# From Discourse to Logic: A Compositional Approach to Discourse Semantics

Tomek Strzalkowski

In this paper, we develop a system of rewriting rules, similar to the Generalized Phrase Structure Grammar and Montague Grammar, that operate directly on fragments of written text transforming it into well-formed expressions of a formal meaning representation language. We consider the task of translating a sentence into a formula of logic as being directly influenced by the context of the surrounding text. The resulting representation captures, besides the logical contents of each proposition, also the various relations in which they remain with respect to one another.

## 1. Introduction and Motivation

The need for a unified approach to the problems of natural language processing is being increasingly felt in Computational Linguistics research. While substantial progress has been made toward a better understanding of various linguistic phenomena, many empirically derived results remain fragmentary, isolated, or even contradictory. One of the consequences of this state of affairs is the fact that we still know relatively little on how to build an automated discourse processing system that would not be limited to a particular narrow domain and often heavily constrained sublanguage. The sublanguage processing systems as those discussed in Grishman et al. (eds.)(1986), Kittredge (1983) and Ksiezyk (1988), usually provide an in-depth analysis of short fragments of text, helped by a detailed domain model. Such systems are capable of "understanding" natural language messages about the modeled domain, but they are largely helpless beyond it. Every new domain requires building a new model and a new sublanguage processor, often from scratch, a costly enterprise. Other systems that aimed at a broader coverage of language, such as the Linguistic String Project (Sager(1981)), tended to give a fairly shallow analysis, usually limited to little more than syntactic parsing. Analysis of syntax, by far the best understood single issue in Natural Language Processing (NLP), is still quite problematic when it comes to the parsing of unconstrained texts, though it does not appear entirely out of reach. However, syntactic parsing is hardly enough for most of the more interesting applications, such as information retrieval, text processing or machine translation. On the other hand, in dealing with unconstrained language, or the language used in broad domains, such as scientific abstracts or business reports, one cannot count on having access to excessive and detailed pragmatic information. Thus, of necessity, we have to forsake the depth of analysis for its coverage, but that does not mean that we cannot move beyond syntax, and more importantly, beyond the boundaries of a single sentence. It also does not mean that we can rid the text processing system of any domain-related information since that would lead to a combinatorial explosion in the number of possible analyses, a situation we can hardly tolerate in practical applications. Therefore, while a detailed domain model cannot be expected, we still need a fair amount of more general *semantic* information about the broad domain of discourse, such as a semantic type hierarchy constraining the use of nouns and verbs, and perhaps other words also. We believe that this kind of information can be integrated directly into the text grammar, in part as an extended lexicon (semantic subcategorization of words), and in part as a control metasystem regulating the use of grammar rules (discourse structure related constraints).

This paper addresses several problems that need to be solved on the way to a more advanced system for discourse processing, a system that would not treat a discourse as a set of unrelated utterances. In the following sections we discuss a prototype model of discourse processing that has been influenced by the works of Montague (1974) and Gazdar et al. (1985), as well as by recent developments in logic grammars, (Pereira & Warren (1980), Shieber (1986)). Unlike these systems, however, we do not limit our rules to isolated sentences; instead, we consider the task of assigning a representation to a sentence as being constrained and influenced by the meanings of other sentences in a discourse.

## 2. From Sentences to Logic

Let us start with a limited subset of English, let's call it L, which can be described by a standard categorial grammar[1]. The basic categories of the grammar, following the Montagovian tradition (Montague(1974)) are *t* of well-formed sentences, and *e*, an empty category of "entities" that serves as a building block for defining other categories. In addition, we introduce a new basic category *d*, for discourse, that would contain sets of sentences. Besides basic categories, there are derived categories, denoted by symbols $\alpha/\beta$ which should be understood as[2]: a category of syntactic elements such that when combined with an element of category $\beta$ yield well-formed elements of category $\alpha$. This same information can also be encoded as two context-free rules: $\alpha ::= \alpha/\beta\ \beta \mid \beta\ \alpha/\beta$. We use the symbol <a,b> to denote the syntactic constituent obtained from combining element a with element b (of appropriate categories). Finally, B($\alpha$) and E($\alpha$) are, respectively, the set of basic elements of category $\alpha$ (lexical items) and the set of all well-formed elements of this category. We do not specify the lexicon for L here, but it should be assumed to contain all required words. Next, we define the meaning representation language, let's call it $\Lambda$,: a typed predicate logic with lambda operator. Every well-formed expression of this language will fall into one of the following types: *t* of well-formed formulas, *e* of entities, and any one of the derived types $\alpha/\beta$, which should be understood as: a type of functions with domain in type $\beta$ and range in type $\alpha$. Now we establish a simple translation scheme between L and $\Lambda$ as follows. First, we map categories in L into the like named types in $\Lambda$,[3] allowing multislashed categories (if any) to map into single-slashed types. Next, we specify the translations for individual expressions. (In the system

[1] We concentrate on the context-free base of the grammar ignoring context-sensitive and other restrictions to make our presentation more perspicuous. These restrictions will be included when we construct a real unification grammar system. For an approach to implement categorial grammars using unification, see Zeevat (1988); for an implementation of traditional Montagovian translation, see Schubert & Pelletier (1982).

[2] We may occasionally need double (and more) slashed categories reflecting the need for a separate syntactic treatment.

[3] The only exception is category *d* which does not have a corresponding type in $\Lambda$.

of rules below: $CON\alpha$, $VAR\alpha$, $WFE\alpha$ are sets of, respectively, constants, variables and well-formed expressions of type $\alpha$.)

*The Basic Translation Scheme:* $R_1$

(i) Let $\alpha$ be any category in L, different than $t/(t/e)$. If $a \in B(\alpha)$ then $R_1(a) \in CON_{R1(\alpha)}$.

(ii) If $a \in B(t/(t/e))$ then $R_1(a) = \lambda P.P(a')$, where $a' \in CON_e$ and $P \in VAR_{t/e}$ [4]

(iii) For any categories $\alpha$, $\beta$ of L different than $d$, if $\sigma$ is any of the following: $\alpha/\beta$, $\alpha//\beta$, $\cdot\ \cdot\ \cdot$, then if $a_1 \in E(\sigma)$, and $a_2 \in E(\beta)$ then $R_1(\langle a_1, a_2\rangle) = R_1(a_1)(R_1(a_2)) \in WFE_{R1(\alpha)}$.

(iv) If $p \in \mathrm{E}(t//e)$ then

$R_1(a/an\ p) = \lambda Q \exists x[R_1(p)(x)\ \&\ Q(x)]$

$R_1(every\ p) = \lambda Q \forall x[R_1(p)(x) \rightarrow Q(x)]$

$R_1(the\ p) =$

$\lambda Q \exists x[R_1(p)(x)\ \&\ C(x)\ \&\ Q(x)\ \&$

$\forall y[\{R_1(p)(y)\ \&\ C(y)\} \rightarrow (x = y)]$

where $x, y \in VAR_e$, $Q \in VAR_{t/e}$, and $C$ is a free context variable, $C \in WFE_{t/e}$

As a simple example, let us consider translating the sentence *John runs.* The proper noun *John* belongs to the category $t/(t/e)$ of L, while the intransitive verb *runs* belongs to category $t/e$. According to (i), the verb *runs* translates as $R_1(runs)$ which is a $\dot{\Lambda}$-constant of type $t/e$; we may denote this constant by $runs'$[5]. Using (ii) we can translate *John* as $\lambda P.\ P(J)$, where $J$ is a constant of type $e$. Now we can translate the sentence *John runs*, as follows:

$$\begin{aligned} R_1\ (<John,\ runs>) &= R_1\ (John)(R_1(runs)) = \\ &\lambda P.\ P(J)(runs') = \\ &runs'(J) \end{aligned}$$

[4] Occasionally we use a dot separator between the lambda variable and the rest of an expression in order to increase readability; it carries no other meaning.

[5] Later, we drop the prime for simplicity.

This simple translation scheme can be further elaborated to account for some more subtle syntactic constructions, but it is designed to work on at most one sentence at a time and it does not take into account the surrounding discourse context. Therefore, the next thing to do is to augment this scheme with translations for the discourse fragments consisting of more than one sentence. We begin by considering pairs of sentences: a context $s_1$ and the current sentence $s_2$. The former is already a part of the discourse representation that we are in process of generating, and thus it has already been translated into $\Lambda$. The latter is the sentence our translator is presently looking at. The task is to translate the current sentence with respect to the context and identify (and perhaps resolve) whatever inter-sentential dependencies there exist between them. As a result the logical form of $s_1$ may be affected so as to reflect the combined semantics of the pair.[6] We shall concentrate here on cases where the current sentence contains at least one explicit anaphoric element whose antecedent is to be found in the context external to this sentence. The potentially explosive number of possibilities for relating $s_2$ to $s_1$ will in practice be limited by the actual structure of the discourse under consideration,[7] as well as by the pragmatic and domain-related information that will be incorporated in a real system.

## 3. Extra-Sentential Anaphora

Let us consider the following two sentence mini-discourse:

$s_1$: *John interviewed a candidate.*
$s_2$: *The man had impressive references.*

In the most natural reading of this fragment, the anaphor of *the man* is resolved against *a candidate* in the first sentence, so that the fragment actually means: *John interviewed a candidate who was a man and who had impressive references.*

$$\exists x[m(x) \ \& \ cnd(x) \ \& \ int(J,x) \ \& \ imp\text{-}refs(x)]$$

[6] This is contrasted with approaches where the discourse is initially considered a set of unconnected sentences (Scha & Pollanyi (1988), Webber (1979).

[7] See, among others, Grosz & Sinder (1986), Scha & Pollanyi (1988).

This effect can be achieved with a generalized translation scheme $R_2$ in which each translation rule takes two arguments instead of one: an expression $s_2$ of L to be translated into $\Lambda$, and an expression $s_1$ of $\Lambda$ which is the context in which to translate $s_2$. The new translation scheme is invoked from $R_1$ by an additional rule (v), whenever translation of more than one sentence is requested.

(v) $R_1(<s_1, s_2>) = R_2(s_2; R_1(s_1)) \in WFE_t$
where $s_1 \in \mathrm{E}(d)$ and $s_2 \in \mathrm{E}(t)$.

The purpose of this rule is to accommodate the semantics of $s_2$ into the logical form of the context provided by $s_1$. As a result, the representation of the discourse will be composed of well-formed formulas which need not correspond to translations of the sentences in the original text when translated in isolation. The new translation scheme $R_2$ is defined as follows:

*Context translation scheme:* $R_2$ [8]

(1) $R_2(s_2; \phi) = R_1(s_2)$
where $\phi$ denotes an empty context: if no context is present, $R_2$ degenerates to $R_1$

(2) $R_2(<a_1,a_2>; c_1(c_2)) = R_2(a_1; c_1)(R_2(a_2; c_2))$
where $a_1$ and $a_2$ belong to categories different than $t$, $d$ or $d/d$ and such that $a_1 \in \mathrm{E}(\alpha/\beta)$ and $a_2 \in \mathrm{E}(\beta)$, $c_1 \in WFE_{\alpha/\beta}$ and $c_2 \in WFE_\beta$ , and at least one of $a_1$ and $c_1$, or $a_2$ and $c_2$ are anaphorically related in such a way that if $a_i$ is an anaphor then $c_i$ is its antecedent.

(3a) $R_2(s_2; \phi) = \phi \ \& \ R_1(s_2)$
where $s_2 \in \mathrm{E}(t)$ and $\phi \in WFE_t$ are anaphorically unrelated.

(3b) $R_2(a_2; \lambda x \phi) = \lambda x[\phi \ \& \ R_1(a_2)(x)]$
where $a_2 \in \mathrm{E}(t/\alpha)$ and $\phi \in WFE_t$ are anaphorically unrelated, and $x \in VAR\alpha$.

(4) $R_2(s_2; \phi \& \psi) = R_2(s_2; \phi) \ \& \ R_2(s_2; \psi)$

[8] The reader may note that the scheme consisting of rules (1) through (7), and further rules defined in this paper, gives only an approximate rendering of an actual system: at this time we do not specify a possible evaluation strategy that would control the use of the rules.

where the actual distributivity of context will be controlled by discourse structure and other pragmatic constraints.

(5) $R_2(<the, p>; \lambda Q \exists x\phi(x)) =$
$\lambda Q \exists x[R_1(p)(x) \ \& \ \phi(x)]$[9]

(6) $R_2(he; \lambda Q \exists x\phi(x)) = \lambda Q \exists x\phi(x)$
where $p \in B(t//e)$, $Q \in VAR_{t/e}$, and $x \in VAR_e$.

(7) $R_2(he; \lambda Q\, \phi(n)) = \lambda Q\phi(n)$
where $Q \in VAR_{t/e}$ and $n \in CON_e$.

Rule (2) defines distributivity of context with respect to the syntactic structure of a discourse fragment which is to be translated with respect to this context. Thus if the context is $F(a)$ then it can be decomposed into $\lambda xF(x)(a)$ with $c_1 = \lambda xF(x)$ and $c_2 = a$, or it can be decomposed as $\lambda P.\ P(a)(F)$ with $c_1 = \lambda P.\ P(a)$ and $c_2 = F$, or other combinations. The only restriction on context distributivity is that the category of the fragment to be translated and the type of its context are compatible. Therefore, when we translate the second sentence of the following sequence:

John walks. He talks.

then, assuming that the first sentence has already been translated, we have to compute the value of the following expression:

$R_2(<\text{he, talks}>;\ walks(J))$

Since the personal pronoun *he* belongs to category $t/(t/e)$ and the intransitive verb *talks* belongs to category $t/e$, we need to find a functional decomposition of context, that is, $walks(J)$ into expressions of corresponding types in Λ. Such a decomposition is easily found to be $\lambda P.\ P(J)$ which is of type $t/(t/e)$, where $P$ is a variable of type $t/e$, and *walks* which is of type $t/e$. We thus obtain:

$$R_2(<\text{he, talks}>; \lambda P.\ P(J)(walks)) =$$
$$R_2(\text{he}; \lambda P.\ P(J))(R_2(\text{talks};\ walks))$$

[9] The presence or absence of a uniqueness clause in translations will be discussed later.

Further translation is accomplished with rules (7) and (3b) as shown below. For an easy understanding of this translation, the reader may note that since *walks* is a function constant of type $t/e$, it can be also denoted by $\lambda x.\ walks(x)$, where $x$ is a variable of type $e$.

$$R_2(\text{he}; \lambda P.\ P(J))(R_2(\text{talks}; walks)) =$$
$$\lambda P.\ P(J)(\lambda x[walks(x)\ \&\ talks\ (x)] =$$
$$walks(J)\ \&\ talks(J)$$

Rule (2) can be broken down into a number of specific cases. For example, the plural pronominal *they* can be resolved with respect to different contexts,[10] as shown below:

$$R_2(<\text{they},\alpha>; \forall x \exists y[\phi(x) \rightarrow \psi(y)]) =$$
$$\text{(a) } R_2(\text{they}; \lambda Q \forall\ x[\phi(x) \rightarrow Q(x)])(R_2(\alpha; \lambda x \exists y \psi(y)))$$
$$\text{(b) } R_2(\text{they}: \lambda Q \forall\ y \exists x[(\phi(x)\ \&\ \psi(y)) \rightarrow Q(y)](R_2(\alpha; \phi))$$

where $\alpha \in E(t/e)$.

If the context is obtained from translating *Every student got a pen*, then the translation in (a) above would be appropriate if the following sentence was *They were happy*, with *they* referring back to the students, while the translation in (b) would be used if the following sentence was *They were cheap*, with *they* referring back to the pens the students got.

Rules (3a), (3b) and (4) are designed to handle situations where the anaphoric connections between the current sentence and the context are either nonexistent of not readily available. In particular, rule (3a) would translate *Mary talks* in context of *walks*($J$), which is a translation of *John walks*, simply by assuming that no relevant context is present. We thus obtain a simple conjunction: *walks*($J$) & *talks*($M$). Similarly, when a constituent of category $\alpha$ in the current sentence is found to be anaphorically related to a subexpression of type $\alpha$ in the context, while the rest of the sentence (of category $t/\alpha$) is unrelated to the remainder of the context (of type $t/\alpha$), we want to combine these latter into a compound predicate of type $t/\alpha$. For example, while translating *He talks* in the context of *John walks* we resolve the anaphor *he* against *John*, and then create a compound predicate by translating the verb phrase *talks* with rule (i) in scheme $R_1$ and attaching the result to the context:

[10] For a detailed discussion of this phenomenon, see Webber (1979).

$\lambda x[walks(x)\ \&\ talks(x)]$

This compound predicate can now be applied to the resolved anaphor to obtain the final translation of the fragment.

Rules (5) and (6) give the translations of extrasentential anaphor in an existential and referential context. Different rules are required to handle discourse fragments where both the anaphor and its antecedent are given non-referential interpretations, as it may be in the following example:

(F1) *John tries to find a unicorn.*
*He wants Mary to see it.*

Now, rule (6) of scheme $R_2$ can compute the anaphoric link between *it* and *a unicorn* only if both sentences receive their referential interpretations, that is the existence of the unicorn is being assumed by the speaker. In the case where both sentences are understood non-referentially, that is, with no particular unicorn in mind, we have to follow a different translation rule, as shown below.[11]

(8a) $R_2(<\text{imp}_2, a_2>; \lambda j\,[\text{imp}_1(j, a_1)]) =$
$\lambda j\,[\text{imp}_1(j, a_1)\ \&\ [\lambda s R_1(\text{imp}_2)(j, s)](R_2(a_2; a_1))]$

where $\text{imp}_1 \in WFE_{(t/e)/t}$, $\text{imp}_2 \in E((t/e)/t)$, $j \in VAR_e$, $s \in VAR_t$, $a_1 = x\phi(x)$ and $a_2 \in E(t)$ contains an anaphor resolvable within $a_1$.

In other words, we recursively move inside the scope of propositional operators before resolving an embedded anaphor. Note that rule (8a) can be used only after at least one application of rule (2) which would anaphorically relate the subject of the current sentence to an appropriate element of the context. In case such correspondence cannot be established, the use of rule (2) is blocked, and rule (8a) is not applicable. Such a situation occurs when we have two distinct sources of attitudes toward the same ob ject, cf. *John tries to find a unicorn. Mary wants to see it.* This may well indicate that a non-referential interpretation of *it* is not possible, but the evidence to support sucha conclusion isn't strong enough (see, however, Partee (1972). To account for such cases we include in $R_2$ an additional rule (8b).

[11] For more discussion see Strzalkowski & Cercone (1986).

(8b) $R_2(<a_2, <\text{imp}_2, a_2>>; a_1(\lambda j[\text{imp}_1(j, a_1)])) = a_1(\lambda j\,[\text{imp}_1(a_1)])$ & $R_1(a_2)(\lambda j[[\lambda s R_1(\text{imp}_2)(j, s)](R_2(a_2; a_1))])$

where $\text{imp}_1 \in WFE_{(t/e)/t}$, $\text{imp}_2 \in E((t/e)/t)$, $j \in VAR_e$, $s \in VAR_t$, $a_1 \in WFE_{t/(t/e)}$, $a_2 \in E(t/(t/e))$, $a_1 = \exists x\phi(x)$ and $a_2 \in E(t)$ contains an anaphor resolvable within $a_1$.

Let us analyze how the translation of the fragment (F1) above can be derived. Suppose that the context (*John tries to find a unicorn*) has already been translated, and now we attempt to translate *He wants Mary to see it* in this context. In other words, we want to evaluate the following expression:

$$R_2(<\text{he wants Mary to see it}>; tries(J, \exists x[uni(x)\ \&\ finds\ (J,x)]))$$

Using rule (2) we reduce the above to:

$$R_2(\text{he}; \lambda P.\ P(J))$$
$$(R_2(<\text{wants Mary to see it}>;$$
$$\lambda j.\ tries(j, \exists\ x[uni(x)\ \&\ finds\ (j, x)])))$$

In order to obtain this reduction we note that if $\phi(J)$ is any expression of $\Lambda$ classified in type $t$, with $\phi$ being of type $t/e$ and $J$ of type $e$, then $tries(J, \phi(J))$ decomposes into $\lambda P.\ P(J)(\lambda j.\ tries(j, \phi(j)))$. This is certainly the case with $tries\ (J, \exists x[uni(x)\ \&\ finds\ (J, x)])$ above, and thus we use rule (2) to get the result shown above. The first component of this expression further reduces to $\lambda P.\ P(J)$, according to rule (7). (Rule (7) differs from rule (6) by allowing an entity in context to be referred by a name rather than an existential quantification.) The second component, i.e., $R_2(<\text{wants Mary to see it}>; \cdots)$, is further reduced with rule (8a) so that we obtain:

$$\lambda P.\ P(J)[\lambda j[tries(j, \exists x[uni(x)\ \&\ finds(j, x)])\ \&\ [\lambda s R_1(\text{wants})$$
$$(j, s)](R_2(<\text{Mary to see it}>;\ \exists x[uni(x)\ \&\ finds\ (j, x)]))]]$$

Now $R_1(wants)$ reduces to *wants*, and we use rule (2) again to reduce the last component, obtaining:

$$\lambda P.\ P(J)[\lambda j[tries(j, \exists x[uni(x)\ \&\ finds(j, x)])\ \&\ \lambda s.\ wants)(j, s)$$
$$(R_2(\text{it}; \lambda Q \exists x[uni(x)\ \&\ Q(x)])(R_2(<\text{Mary to see}>;$$
$$\lambda x.\ finds(j, x))))]]$$

Using rule (6) to translate *it* and rule (3b) to translate *Mary to see* we obtain the following reduced formula:

$$\lambda P.\ P(J)[\lambda j[tries(j, \exists x[uni(x)\ \&\ finds(j, x)])\ \&\ [\lambda s.\ wants(j, s)\ (\lambda Q \exists x[uni(x)\ \&\ Q(x)]\ (\lambda y[finds\ (j, y)\ \&\ sees(M, y)]))]]$$

After $\lambda$-reduction we get the final translation, as shown below:

$$tries(J, \exists x[uni(x)\ \&\ finds(J, x)])\ \&\ wants\ (J, \exists x[uni(x)\ \&\ finds(J, x)\ \&\ sees\ (M, x)])$$

The reader may note that we resolved two anaphors *he* and *it* in one translation pass.[12]

A slightly different problem is created by nonreferential interpretations of discourse entities occurring in scope of epistemic operators, such as *believe, know, disagree,* (see also Strzalkowski (1986a,b), Strzalkowski & Cercone (1986)) for example,

> *John believes that a unicorn lives in the park. He thinks the creature has a long horn.*

In their non-referential interpretation, fragments like the one above cannot be translated with rule (8a), since the epistemic operator, such as *believes,* cannot be recursively eliminated, as was done in the case of propositional operators such as *wants.* Here the epistemic context will persist even as we decompose the current sentence into smaller constituents. The following rule is appropriate:

$$(9a)\ R_2(<\alpha_2, <\text{att}_2, a_2>>; \alpha_1(\lambda j\,\text{att}_1(j, a_1))) = \alpha_1(\lambda j\,\text{att}_1(j, a_1))\ \&\ X(\alpha_2, \alpha_1)(\lambda j[[\lambda s R_1(\text{att}_2)(j, s)]\ (R_2(a_2; \alpha_1(\text{att}_1(a_1)))]))$$

where $\text{att}_1 \in WFE_{(t/e)/t}$, $\text{att}_2 \in E((t/e)/t)$, $j \in VAR_e$, $s \in VAR_t$, $a_1 \in WFE_{t/(t/e)}$, $\alpha_2 \in E(t/(t/e))$, $a_1 = \exists x \phi(x)$, and $X(\alpha_2, \alpha_1) = R_2(\alpha_2; \alpha_1)$ if $\alpha_2$ is an anaphor resolvable against $\alpha_1$, or else $X(\alpha_2, \alpha_1) = R_1(\alpha_2)$.

For a detailed explanation of why this is so the reader is referred to the above works. As a consequence of rule (9a) we add specialized rules for handling non-referential attitude report contexts; rule (9b) below is one

[12] The translation presented here was straightforward because the logical structures of both sentences are nearly parallel. If we replace the second sentence by *Mary wants to see him,* with *him* referring back to *John,* then in order to use rule (2) we need to break this sentence into *he* and (*is whom*) *Mary wants to see.*

of them.

(9b) $R_2(s_2;\alpha(\text{att}(\exists x\phi(x)))) = R_2(s_2;\ \exists x[\alpha(\text{att}(\phi(x)))])$

This rule says that an anaphoric reference to a discourse entity $\xi$ within a non-referential belief-context brings this entity out of the belief-context, and assigns to it the status which is consistent with the status of the anaphor. We may still obtain a non-referential interpretation of $\xi$ if the anaphor is in scope of another belief-operator (cf. rule (9a)). In the example given here, the second sentence translates to:

$$thinks(J, \exists x[believes(J,[uni(x)\ \&\ lives-park(x)])\ \&\ cre(x)\ \&\ has-lh(x)])$$

This should be read as: *John thinks that a creature such that he believes it is a unicorn and lives in the park has a long horn.*

We also need a couple of rules to handle situations when the antecedent of an anaphor is a proper name rather than a description, as in the fragment below:

*Morris tries to catch a bird. The cat is clumsy.*

We saw already one such rule, namely (7); now we add one more as (10). These rules are variants of rules (5) and (6) but do not involve a quantification over the argument of $\phi$.

(7) $R_2(he;\lambda Q\phi(n)) = \lambda Q\phi(n)$

(10) $R_2(<the, p>;\lambda Q\phi(n)) = \lambda Q[\phi(n)\ \&\ R_1(p)(n)]$
where $p \in B(t//e)$, $Q \in VAR_{t/e}$, and $n \in CON_e$.

In the example given here, using rule (10) will result in the following translation (M is an individual constant denoting the individual named Morris):

$$tries(M, \exists x[bird(x)\ \&\ catches(M, x)])\ \&\ cat(M)\ \&\ clumsy(M)$$

Further rules can be devised in the same manner for different types of anaphora, as well as more types of context including expressions denoting sets of individuals, universally quantified terms, and more non-referential contexts. We also need to account for the presence of forward/backward linking between sentences. This last problem has a special importance, also because it has been largely ignored in the research on discourse anaphora to date.

All definite anaphora cases (such as these we've discussed above) can be grouped into two more or less separate classes: *backward links* and *forward links.*[13] A backward link occurs when an anaphor is used to refer to an object whose uniqueness has already been established with respect to the present discourse, that is, the discourse thus far provided enough information (direct or implied) about the object so that the hearer can identify it, or he believes he can. In the cases of anaphora we have considered thus far we did not assume that we have dealt with backward links, which explains the absence of the uniqueness clause in translations. A forward link occurs whenever the uniqueness of the referent has not been yet determined, whether or not it has been referred to before in the discourse. In such cases the use of a definite pronoun or a definite description, both of which presuppose uniqueness of the referent, can only be justified by the fact that the speaker is in possession of the required information and that he will reveal it later in the discourse. Therefore, we have to postpone the creation of uniqueness clauses until we have reasons to believe that the object in question has been given a sufficient identification. For example, in the following discourse we would not normally consider the first reference to the man on Broadway as providing a sufficient identification: it's hard to believe that you saw just one man.

> Walking down the street on Broadway I saw a man. He waved at me. He wore a heavy coat even though it was pretty warm outside. The man asked me for a dime.

The information about waving is more discriminating, and about the heavy coat virtually pins down the discourse referent, so that we can risk introducing the uniqueness clause into the translation. In order to account for backward links, we introduce two additional rules into the scheme $R_2$.

(12) $R_2(<the, p>; \lambda Q\ \exists x\phi(x)) = \lambda Q\ \exists u[R_1(p)(u)\ \&\ \phi(u)\ \&$
$y[\{R_1(p)(y)\ \&\ \phi(y)\} \rightarrow (y=u)]]$

[13] The distinction made here differs somewhat from a traditional linguistic account; see, for instance, Brown & Yule (1984).

(13) $R_2(he; \lambda Q \exists x\phi(x)) = \lambda Q \exists u[\phi(u) \ \& \ \forall y[\phi(y) \rightarrow (y=u)]]$

where $p \in B(t//e)$, $Q \in VAR_{t/e}$.

The use of forward/backward rules will be regulated by some discourse related set of restrictions that need to be imposed upon the translation scheme. There seem to be several ways of approaching this problem but we shall not discuss them here. We want to point out, however, that the treatment presented here is intuitively more satisfactory than the use of extralogical operators *referred-to-in-the-nth-sentence* or some such; see, for example, Hirst (1981), Webber (1979).

## 4. Non-Singular Terms in Discourse

The rules discussed in section 3 cover selected cases of inter-sentential anaphora where the reference level in discourse does not change from one sentence to another. There exists, however, a class of intersentential dependencies where by which a reference is made across boundaries of different detail-levels in discourse. For example, in the fragment below *the alligator* noun phrase in the second sentence is most likely taken as referring to a generic kind of which the alligator in the first sentence is an instance or extension.

> John saw an alligator in the local zoo. It wasn't particularly large one, but Mary read that the alligator can grow up to ten feet in length.

We say that the level of reference has changed between these sentences from an individual level (reference to an individual alligator) to a generic level (reference to a kind, or *superobject*). The definite noun phrase *the alligator* is not an anaphor in a usual sense, but it establishes a cohesive link which we call a *remote reference.* In order to design a proper representation for remote references in discourse, we build a multi-level model for the natural language denotational base, such that the levels in the model correspond (roughly) to the levels of detail in discourse. It turns out that this approach extends naturally to account for various kinds of habitual and generic sentences found in discourse, such as, for example, *John walks* *to work*, or *Tourists start forest fires.* In the alligator example above, the resulting representation would have both alligators placed at different, though related, "detail levels". Because of an inherent subjectivity of such classifications, the levels are only partially ordered with the *lower than* (i.e. *more detailed than*) relation with respect to some current level of detail (at a present point in discourse). A detailed account of some aspects of this design can be found in Strzalkowski (1986b, 1987, 1989), Strzalkowski & Cercone (1989).

Let us consider the alligator example in a slightly simplified form:

> John saw an alligator in the local zoo. Mary read that the alligator can grow up to ten feet in length.

Disregarding a possible (though unlikely) anaphoric reference linking the two sentences, we have to account for the apparent connection between them. If the first sentence is taken as making a reference to a particular individual alligator, the second sentence is usually understood as referring to a generic kind, the species. Therefore, the two sentences operate at different, though related levels in the model. We might thus suggest the following translations for them (where $al-sp$ denotes alligator-species):

$$R_1(S_1) = \exists x[al(x) \ \& \ in\ (x, zoo) \ \& \ saw\ (J, x)] \text{ at } L_{-1}^{al-sp,\triangle}$$
$$R_1(S_2) = \exists u[al-sp(u) \ \& \ read(M, grow-to(u, 10ft))] \text{ at } L_0$$ [14]

In addition, we know that the relationship between entities denoted by variables $x$ and $u$ is that of being an instance with respect to some spatio-temporal decomposition $\triangle$. We want to translate the discourse fragment consisting of sentences $S_1$ and $S_2$ as $R_2(S_2;R_1(S_1))$ and obtain the following result:

$$\exists u \exists \triangle \exists x[x \in L_{-1}^{u,\triangle} \ \& \ al-sp(u) \ \& \ read(M, grow-to(u, 10ft)) \ \& \ al(x) \ \& \ in\ (x, zoo) \ \& \ saw\ (J, x)]$$

These considerations lead us to new rules that can be attached to the trans-

[14] Here $L_0$ is the current level of reference (when $S_2$ is evaluated) containing the generic entity al-sp. The level $L_{-1}^{al-sp,\triangle}$ is the level where individual alligators belong. $\triangle$ is the decomposition used to move between these levels. For more discussion, see Strzalkowski & Cercone (1989).

lation scheme $R_2$. To simplify the notation we use the short form $\exists x^{\xi,\triangle}_{-1}\ \phi(x)$ to stand for $\exists \xi \exists \triangle \exists x[x \in L^{\xi,\triangle}_{-1}\ \&\ \phi(x)]$.

(14) $R_2(<the,\ p>;\lambda\xi\exists\ \phi x)) = \lambda\xi\exists x^{\xi,\triangle}_{-1}\ [R_1(p)(\xi)\ \&\ \phi(x)]$

(15) $R_2(he;\lambda Q\exists\ \phi(x)) = Q\exists\ x^{\xi,\triangle}_{-1}\ \phi(x)$

where $p \in B(t//e)$, $Q \in VAR_{t/e}$

Similar rules can be defined for the cases where the link is established from an instance to the concept (an example is obtained by reversing the order of sentences in the alligator example). We summarize the above as follows. In some part of a discourse a reference is made to a certain entity $\zeta$ by using a description $D_1$. Let this description translate into $\Lambda$ as $\lambda Q\phi(\zeta)$. In a subsequent part of the discourse we change the level of reference and use another description $D_2$ to make a reference to a generalization of $\zeta$ with respect to a certain decomposition $\triangle_{\xi}$, where $\xi$ is this generalized entity. We thus obtain that $\zeta \in L^{\xi,\triangle\xi}_{-1}$. We say that $\lambda Q\phi(\zeta)$ creates a subcontext[15] for $D_2$, and that $D_1$ and $D_2$ are *remotely co-referential*

## 5. Conclusions

There are, of course, other approaches to discourse analysis which do not rely so much on grammar and logic, but instead concentrate on issues such as discourse structure or selected pragmatic aspects. These include Carberry (1989), Grosz (1977), Litman & Allen (1987), Pollanyi & Scha (1984), Scha & Pollanyi (1988). These works were usually aimed at analysis of specific types of discourse that display certain characteristics of form: task oriented dialogues, arguments, plans, access to information, etc., or else at handling selected structural phenomena in discourse such as interruptions, topic chains, lists, narratives, and so on. In our work we aim at an adequate analysis of written texts for which restrictions of form may not obtain, although we may have to deal with the various structural phenomena. For unconstrained texts grammar-based approaches were usually more appropriate, as evidenced by Grishman (1986), Hobbs (1976), Hobbs

[15] When a level change occurs in the opposite direction, that is, from a generic entity to an individual, then we talk about *supercontext*.

et al. (1982), Sager (1981). Nonetheless, the structural aspect of discourse needs to be handled, and this we propose to do by adding control and other pragmatic restrictions to the grammar.

There were also numerous other approaches to the problem of inter-sentential dependencies, most notably inter-sentential anaphora. Perhaps the most influential were Grosz (1977), Sinder (1979), Webber (1979). Although we will not attempt to review them here, the reader mai:y wish to refer to Hirst (1981) for an excellent survey. From our viewpoint the most interesting system is Webber's because, unlike most of the others, it was designed to capture the logical properties of language at large, rather than to work within a narrowly defined sublanguage. For this reason we utilize various insights made there, while trying to avoid the pitfalls.

The prototype presented in this paper is quite simple in that it is constructed on the basis of a categorial grammar that covers only a small portion of syntactic constructions in English; this is because we aimed more at perspicuity and conceptual clarity than at actual coverage. For all its present limitations, however, our initial prototype moves beyond the range of inter - sentential dependencies in discourse that are usually accounted for by the process of anaphora resolution. We consider various kinds of non-referential contexts occurring in scope of propositional attitude operators. We also propose dealing with the problem of chaning reference level in discourse, where certain objects can be alternately referred to at different stages of aggregation: at generic level, group level, individual level, or even sub-individual level. Of course, many problems remain to be worked out, including further cases of intersentential dependencies, a control system imposed by discourse structure, and an empirical method for recognizing reference level changes between sentences, among others.

## 6. Acknowledgments

This paper is based upon work supported by the Defense Advanced Research Project Agency under Contract N00014-85-K-0163 from the Office of Naval Research, and by the National Science Foundation under Grant IRI-89-02304.

## References

Brown, G. , G. Yule (1984) *Discourse Analysis*, Cambridge University Press.

Carberry, S. (1989) 'A Pragmatics-Based Approach to Ellipsis Resolution,' *Computational Linguistics*, 15(2), pp. 75-96.

Cohen, R. (1987) 'Analyzing the Structure of Argumentative Discourse,' *Computational Linguistics*, 13(1-2), pp. 11-24.

Gazdar, G. , E. Klein, G. K. Pullum, I. Sag (1985) *Generalized Phrase Structure Grammar*, Basil Blackwell, Oxford.

Grishman, R. (1986) *Computational Linguistics*, Cambridge University Press.

Grishman, R. , R. Kittredge, eds. (1986) *Analyzing Language in Restricted Domains: Sublanguage Description and Processing*, Lawrence Erlbaum Assoc. , Hillsdale, NJ.

Grosz, B. J. (1977) 'The Representation and Use of Focus in a System for Understanding Dialogues,' *Proceedings of the Fifth Int. Joint Conference on Artificial Intelligence* (IJCAI), Cambridge, MA. pp. 67-76.

Grosz, B. J., C. L. Sidner (1986) 'Attention, Intension and the Structure of Discourse,' *Computational Linguistics*, 12(3), pp. 175-104

Hirst, G. (1981) *Anaphora in Natural Language Understanding: A Survey*, Lecture Notes in Computer Science, 119, Springer-Verlag.

Hobbs, J. R. (1976) 'A Computational Approach to Discourse Analysis,' *Research Report* 76-2, Department of Computer Science, City University of New York.

Hobbs, J. R. , D. E. Walker, R. A. Amsler (1982) 'Natural Language Access to Structured Text,' *Proceedings of COLING '82*, Prague, Czechoslovakia, pp. 127-132.

Kittredge, R. (1983) 'Sublanguage,' *Am. Journal of Computational Linguistics*, 8(2), pp. 79-82.

Ksiezyk, T. (1988) *Simulation-Based Understanding of Texts about Equipment*, Doctoral Dissertation, Proteus Project Memorandum #17, Department of Computer Science, Courant Institute of Mathematical Sciences.

Litman, D. , J. F. Allen (1987) 'A Plan Recognition Model for Subdialogues in Conversation,' *Cognitive Science*, 11, pp. 163-200.

Montague, R. (1974) *Formal Philosophy, Selected Papers of Richard Montague.* R. H. Thomason (ed.), Yale University Press.

Partee, B. H. (1972) 'Opacity, Coreference and Pronouns,' In D. Davison and G. Harman (eds.), *Semantics of Natural Language*, Reidel, Dordrecht, pp. 415-441.

Pereira, F. C. N. and Warren, D. H. D. (1980) 'Definite Clause Grammars for

Language Analysis,' *Artificial Intelligence*, 13, pp. 231-278.

Pollanyi, L. , R. Scha (1984) 'A Syntactic Approach to Discourse Semantics,' In *Proceeding of COLING '84*, Stanford University, CA. pp.413-419.

Sager, N. (1981) *Natural Language Information Processing*, Addison-Wesley.

Scha, R. , L. Pollanyi (1988) 'An Augmented Context Free Grammar for Discourse,' *Proceedings of COLING '88*, Budapest, Hungary, pp. 573-577.

Schubert, L. K. , F. J. Pelletier (1982) 'From English to Logic: A Context-Free Computation of 'Conventional' Logical Translation,' *Computational Linguistics*, 8(1), pp. 27-44.

Shieber, S. M. (1986) *An Introduction to Unification-Based Approaches to Grammar*, Chicago University Press, Chicago.

Sidner, C. L. (1979) 'The Role of Focusing in Interpretation of Pronouns,' *Proceedings of the 17th Annual Meeting of the ACL*, pp. 77-78.

Strzalkowski, T. (1986a) 'Representing Contextual Dependencies in Discourse,' *Proceedings: Canadian Conference on Artificial Intelligence (CSCSI/SCEIO '86)*, Montreal, Canada, pp. 57-61.

Strzalkowski, T. (1986b) 'An Approach to Non-Singular Terms in Discourse,' *Proceedings of COLING '86*, Bonn, Germany, pp. 362-364.

Strzalkowski, T. (1987) *A Theory of Stratified Meaning Representation*, Doctoral Dissertation, Technical Report TR 87-5, Department of Computing Science, Simon Fraser University, Burnaby, B. C.

Strzalkowski, T. (1989) 'Inter-Sentential Dependencies, Meaning Representation and Generics,' In J. P. Martins and E. M. Morgado (eds.), *Lecture Notes in Artificial Intelligence*, 390, Springer-Verlag, pp. 210-221.

Strzalkowski, T. , N. Cercone (1986) 'A Framework for Computing Extra-Sentential References,' *Computational Intelligence*, 2(4), pp. 159-179.

Strzalkowski, T. , N. Cercone (1989) 'Nonsingular Terms in Natural Language Discourse,' *Computational Linguistics*, 15(3), pp. 171-186.

Webber, B. L. (1979) *A Formal Approach to Discourse Anaphora*, Doctoral Dissertation, Harvard University.

Zeevat, H. (1988) 'Combining Categorial Grammar and Unification,' In Reyle U. and C. Rohrer (eds.), *Language Parsing and Linguistic Theories*, Reidel, Dordrecht, pp. 202-229.

Courant Institute of Mathematical Sciences

New York University
251 Mercer Street
New York, NY 10012
U. S. A.