Rethinking the Semantics of Complex Nominals

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Abstract. Complex Nominals (CNs) have simple syntactic structure that conceals non-trivial semantic characteristics. While speakers of natural languages combine noun(s)/adjective(s) with a head noun to indicate existing or novel concepts with ease, formalizing such a semantic process, however, has proven to be a daunting task. In this paper, we present a unified semantic approach for constructions involving a head-noun and modifier(s), i.e., adjective(s)/noun(s). Based on a rigorous typing system, this approach uses set intersection as the only underlying semantic rule. We argue that this novel approach is compositional and warrants consistent inferences.

1 Introduction

A CN is a sequence of one or more nouns or adjectives preceding a head noun.[1] Instances of such a construction include *apple pie*, *information retrieval system*, *computer book sale*, *former political activist*, etc. CNs have been investigated in many fields: linguistics (e.g., [3, 12, 19, 16, 5, 17]), cognitive science (e.g., [4, 8, 18]), and AI ([2, 11, 7]), among others. The bulk of such research in AI and linguistics is concerned with identification and classification of the semantic relations in noun-noun constructions. Other problems such as adjective-noun combinations and bracketing are treated separately. Each field, understandably, uses different tools to address the respective concerns. Corpus analysis is by far AI's most commonly used tool in the treatment of CNs.

Although corpus-based systems have met some successes, a more systematic approach to CNs is yet to emerge. Such a semantic approach must address two fundamental questions: what are the semantic values of common nouns, and adjectives? And what are the semantic values of their combinations?

What makes the semantic analysis of CNs difficult is that some modifiers are reference-modifying (i.e., intensional), some are referent-modifying (i.e., extensional), and some can be both. The difficulty of analysis increases when modification involves multiple modifiers.

We address these issues and present a formal system that, we argue, is capable of overcoming limitations posed to corpus-based approaches. In addition, as AI workers, we take the issue of machine-implementability seriously into consideration, without compromising the philosophical and linguistic concerns.

[1] This use of the term "complex nominal" is more general than is commonly used in the literature, e.g., in [17] modifiers are limited to nouns and non-predicating adjectives.

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2 On Compositionality

Also known as *Frege's Principle*, *compositionality* is informally stated[2] as: the meaning of a whole expression is a function of the meaning of its constituents and their syntactic mode of combination. In formal languages this principle is taken for granted. In computer programming, it is implicitly assumed when proving some aspects of programs such as correctness and termination. Within natural languages, however, it is debatable. While the bulk of language expressions seem to adhere to compositionality, it is obvious that some expressions such as idioms and lexicalized expressions, e.g., *white wine*, *potential energy*, etc. deviate from it. However, generally speaking, idioms and lexicalized expressions are very limited in number within a language and are normally listed as entries in a conventional dictionary. Thus, they are treated as lexemes and consequently pose no threat to compositionality. However, as [13] points out, what remains controversial is where to draw the line between compositional expressions, on one side, and lexicalized/idiomatic expressions, on the other side.

In Richard Montague's highly formalized semantic theory, compositionality occupies centre stage. It is expressed as rule-to-rule correspondence between the syntax and semantics. That is, for every rule of the syntax, there is a corresponding semantic rule for computing its meaning. For example, given the syntactic rule (1), in BNF notation, a possible corresponding semantic rule is (2):

1) CN ::= M N , where M stands for a modifier 2) $\| CN \| = F (\| M \|, \| N \|)$

That is, given a CN, its meaning is determined by the meanings of the modifier and noun involved, whatever they might be, plus the way they are linearly organized, namely a head noun preceded by a modifier.

Our views regarding compositionality parallel that of Frege's and Montague's. For a non-compositional approach would face numerous problems, see [10] for examples of non-compositional semantic approaches. In section (6) we show how to account for compositionality by taking the semantic values of the parts to be typed sets, and the function *F* a set intersection.

3 On the Semantic Theory

Lexical categories such as nouns and adjectives belong to the set of linguistic realm. They acquire meanings when they correlate to entities in the world or model. Thus, the semantics of a language can be thought of as a process by which a link between the linguistic and the extra-linguistic is established. This is the approach taken by extensional semantic theories.

In a purely-extensional semantic theory, the meaning of a term in a language is taken to be the denotation of that term within a world or a model. Based on such a theory, co-extensive terms can be (counter-intuitively) interpreted to have the same meaning. For example, the terms *the largest integer*, *dragon* and *unicorn* are interpreted to mean the same thing.

[2] See [13, p 135] on suggestions as to how to make this definition precise.

Intensional semantics overcomes this difficulty by taking meaning to be composed of intensions as well as extensions. Intensions are considered as functions with indices as domains. One of the indices can be *possible worlds*. It is then said that intensions determine extensions. With the inclusion of intensions, a semantic theory will not admit the terms *the largest integer* and *unicorn* as having the same meaning. For in some other world the set of unicorns might not be empty.

Thus, a semantic framework that invokes notions such as possible worlds seems to be ideal for CNs, e.g., Montague took the meanings of adjectives to be functions from intension to extension, see [13] and [22]. Yet, as [10] points out NLU systems based on Montague semantics with its use of infinite sets and functions to functions render developing such systems impossible.

We will show that the formalism we are proposing in this paper is capable of capturing intensions, in some sense, and yet is still machine-implementable.

4 On the Semantic Values of Nouns and Adjectives

In the previous section, we pointed out that our goal is a compositional account of CNs. We hinted that this can be achieved via the function F. However, we have not provided any characterization of its arguments. That is, the values of the objects ||M|| and ||N||. This brings up the question regarding the nature of the denotations of adjectives and nouns. Jespersen [12] (*see* also [21]) provides the following account regarding adjectives and nouns (termed ‘substantives’ by Jespersen):

> *On the whole, substantives are more special than adjectives, they are applicable to fewer objects than adjectives, in the parlance of logicians, the extension of a substantive is less, and its intension is greater than that of an adjective.*

The difference between adjectives and that of common nouns has also been expressed by Strawson (see, [9]) as that between *sortal and nonsortal* predicates. Strawson states that a sortal predicate, “supplies a principle for distinguishing and counting individual particulars which it collects”, while a nonsortal predicate “supplies such a principle only for particulars already distinguished, or distinguishable, in accordance with some antecedent principle or method”.

Jespersen’s and Strawson’s accounts shed some light into the possible semantic values for both nouns and adjectives. Jerspersen’s suggests, among other things, that adjectives have wider “applicability” and Strawson suggests, among other things, that adjectives denote properties. Both analyses seem to be in accord and are plausible in adjective-noun constructions. The formalism we propose next takes these observations into consideration.

5 On Modification

Despite the ontological differences between nouns and adjectives, they have a common functionality of interest: modification of head nouns. This functionality is evident at both the syntactic and semantic levels. In the case of the former, both nouns and adjectives can occupy the attributive position, i.e., preceding a head noun. At the semantic level, although a noun and an adjective modifier may contribute differently to the meaning of the compound, a near-universal truism is that the denotation of the compound is a subset of the denotation of its constituent head noun. Expressions admitting such reading are called *subsectives*. In some special cases, the denotation of the compound is a subset of both the denotation of the head noun and the denotation of the modifier. This is called the *intersective* reading. Modifiers that allow intersective reading are, also, referred to as referent-modifying (i.e., extensional), while those that do not allow such a reading are called reference-modifying, i.e., intensional, see [22] for details. Table 1, where 'M' and 'H' stand, respectively, for modifier and head noun, illustrates by example the points raised in this paragraph.

Table 1. Similarity of modification in nouns and adjectives

Noun-Noun example	**‖M H‖ ⊆ ‖H‖**	**‖M H‖ ⊆ ‖M‖**	**Modifier: int/ext**	**Adjective-Noun example**
player coach, child murderer[3]	Y	Y	Ext	Canadian coach
soccer game	Y	N	Int	competitive game
Glass cup	Y	Y	Ext	red car
elephant chocolate	Y	N	int	toy store[4]

We believe that such a common behavior warrants a uniform semantic treatment that takes into account the intensional and extensional behavior of modifiers. This, as compositionality demands, should be expressed by providing a single semantic rule that mirrors the syntactic one. In our system, such a rule is set intersection.

6 The Formalism

In this section we present a formal system for CNs. It starts by introducing typed-sets: the semantic values for the parts in a complex expression. Next, it defines rules, axioms, and the typing system for handling complex compounds. In devising the formalism, we have taken the following factors into considerations:

- The duality of the semantic behavior of nouns: a noun can be in the head or the modifier positions of a CN, e.g., *boat house* and *house boat.*
- The bracketing problem.
- The general applicability of adjectives.
- The desire to strike a balance between simplicity and machine- implementability of extensional semantics and the sophistication of intensional ones.

The resulting system, we argue, has the following characteristics:

1) Captures meanings' two aspects, i.e., intension and extension.
2) Is machine-implementable.
3) Can fit within logical frameworks such as that of Montague's.

[3] This expression can mean "one who murders children" or "a child who commits murder". It is the latter reading that is considered here.

[4] For discussion of subsective reading of privatives, see [1] and for linguistic evidence see [20].

4) Is Russell-Paradox-free.
5) Is an extension to and/or modification of set theory or lambda calculus notations, which are well studied and used.

6.1 The Case for Typed-Sets

The Cantorian notion of a set has been affectionately embraced by mathematicians: "No one shall expel us from the paradise which Cantor created for us", as David Hilbert succinctly puts it. While it is hard to disagree with Hilbert wholesale, one can argue that a set, as conceived and defined by Cantor, makes rather simplistic assumptions. One can identify at least two shortcomings: an element is either in the set or not, that is, a world with sharp boundaries; an element once in a set is completely identified with it. That is, the only property that a member has is its membership in the respective set, all other properties are "lost"—individuality is sacrificed for plurality. The former, was addressed by fuzzy sets. The latter we address here by adding types for both members of the set and the set itself. This newly conceived set is termed a "typed-set". We argue that one application of such an abstract typed-set is to model modification in CNs. We argue that this modification allows an extensional representation of terms usually described as intensional while at the same time preserving the original Cantorian conception of the set. We will show that this augmentation of the classical set allows representations of terms that are "normally" hard to represent such as frequency terms, e.g., *occasional*, and non-committal terms, e.g., *alleged*. Such a representation is not possible using the classical set or the fuzzy one. This is accomplished while maintaining the original classical set properties, i.e., typed sets can be seen as a generalization of classical sets.

(Typed Sets) A typed set is a set-theoretic set that has the following form:

$$M = \{e:\ \alpha, \ldots\}:\ \beta \qquad (1)$$

Here, M is a set of type β. Its member e is of type α. It should be noted here that the set member and its type are one integral whole.[5] In lambda notation, this can be expressed as in (2), where Γ is a context or environment:

$$\begin{array}{ll} \Gamma, e:\alpha \vdash e:\alpha & \Gamma,\ M:\beta \vdash M:\beta \\ (\lambda x.M(x))\ (e:\ \alpha) & \end{array} \qquad (2)$$

From (1) and (2), it should be obvious that set members are first-order elements, i.e. individuals. Thus, a set cannot be a member of another set of the same order, including itself.

6.2 The Semantic Values of Complex Expressions

It is assumed that the types α and β in (1) range over types in a type hierarchy, where each node in the hierarchy represents a type. A fully-fledged system will need such a hierarchy. However, for our illustrative purpose we will be using the following subset of types:

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[5] One may think of this as an approximation of the Aristotelian view of a *universal* inhering in a *particular*.

- The type "$\top$", assigned to extensional[6] terms, e.g., *red*, *Canadian*, etc.
- The type "$\perp$", the absurd type, is assigned to "non-committal" terms, e.g., *potential*, *alleged*, *presumed*, etc.
- The type "role", is assigned to common nouns denoting roles, e.g., *senator*, *employee*, *manager*, *dancer*, etc.

Given a type $\top$ that is assigned to extensional terms, then, we can define the classical set to be of that type.

(Classical Set) A classical set is a typed set which is of type $\top$ and all its members, if any, are of type $\top$.

(Subtype Relation «) Types in the hierarchy are constrained by the partial-order subtype relation indicated by «. The expression $\alpha«\beta$ is read "α is a subtype of β."

For example the subtyping relation that holds between the types `employee` and `manager` and `role` can be expressed as follows:

`manager « employee « role`

(Complex Type) The type hierarchy contains the simple types. To handle cases where more than one modifier is involved in a CN, we need a systematic way to assign types that mirrors the complexity of the expressions.

Definition (Types). Assume a (non-empty) set of simple types τ. Define the set T of types as follows:

i) $\tau \subset T$
ii) if α and $\beta \in T$ then $(\alpha:(\beta)) \in T$

According to these type-forming rules, the expression *deep blue sea*, will be assigned the types `(deep:(blue:(sea)))` and `((deep:(blue)):( sea))` or by removing redundant parentheses `deep:(blue: sea)` and `(deep: blue): sea`. These complex types correspond, respectively, to the wide- and narrow-scope readings of the adjective *deep*.

6.3 Operations on Typed Sets

In this subsection, we define the basic set operations and related axioms necessary to compute the meaning of CNs. This includes set intersection, equality of sets, and equality of particulars (or set members).

(Convention) Greek letters stand for types, lower-case letter for members, and upper-case letters for sets.

(The most specialized types) $\perp « \alpha$ ($\perp$ is the lower-most type)

(Type of complex expressions) The type of a complex expression is the right-most:

Given set X: α:

[6] For classification of adjectives, see [1] and [13].

$$\frac{X:\alpha}{X: \Im(\alpha)}$$

Where $\Im$ is a function defined as follows:

$$\Im(\alpha : (\beta)) = \begin{cases} \beta, if \beta \in \tau \\ \Im(\beta), otherwise \end{cases}$$ where τ is the set of simple types.

(Particulars) Since a particular (or a set member) and its type are an integral whole, we define equality between them using the symbol '≡'. Given particulars $e_1:\alpha$ and $e_2:\beta$

$$e_1 \equiv e_2 \iff e_1 = e_2 \wedge [(\alpha = \beta) \vee (\alpha \ll \beta)] \text{ (particular equality)}$$

Using this rule, we can say that a cat is an animal, but not the other way around.

(Subset) $X:\alpha \subseteq Y:\beta \iff$

$$(\forall e: \sigma)\ e: \sigma \in X: \alpha \Rightarrow [\ (e: \sigma \in Y:\beta) \vee (\exists \rho)\ \rho \in T \wedge e: \rho \in Y:\beta \wedge (\sigma \ll \rho)\ )]$$

(Set equality) $X:\alpha = Y:\beta \iff [(X:\alpha \subseteq Y:\beta \wedge Y:\beta \subseteq X:\alpha) \wedge (\alpha = \beta)]$

(Extensional intersection)

$$\frac{(e_1: \top) \in X: \alpha \qquad (e_2: \alpha) \in Y: \beta \qquad e_1 = e_2}{Z = X \cap Y \text{ s.t. } (e_1: \alpha) \in Z: \alpha:(\beta)}$$

Where *s.t.* stands for such that. This rule is used with extensional modifiers. Using this rule, we can validly deduce that *Mary is a Canadian dancer* from *Mary is beautiful dancer* and *Mary is Canadian*. For the adjective *Canadian* is extensional.

(non-extensional intersection)

$$\frac{(e_1: \rho) \in X: \alpha \qquad (e_2: \sigma) \in Y: \beta \qquad e_1 \equiv e_2}{Z = X \cap Y \text{ s.t } (e_1: \sigma) \in Z: \alpha:(\beta)}$$

This rule blocks wrong inferences due to reference-modifying modifiers. Examples of this rule are in the next section.

(Ø-Intersection)

$$\frac{X: \alpha \qquad Y: \beta \qquad Z = X \cap Y = \emptyset}{Z: \alpha:(\beta)}$$

This rule allows us to speak about predicates with empty extensions, e.g., *white unicorn*. An empty set, Z, can be formed with the appropriate type.

6.4 Computing the Meaning of Compounds

Now that typed-sets and operations on them have been defined, in this section we will demonstrate how to compositionally compute the meaning of CNs. Since CNs are instances of one syntactic rule that states that a head noun can be preceded by some modifier(s), we argue, as compositionality demands, that a single semantic rule, F, corresponding to a single syntactic rule can be defined in terms of typed-sets and set intersection. For the simplest case where a head noun is modified by a single modifier, F can be defined as follows:

F(M N) = ||M|| ∩ ||N||, where ||M|| and ||N|| are typed-set-valued functions

Since the modifier ‘M’ may involve more than one adjective or noun, the definition of F is refined to the following:[7]

$$F(MN) = \begin{cases} \| N \|, if\ (M = null) \\ \| M \| \cap F(N), if\ (\| M \| = X : \alpha \wedge (\alpha \in T)) \\ F(M) \cap \| N \|, if\ (\| N \| = X : \beta \wedge (\beta \in T)) \\ F(M) \cap F(N), otherwise \end{cases}$$

where T is the set of types

The domain of *F* is a bracketed expression. Such an expression can be obtained from a parse tree. For instance, the expression *liberal party scholarship scandal* can have the parse tree depicted in Fig. 1. This corresponds to the reading [[[liberal party] scholarship] scandal].

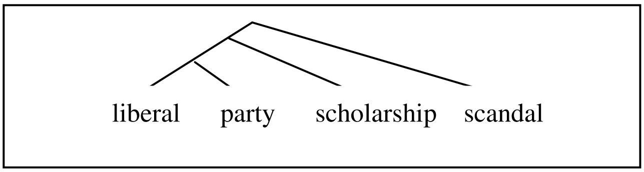

Fig. 1. Tree representation of *liberal party scholarship scandal*

Eliminating the outermost brackets, such an input can have one of the three forms: M [N], i.e., ‘M’ is single word and ‘N’ multiple-words, [M][N], i.e., both ‘M’ and ‘N’ contains multiple words, and [M] N, i.e., ‘M’ contains multiple words and ‘N’ is a single word.

To demonstrate how compounds can be represented and computed, consider the utterances *Fido is a dog*, *Fido is clever*, *John is a man*, and *John is clever*. The adjective *clever* and the nouns *dog* and *man* can be represented, given some state of affairs where John is the only man and Fido is the only dog, as follows:

```
M = {j:man}:man                D = {f:dog}:dog
C = {j: man, f:dog}:clever
```

Where: M, D, and C denote, respectively, the sets of men, dogs, and clever things
|| John|| = j, and || Fido|| = f

It should be noted how Jesperson’s definition is captured in the case of the adjective *clever*. The set C contains in its extension things that are said to have something in common: John is clever as a man, while Fido is clever as a dog. What they have in common is “cleverness”.

Given the data regarding Fido and John, we can provide truth-conditions for the utterance *Fido is a clever dog*. This statement is true if, and only if, the following boolean expression is true:

(f:dog) ∈ || clever dog||
= *F (clever [dog])* = ||clever|| ∩ *F (dog)* = ||clever|| ∩ ||dog||

[7] In fact *F* can be abbreviated to $F(MN) = \begin{cases} \| N \|, if\ (M = null) \\ F(M) \cap F(N), otherwise \end{cases}$.

= {j: man, f:dog}:clever∩{f:dog}:dog
= {f:dog}:clever:(dog) (by the non-extensional intersection rule)
True

Now, assume that *Fido is a veteran shepherd*. This can be represented as follows:

|| shepherd || = {f: shepherd}: shepherd ||veteran || = {f: shepherd}: veteran

It should be noted that a wrong inference such as *Fido is a clever shepherd* cannot be deduced, as desired. To further demonstrate our approach, consider the following utterances *John is a bank manger* and *John is an excellent employee*. A representation of these utterances results in the sets:

||bank|| = {j:manager, …}:bank
||manager|| = {j:manager}:manager
||excellent || = {j:employee, …}:excellent
||employee || = {j:employee }:employee

Next, we try to get answers to the following questions: Is John an excellent manger? Is John a bank employee? These can be translated, respectively, into the following forms, numbered (1) and (2):

(1)

(j:manager) ∈ || excellent manager|| = *F (excellent [manager])*
= ||excellent|| ∩ *F (manager)* = ||excellent|| ∩ ||manager||
= {j:employee,…}:excellent∩{j:manager}:manager
= { }:excellent: manager (by Ø-Intersection)
False

(2)

(j:employee) ∈ || bank employee|| = *F (bank [employee])*
= ||bank|| ∩ *F (employee)* = ||bank|| ∩ ||employee||
={j:manager}:bank∩{j:employee}:employee
={j:employee }: bank :employee
(by non-extensional intersection, by ≡, and because manager « employee)
True

In these examples, it should be clear how the inference and typing rules are working in tandem in the semantic evaluation process.

6.5 Capturing Non-committal Set Membership

One advantage of using typed-sets is the representation of entities that are associated with some predicate but which do not fall within its extension. In other words, referents of such a predicate have a "pending" membership in the set denoted by the predicate. Terms of modal import possess such a phenomenon: e.g., *potential*, *possible*, *presumed*, etc. fall into this category. To illustrate, consider the utterances *Hillary Clinton is a popular senator and a potential president* and *George Bush is a popular president*. These utterances can be represented as follows:

|| senator || ={h:senator,..}:senator
||potential || ={h: ⊥ }:potential

||president|| ={ h: ⊥, g: president}:president
||popular|| ={g: president, h :senator}:popular

where

|| Hillary Clinton|| = h, ||George Bush||= g, and "⊥" is the subtype of every type

Looking at the set representation of the president predicate, we notice that the individuals h and g have different associations with the set. The latter has a full membership, for its type matches that of the set. This is not the case with the other individual. Since the type ⊥ is a subtype of every type in the type hierarchy, nothing commits us to believe that h is a member of the set. More formally, h:president ∉ ||president||, for h:president is not equal to h: ⊥ by the definition of ≡. Also, a negative answer is obtained for the question, *Is Hilary Clinton a popular president?* Because h:president∉ ||popular||∩ ||president||. But affirmative answers to the questions *Is Hilary Clinton a potential president?* or *Is Hilary Clinton a potential official?* are always obtained.

Thus, by assigning the type ⊥ to the adjective *potential* we were able to represent the non-committal membership notion formally. An ad hoc approach would require a non-compositional, non-practical hand-coding of phrases such as *presumed dead*, *alleged thief*, and so on.

7 Comparison with Other Approaches

We will compare our approach to CN analysis of modification with that of Montague's and Davidson's approaches. In Montague semantics, modifiers are syntactically analyzed as functions from predicates to predicates, and semantically as functions from predicate intensions to predicate extensions. This approach, in line with Montague's doctrine of generalizing to the hardest case, provides a uniform treatment of modification. However, this generalization, as [14] notes, "blurs" the fact that when an extensional modifier is applied to a predicate the compound is interpreted as the conjunction of the two predicates[8], as in (a). For work regarding CNs within Montague's framework, see [22] and [6].

In the Davidson approach, as in the work of [15], on the other hand, the constituents of a CN are analyzed as conjunctions of a number of predicates, whose domains range over the set of individuals. Such an analysis is simple and straightforward with regard to extensional modifiers such as *red* and event-indicating, non-extensional modifiers such as *former*. Thus, the expressions in (a) and (c), from [15], are, respectively, represented as in (b) and (d):

a) That is a red rose b) $\exists$ x red(x) $\wedge$ rose(x)
c) Jerry is a former president d) $\exists$ e[presidency(e) $\wedge$ Theme(jerry,e) $\wedge$ former(e)]

As these examples show, predicates are of first-order nature, which is an advantage over Montague's, which invokes, as seen by some people, ontologically dubious notions such as possible worlds. However, things get complicated for the Davidsonian

[8] This conjunctive reading can be accounted for with additional semantic rule to the grammar.

analysis when non-committal modifiers are involved. It is difficult to see how a uniform approach can be obtained, where the syntactic and semantic functions stay in close correspondence as compositionality demands and as demonstrated in Montague's. Thus, uniformity is seriously compromised by simplicity.

Our approach, on the other hand, avoids the difficulty encountered by the two approaches. We obtained uniformity not by generalizing to the hardest case, as Montague did, but to the simplest case, conjunction or intersection. This, of course, has been achieved at the expense of adding types to both sets and their elements. Thus, in our approach, as in Davidson, (a) is interpreted as conjunction of the modifier *red*, given the type $\top$, and the noun *rose*. Also, as demonstrated in (6.5), we were able to represent non-subsective modifiers; something that Davidson's approach has difficulty accounting for. This is, of course, in addition to our approach's capability of accommodating bracketed expressions and its machine-implementability. The latter is the case since our predicates, as in Davidson's approach, are first-order with some extra overhead computation to work out types.

8 Conclusion

We have presented a unified semantic approach to complex nominals. We started by providing an analysis of the ontological nature of the constituents of complex nominals, the adjectives and common nouns. We argued that typed sets are capable of capturing the semantic aspects of extensional and intensional terms, using first-order predication. We argued that typed sets can, without resorting to notions such as possible worlds, show that co-extensive terms have different meanings. Then, we presented the rules and axioms, as well as typing rules, for handling complex expressions. We demonstrated the new approach by applying it to several examples. In particular, we showed how typed set could capture the semantic values of otherwise hard to represent terms such as *presumed*. We then compared our approach to the way CNs are analyzed within two well studied semantic frameworks, Montague and Davidson. We argued that our approach is as general as Montague and is as first-order-predication-oriented as Davidson. We argued that this feature is of significant importance for machine-implementability.

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