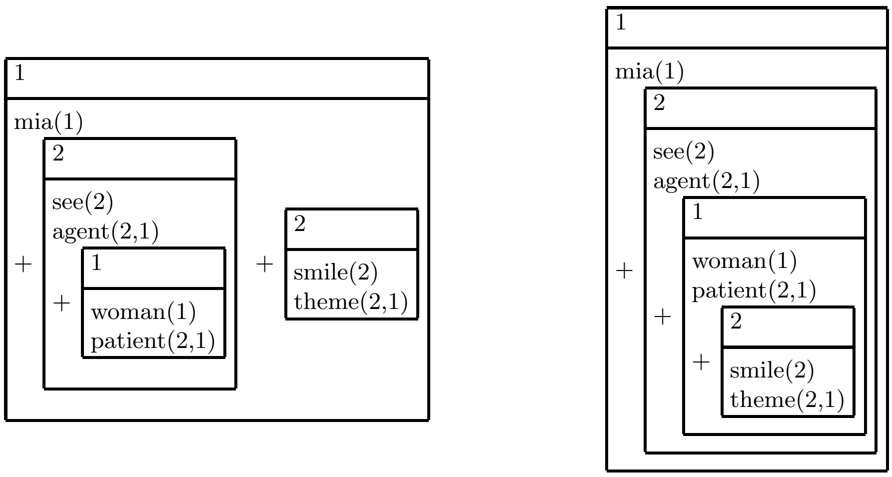

Fig. 9. Possible EDRSs for the discourse *Mia saw a woman. She smiled.*

The general mechanism for processing pronouns imposes a couple of limitations on the use of pronouns by EDRT. A simple sentence can have at most one pronoun referring back to antecedents introduced in the discourse processed so far. It is easy to see why: we can have at most two free discourse referents.

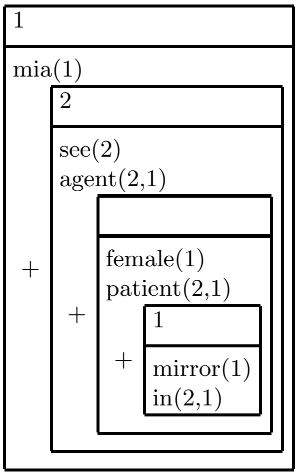

Fig. 10. EDRS for *Mia saw herself in the mirror*

But one discourse referent is already taken to represent the event introduced by the clause in which the pronoun occurs. That leaves one for any pronoun. This also suggest that pronouns need to be in subject position. Because if they would occur in object position, they would be interpreted as reflexive pronouns, referring to the subject of the sentential clause (Fig. 10).

If we assume that when processing a text in which sentences are interpreted incrementally, then we need to say something about how an EDRS constructed for a part of a certain text is combined with an EDRS of a subsequent sentence of this text. Put differently, we need to define conjoining of sentences. In ordinary DRT this is often done by merge reduction, a process in which the domains and conditions of two DRSs are taken together forming a new DRS. In EDRT no new machinery is needed for conjoining sentences, and merging of EDRSs is performed with the aid of the unary + operator, which is already part of the EDRS language. A first definition of conjoining is the following:

Definition 6 (Conjoining). *Let* B_1 *and* B_2 *be EDRSs, and* $B{=}{<}D,C{>}$ *an insertable EDRS in* B_1. *Conjoining* B_1 *and* B_2 *yields the EDRS* B_1 *with* B *replaced by* ${<}D,C \cup +B_2{>}$.

This definition does essentially what is shown in Fig. 9. However, it is non-deterministic, because an EDRS can have several insertable sub-EDRSs, or "landing sites". As a consequence, it could introduce spurious ambiguities. It actually does so for the DRS on the left-hand side in Fig. 8, since there are three possible locations for insertion: the outermost EDRS, the intermediate EDRS, and the deepest nested EDRS. The first possibility of insertion is shown on the left in Fig. 9, and the third possibility on the right. The second possibility would correspond to an interpretation equivalent to that of the first.

In order to remove these unwanted ambiguities, we redefine conjoining while distinguishing between open and closed EDRSs. A closed EDRS is an EDRS without free discourse referents (capturing the meaning of a sentence without pronouns), and an open EDRS is an EDRS with a free discourse referent (capturing the meaning of a sentence with a pronoun).

Let's first look at the case for closed EDRSs. Here we can constrain the landing site to be the outermost level of the EDRS (which is by definition insertable) representing the discourse processed so far. This is done in the following revised definition for conjoining:

Definition 7 (Conjoining for closed EDRSs). *Let B_1 and B_2 be EDRSs, such that $B_1{=}<D,C>$ and B_2 is closed. Conjoining B_1 and B_2 yields the EDRS $<D,C \cup +B_2>$.*

Now consider the case for open EDRSs. We call an open EDRS with a free variable u an "EDRS open for u". For an EDRS open for u, we can constrain the landing site to any insertable EDRS with a domain {u} This yields the following definition:

Definition 8 (Conjoining for open EDRSs). *Let B_1 and B_2 be EDRSs, and $B{=}<\{u\},C>$ an insertable EDRS in B_1, and B_2 an EDRS open for u. Conjoining B_1 and B_2 yields the EDRS B_1 with B replaced by $<\{u\},C \cup +B_2>$.*

What about anaphoric phenomena related to pronouns, such as names and definite noun phrases? In EDRT, proper names and nouns headed by the definite article are dealt with in a similar way to indefinite noun phrases. Like indefinites, they introduce a discourse referent *in situ*. Unlike indefinites, they trigger a uniqueness presupposition, which is accommodated as part of the background knowledge. Uniqueness statements are formulated in first-order logic. This can be done with not more than two variables, so we're not leaving the two-variable fragment. Basic lexical knowledge can also formulated in this way. Consider for instance the background knowledge computed for the EDRS of Fig. 10:

$\forall$x(mia(x)$\rightarrow$person(x))
$\forall$x(mirror(x)$\rightarrow$artifact(x))
$\forall$x(see(x)$\rightarrow$event(x))
$\forall$x$\forall$y((mia(x)$\wedge$mia(y))$\rightarrow$x=y)
$\forall$x$\forall$y((mirror(x)$\wedge$mirror(y))$\rightarrow$x=y)
$\forall$x(artifact(x)$\rightarrow$ $\neg$event(x))
$\forall$x(artifact(x)$\rightarrow$ $\neg$person(x))
$\forall$x(event(x)$\rightarrow$ $\neg$person(x))

7 Conclusion

The presented DRT fragment is of course far more restricted than the full blown version of DRT (for one, EDRT cannot represent donkey sentences). Nevertheless, we hope to have shown that the two-variable fragment has potential for controlled natural language applications. For instance, the use of neo-Davidsonian event-style semantics has no restrictions on the number of modifiers, even though it does on pronouns or universal quantified noun phrases.

Several questions remain to be resolved, most of them of theoretical nature. Some of them concern the translation from EDRS to the two-variable fragment of first-order logic. Is this translation meaning preserving? (We assume so, but we haven't given a proof.) Is there a translation from an arbitrary formula of FO^2 to EDRS? (If there isn't, EDRS would be a fragment of FO^2.)

Further future work could address the integration of certain plural phrases in FO^2, or in an extension of the EDRS language that still falls within a decidable fragment. And finally, the grammar presented in this article could be extended with a particular real-world application in mind. This would require a grammar covering more syntactic constructions, and be an ideal test for the proof-of-concept of using "semantically controlled" languages.

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