Article

Non-Axiomatic Logic Modeling of English Texts for Knowledge Discovery and Commonsense Reasoning

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Abstract: Non-Axiomatic Logic (NAL) is a term-based, non-monotonic, multi-valued logic with evidence-based formal semantics. All those characteristics position NAL as an excellent candidate for modeling natural language expressions and supporting artificial agents while performing knowledge discovery and commonsense reasoning tasks. In this article, we propose a set of rules for automatic translation of natural language (NL) text into the formal language of Non-Axiomatic Logic (NAL). Several free available tools are used to support a previous linguistic analysis, and a common sense ontology is used to populate a background knowledge base that helps to delimit the scope and the semantics of logical formulas translated. Experimentation shows our set to be the most complete NL to NAL translation rule set known so far. Also, we included a complete set of examples to show how our proposed set of rules can be used for logical inference on the contents of NL texts.

Keywords: non-axiomatic logic; computational linguistics; knowledge discovery; commonsense reasoning

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1. Introduction

Endowing artificial agents with the ability to understand natural language in a way similar to humans is a task in which Artificial Intelligence has not yet made enough progress [1] [2] [3]. Even the most advanced connectionist and generative models, trained with gigabytes of examples and executed on large scale high-performance clusters perform poorly when faced with the task of commonsense reasoning based on the contents of natural language texts [4][5]. From the symbolic perspective, modeling natural language with logic has also yielded poor results, but it is believed that those poor results are a consequence of the low expressive power of the logics used for modeling [6] [7]. When Predicate Logic (PL), or any of its subsets has been used, poor results are also attributed to the mathematical orientation of those logics as well as their inability for modeling everyday concept acquisition and processing [8] [9]. If a radically different logic is used, it may be possible to get better results, and that is exactly the case with Non-Axiomatic Logic (NAL), a formal language designed to model the process of an agent pragmatically learning its environment [10] [11]. As such, NAL offers several advantages over other symbolic logics [12] [13], like the ability to define higher-order expressions and use a variety of inference models besides deduction.

In this paper, we propose a set of translation rules for automatically modeling English sentences with NAL expressions called judgements [14] [15]. By using a few auxiliary and freely available linguistic tools, a knowledge base can be constructed from texts and a background context for those judgements can be precisely defined, expanded, and delimited. With such knowledge base it would be possible to perform knowledge discovery tasks, as well as to mimic commonsense reasoning [16].

The difficulty of clearly presenting this research faces many obstacles, but the most relevant is the initial requirement for the reader to have a not-so-small familiarity, both with linguistic analysis techniques and with Non-Axiomatic Logic. Since the combination of those two knowledge areas is not common in a reader's profile, we have modified the classic structure of this paper, removing the "related previous works" section and compensating with a concise presentation of the minimum required concepts in linguistic analysis and Non-Axiomatic Logic.

2. Theoretical Foundations and Required Background Knowledge

2.1. Non-Axiomatic Logic

Non-Axiomatic Logic (NAL) [17] [18] is a non-monotonic and multi-valued term logic developed in order to model everyday thinking as well as the process of an artificial agent learning its environment and adapting to it. NAL is not an agent-logic in the modern computational sense, but only a formal language that serves as a sufficiently expressive knowledge representation tool, and as a reasoning guide for an agent who must always operate under the *Assumption of Insufficient Knowledge and Resources* (*AIKR*). This assumption implies that the agent can never assume it has neither complete knowledge of any situation nor infinite time and/or processing resources to obtain it. Also, to operate under *AIKR* implies that there is no constraint defined on the content of the experience the agent may have. Most notably, the classic monotonic-reasoning restriction of many other logics is not present in NAL.

As a non-monotonic logic, in NAL it is not required for each new formula just learned, to be consistent with all formulas previously known. This characteristic allows to better model the flow of a text in natural language [19]. As a multi-valued logic, truth values of formulas in NAL are not limited to be either *true* or *false*. This allows the grading of truth based not on predefined axioms, but strictly on the account of evidence supporting each formula in the agent's experience. Lastly, being a term logic means that formulas do not adhere to the mathematical predicate logic syntax and semantics. NAL formulas are more closely related to Aristotle's logic where each formula is composed by two *terms* (called *subject* and *predicate*) related by a relational operator (called *copula*). A *term* is either a constant labeling a specific concept within the *universe of discourse* (also called *domain*) or a quantified variable that represents a subset of concepts within the same domain, and which are still to be determined [20].

Since *Götlob Frege* first defined Predicate Logic [21], he claimed that its crucial advantage over term logics was its capability for expressing any conceivable relation between concepts, while a term logic can only represent a finite and small number of relations depending on the copulas defined. NAL has only five native copulas defined (See Table 1), and although these five copulas are evidently not enough to match the expressive power of Predicate Logic, that handicap is compensated with NAL's capabilities to express *compound terms*, and *user-defined relations*.

Compound terms are constructed using some set theory operators (union, intersection, and difference), while user-defined relations are constructed by associating a compound term including all related terms with a new term that names the relation among them. This last extension is what really helps to harness the expressive power of NAL, and it is a crucial modeling element of the proposed method. Tables 1 and 2 summarize basic compound term capabilities in NAL.

An element that notably highlights the distinction between NAL and other symbolic logics are the truth values of formulas. In order to support a semantics based exclusively on evidence (*pragmatic* semantics), in NAL each formula is assigned a truth value which is a vector $\langle f, c \rangle$ where [18]:

- *Frequency* (f) is a real number in the interval [0,1] computing the ratio of positive evidence (w^+) for the formula over the total available evidence about it (W), therefore $f = w^+/W$.
- *Confidence* (c) is another real number in [0,1) computing the ratio of currently available evidence (W) for the formula over the total amount of evidence expected to exist ($W + k$), so $c = W/(W + k)$, where the k variable is a constant expressing the system's learning speed and it is usually set at $k = 1$.

Table 1. Native NAL copulas

Copula	Formula structure	English meaning	Example
Inheritance	$S \rightarrow P$	S is a type of P	$canary \rightarrow bird$ (Canaries are a type of bird)
Similarity	$S \leftrightarrow P$	S is similar to P	$tweety \leftrightarrow birdy$ (Tweety is similar to Birdy)
Instance	$\{S\} \rightarrow P$	S is an instance of P	$\{tweety\} \rightarrow canary$ (Tweety is a canary)
Property	$S \rightarrow [P]$	S has property P	$canary \rightarrow [yellow]$ (Canaries are yellow)
Instance-property	$\{S\} \rightarrow [P]$	Instance S has property P	$\{tweety\} \rightarrow [yellow]$ (Tweety is yellow)

Table 2. Compound terms and relations definition in NAL

Term Connector	Term Structure	English concept	Example
$\cup$ Set Union	$T1 \cup T2$	Any element of concept T1 or concept T2	$(bird \cup [yellow])$
$\cap$ Set Intersection	$T1 \cap T2$	An element of concept T1 and of concept T2	$(bird \cap [yellow])$
$-$ Asymmetric Set Difference	$T1 - T2$	An element of concept T1 but not of concept T2	$(bird - [yellow])$
$\ominus$ Symmetric Set Difference	$T1 \ominus T2$	An element with properties of T1 but no properties of T2	$(canary \ominus bird)$
$\times$ Relation	$(\times T1, ..., Tm) \rightarrow Tn$	Terms T1 to Tm are related by a Tn relation	$(\times cat, bird) \rightarrow chase$

Therefore, whenever a NAL formula is assigned its truth value, the $frequency$ component of it shows the ratio of *positive evidence* available for the formula, and its $confidence$ component shows how much evidence is available compared with that which is expected to exist.

Finally, NAL as almost all predicate logic variants, also has *variables*. Variables in NAL formulas are terms representing another term whose value has not been defined yet. It is not necessary to ground variables when performing inference since an adequate structure of the conclusion formula does not depend on the value of variables. Syntactically, all variables start with a '#' character followed by a name written in italic font. Also, we named variables with the grammatical element that the variable represents in each formula, so you can find variables as $\#Whomever$ or $\#Whatever$.

2.2. Linguistic Tools

In order to properly define rules for NL to NAL translation, it is first necessary to obtain the linguistic structure of the NL text. Particularly, *dependency parsing*, *part of speech tagging*, *named entity recognition*, and *search for hypernyms* are the more relevant linguistic analyses needed.

Dependency parsing [22] is a linguistic analysis that identifies the grammatical structure of sentences and constructs a dependency tree that represents such structure. This process finds sets of related words within a sentence, as well as the specific type of each one of those relations. Found relationships are called *dependencies* and *universal dependencies* [23] is a representative set of dependencies designed to cover a great majority of use cases in all languages.

Part of Speech Tagging (PoS tagging) [24] is a process that marks each word in a sentence with a tag that indicates its grammatical role in that sentence. PoS tags include the eight classic categories (noun, verb, participle, article, pronoun, preposition, adverb, conjunction) as well as other related subcategories. Both, dependency parsing and part of speech analysis are used to define the type of terms and the hierarchical structure of the NAL expressions defined and The Stanford Typed Dependencies module of the Stanford Parser is used for this process [25].

Named entity recognition [26] involves the identification and categorization of certain words or part of sentences considered as key information or entities. An entity is basically anything that is consistently talked about or referred to in the text. Named entities include persons, geographic locations, dates, ages, addresses, phone numbers, organizations, companies, etc. The Stanford Named Entity Recognizer [27] is used for this process with only Person, Organization, and Location labels.

Lastly, *hypernyms* are words with a more general meaning than another word with a related but more specific meaning. We use *search for hypernyms* to establish and enrich the context of each concept used in the NL text being translated (i.e. each *term* modeled in a NAL expression). Hypernyms and their opposite hyponyms define a hierarchy of concepts extremely similar to that defined by the *intension and extension calculus* definitions which are the basic ideas that conform the formal semantics in NAL expressions. WordNet [28] is used for finding chains of related hypernyms (i.e. the *intension* of a term).

Table 3. Universal Dependencies, table of core, non-core and nominal dependencies used in this article

	Nominals	Clauses	Modifiers	Function words
Core Arguments	nominal subject object indirect object	clausal subject clausal complement open complement		
Non-core Dependents	oblique nominal expletive	adverbial cl modifier	adverbial modifier	copula marker
Nominal Dependents	nominal modifier appositional mod numeric modifier	clausal modifier	adjectival modifier	determiner case marking

Table 4. Universal Dependencies, table of other dependencies used in this article

Coordination	**Multi Word Expression**	**Special**
conjunct coordinating conjunct	fixed flat compound	goes with

3. Proposal

Linguistic analysis tools facilitate the identification of concepts and relationships expressed in a NL text. But in order to decrease the amount of background knowledge necessary for an agent to reason with the generated logical formulas, on the logic side it is required to establish some previous concepts. Therefore, the core of our proposal is the definition of a group of NAL terms with pre-established semantics, a group of user relationships with predefined structure and semantics, and an informal convention on the use of NAL variables. These fundamental definitions provide a solid ground for simplifying the translation process, as well as a common base for performing inference tasks with the generated NAL formulas.

Pre-defined terms delimit the scope of some fundamental concepts *implicit* in the NL text that would require human-level knowledge and experience to grasp, such as those expressed by the question words *when* or *where*. We highlight these terms writing them in italic font and always ending with a '*' character. Table 5 shows the pre-defined NAL terms and their semantics.

Table 5. Pre-defined terms and their semantics

Pre-defined term	Semantics
*where**	Term for expressing the location of something or of an event. See example 1. Nominal subject, case (e)
*when**	Term for expressing when something occurred or to indicate that two events happened at the same time. See example 7. Oblique nominal, case (b)
*but**	Term for expressing concession between two events. See example 9. Adverbial clause modifier, case (c)
*purpose**	Term for expressing that an event is the purpose of another. See example 9. Adverbial clause modifier, case (e)
*reason**	Term for expressing that an event is the reason of another. See example 9. Adverbial clause modifier, case (f)
*how**	Term for expressing that an event modifies the manner another occurred. See example 9. Adverbial clause modifier, case (h)

Pre-defined relations, on the other hand, allow logical formulas to mimic the grammatical structure of NL sentences. Notably, we use a pre-defined four-term relation to express the grammatical relation between a subject and its direct and indirect objects with the verb in a NL sentence. As these elements are not always *explicit* in a sentence, we also defined the special term '_' (underscore) playing the role of an anonymous variable whose value is not explicitly included in the sentence but it is not needed for its understanding or processing. Table 6 shows the pre-defined relations with their structure and semantics.

3.1. Translation rules

The proposed set of NL to NAL rules was designed to cover all universal dependencies (See tables 3 and 4) with some few exceptions [30]. Rules are grouped into four different sets:

- ***Entity rules***: Rules that only require as input the result of the named-entity recognition analysis. These rules ground some of the logical terms and establish some of the context judgements. With these rules, the words "Bill Gates" will be translated to a single term $\{\text{Bill-Gates}\}$ and the judgment $(\{\text{Bill-Gates}\} \rightarrow \text{person})$
- ***Term rules***: These rules take as input the lemmatization of the text, dependency parsing and PoS tagging results of the text. This type of rules obtain some compound and non-compound terms that will be used in the translation—for example, the words "the manual", "chasing" and "important" will be mapped to the terms $\{\textit{the-manual}\}$, *chase* and $[\textit{important}]$
- ***Hypernym rules***: As the name suggests, these rules take as input hypernyms of concepts in the text via WordNet. The output of these rules are judgments representing "is a" context, for example $(\text{canary} \rightarrow \text{bird})$
- ***Text rules***: Their input consist of the dependency parsing of the text, PoS tagging results and hypernyms of some of the concepts in the text. Establishing judgements that involve defined terms and express the content of the text is the main goal of this group of rules. Suppose the sentence "Ana writes poems" is in the text, then these rules will obtain the judgment $(\{Ana\}, poem, \_) \rightarrow write$

Figure 1 shows the data flow for applying the proposed set of rules. Parallelograms indicate the specific group of rules applied in each case and shaded rectangles indicate the type of NAL formulas yielded. A complete example of the application of rules is shown

Table 6. Pre-defined relations and their semantics

Pre-defined relation	Semantics
$(\times, subject, object, recipient) \rightarrow verb$	*subject* (actor, agent or experiencer as in [29]) makes *verb* (an action), the direct object (not a recipient) of *verb* is *object* and *recipient* is the recipient. See example 1. Nominal subject, case (a) or 3. Indirect object, case (a)
$(\times, argument1, argument2) \rightarrow$ *pre-defined term*	*argument1* and *argument2* are related under the semantics of the *pre-defined term*. See example 1. Nominal subject, case (e) or 7. Oblique nominal, case (b)
$(\times, argument1, argument2) \rightarrow adjective$	*argument1* and *argument2* are related following the semantics of *adjective*. See example 6. Open clausal complement, case (b) or 7. Oblique nominal, case (e)
$(\times, argument1, argument2) \rightarrow comparative$	*argument1* and *argument2* are related following the semantics of *comparative*, which represents a comparative or superlative adjective. See example 6. Open clausal complement, case (b) or 7. Oblique nominal, case (e)
$(\times, argument1, argument2) \rightarrow equality$	*argument1* and *argument2* are related following the semantics of *equality*, which represents an equality comparison. See example 9. Adverbial clause modifier, case (g) or 15. Adjectival modifier, case (c)

below, and Section 4 contains a complete list of examples in the translation of all universal dependencies used.

Example 1. *Consider the sentence:*

"The important manual was reluctantly given to Bill Gates by Ford".

Following the diagram in Figure 1 first, a named-entity recognition analysis is made and it should state that Bill Gates and Ford are entities—the first one is a person, and the second one is an organization, hence, the application of Entity rules will give as result:

$$\begin{aligned} \{\text{Bill-Gates}\} &\rightarrow \text{person} \quad \%\textit{Bill Gates is a person} \\ \{\text{Ford}\} &\rightarrow \text{organization} \quad \%\textit{Ford is an organization} \end{aligned}$$

After this, Dependency Parsing and PoS Tagging should be made. The result of this analysis should be similar to the following:

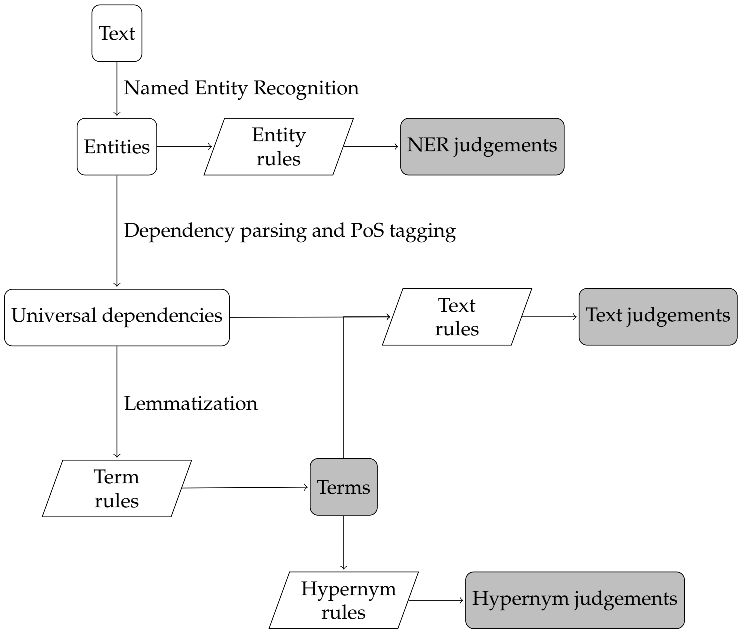
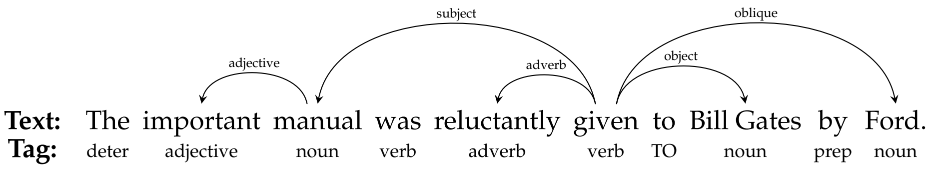


Figure 1. Translation process



Applying Term rules, the terms $\{$*the-manual*$\}$ (the manual is an instance), [*important*] (important is a property), [*reluctantly*] (reluctantly is a property) and *give* (give is an atomic term) will be obtained.

With the information of WordNet and the Hypernym rules, the following judgements will be added to the translation as context:

$$
\begin{aligned}
\{\text{the-manual}\} \rightarrow \text{manual} &\quad \%\textit{The manual is a manual}\\
\text{manual} \rightarrow \text{handbook} &\quad \%\textit{Manuals are handbooks}\\
\text{handbook} \rightarrow \text{book} &\quad \%\textit{Handbooks are books}\\
\\
\text{person} \rightarrow \text{organism} &\quad \%\textit{Persons are organisms}\\
\text{organism} \rightarrow \text{living-thing} &\quad \%\textit{Organisms are living things}\\
\\
\text{organization} \rightarrow \text{social-group} &\quad \%\textit{Organizations are social groups}\\
\text{social-group} \rightarrow \text{group} &\quad \%\textit{Social groups are groups}\\
\\
\text{give} \rightarrow \text{transfer} &\quad \%\textit{Giving is transferring}
\end{aligned}
$$

Lastly, applying the Text rules, the following judgements are obtained:

% *Ford, the manual, and Bill Gates are related under the relation of giving reluctantly*

$$(\times, \{\text{Ford}\}, \{\text{the-manual}\}, \{\text{Bill Gates}\}) \rightarrow \text{give} \cap [\text{reluctantly}]$$

% *the manual has the property of being important*

$$\{\text{the-manual}\} \rightarrow [\text{important}]$$

Every judgment obtained will be assigned an initial truth value of $\langle 1.0, 0.9\rangle$. This value corresponds to a verified positive example of the related statement. Also, note that in NAL evidence-based semantics each repetition of a statement will be counted as positive evidence for the formula representing that sentence. Although the translation process may result in several judgements with the same assertion but different truth values, NAL includes some inference rules for unifying such judgments (e.g. *revision* and *choice*).

The final set of NAL judgements will show two important characteristics:

1. Every concept appearing in the text will be implicitly represented and its meaning extended with the help of auxiliary background judgements from the WordNet ontology.
2. As NAL is a non-monotonic logic, an agent wielding that logic can always *learn* new concepts and receive new information, consequently adding new formulas to its knowledge base, even when such new formulas seem as contradictory information.

4. Experiments and results

4.1. Experiments per case

This section shows some examples of natural language sentences translated into NAL formulas. The examples follow Table 3 with the exception of Function words (last column) and are labeled accordingly to facilitate their identification and association with the corresponding dependency cases. Each case shows an example sentence and the translated NAL formula we obtain by applying the proposed methodology.

1. **Nominal subject**

(a) **Active voice with a verb as root and nominal core arguments**

Clinton defeated Dole

$(\times, \{\text{Clinton}\}, \{\text{Dole}\}, \_) \rightarrow \text{defeat}$

(b) **Passive voice with a verb as root and nominal core arguments**

Dole was defeated by Clinton

$(\times, \{\text{Clinton}\}, \{\text{Dole}\}, \_) \rightarrow \text{defeat}$

(c) **Adjective as root**

This toy is red

$\{\text{this-toy}\} \rightarrow [\text{red}]$

(d) **Nominal as root and no case dependency**

Roses are flowers

$\text{rose} \rightarrow \text{flower}$

(e) **Nominal as root and case dependency**

We are in the barn

$(\times, \{\text{we}\}, \{\text{the-barn}\}) \rightarrow \textit{where}^*$

(f) **Copular sentence with clausal complement (outer)**

The important thing is to keep calm

$\{\text{the-thing}\} \cap [\text{important}] \rightarrow ((\times, \#\textit{Whoever}, \text{calm}, \_) \rightarrow \text{keep})$

2. **Object**

(a) **Active or passive voice with a verb as root**

Ana teaches Logic

$(\times, \{\text{Ana}\}, \text{logic}, \#\textit{To-whomever}) \rightarrow \text{teach}$

3. **Indirect object**

(a) **Active or passive voice with a verb as root**

Ana teaches the students Logic

$(\times, \{\text{Ana}\}, \text{logic}, \{\text{the-students}\}) \rightarrow \text{teach}$

4. Clausal subject

(a) **Active voice with a verb as root**

Taking a nap will relax you

$(\times, ((\times, \#\mathit{Whoever}, \{\text{a-nap}\}, \_) \rightarrow \text{take}), \{\text{you}\}, \_) \rightarrow \text{relax}$

(b) **Passive voice with a verb as root**

That she lied was suspected by everyone

$(\times, \{\text{everyone}\}, ((\times, \{\text{she}\}, \#\mathit{Whatever}, \#\mathit{To\text{-}whomever}) \rightarrow \text{lie}), \_) \rightarrow \text{suspect}$

(c) **Adjective as root**

Taking a nap is relaxing

$((\times, \#\mathit{Whoever}, \{\text{a-nap}\}, \_) \rightarrow \text{take}) \rightarrow [\text{relaxing}]$

(d) **Nominal as root and no case dependency**

What she said is a proverb

$((\times, \{\text{she}\}, \#\mathit{Whatever}, \#\mathit{To\text{-}whomever}) \rightarrow \text{say}) \rightarrow \text{proverb}$

(e) **Copular sentence with clausal complement (outer)**

To hike in the mountains is to experience nature

$((\times, \text{hike}, \{\text{the-mountains}\}) \rightarrow \mathit{where}^*) \rightarrow ((\times, \#\mathit{Whoever}, \text{nature}, \_) \rightarrow \text{experience})$

5. Clausal complement

(a) **Active or passive voice with a verb as root and the explicit subject of the complement**

He says you like flowers

$(\times, \{\text{he}\}, ((\times\{\text{you}\}, \text{flower}, \_) \rightarrow \text{like}), \#\mathit{To\text{-}whomever}) \rightarrow \text{say}$

(b) **Active or passive voice with an adjective as root and the explicit subject of the complement**

Ana is delighted that you could help

$(\times, \{\text{Ana}\}, ((\times, \{\text{you}\}, \#\mathit{Whatever}, \#\mathit{To\text{-}whomever}) \rightarrow \text{help})) \rightarrow \text{delighted}$

(c) **Active or passive voice with a verb as root and not specified subject of the complement**

The boss said to start digging

$(\times, \{\text{the-boss}\}, ((\#\mathit{Whoever}, \text{dig}, \_) \rightarrow \text{start}), \#\mathit{To\text{-}whomever}) \rightarrow \text{say}$

6. Open clausal complement

(a) **Active or passive voice with a verb as root and the implicit subject of the complement**

I consider her honest

$(\times, \{\text{I}\}, (\{\text{she}\} \rightarrow [\text{honest}]), \_) \rightarrow \text{consider}$

(b) **Adjective as root and implicit subject of the complement**

Susan is liable to be arrested

$(\times, \{\text{Susan}\}, \text{arrest}) \rightarrow \text{liable-to}$

7. Oblique nominal

(a) Locational modifier dependent on a verb

The will arrive in Boston

$(((\times, \{\text{they}\}, \_, \_) \rightarrow \text{arrive}), \{\text{Boston}\}) \rightarrow \textit{where}^*$

(b) Temporal modifier dependent on a verb

They will arrive on Friday

$(((\times, \{\text{they}\}, \_, \_) \rightarrow \text{arrive}), \{\text{Friday}\}) \rightarrow \textit{when}^*$

(c) Element of the dative alternation dependent on a verb

Ana teaches Logic to the students

$(\times, \{\text{Ana}\}, \text{logic}, \{\text{the-students}\}) \rightarrow \text{teach}$

(d) Agent dependent on a passive verb

The cat was chased by a dog

$(\times, \{\text{a-dog}\}, \{\text{the-cat}\}, \_) \rightarrow \text{chase}$

(e) Dependent on an adjective

He is afraid of sharks

$(\times, \{\text{he}\}, \text{shark}) \rightarrow \text{afraid-of}$

(f) Adverbial modifiers

The director is 65 years old

$\{\text{the-director}\} \rightarrow [\text{old}] \cap [\text{65-years}]$

8. Expletive

(a) Existential there with an oblique modifier

There is a ghost in the room

$(\times, \{\text{a-ghost}\}, \{\text{the-room}\}) \rightarrow \textit{where}^*$

(b) “It” in extraposition constructions

It is clear that we should decline

$((\times, \{\text{we}\}, \#\textit{Whatever}, \_) \rightarrow \text{decline}) \rightarrow [\text{clear}]$

(c) Existential there without oblique modifiers

There are children

$\#\textit{Some} \rightarrow \text{child}$

9. Adverbial clause modifier

(a) **Temporal modifier**

The accident happened as night was falling

$(\times, ((\times, \{\text{the-accident}\}, \_, \_) \rightarrow \text{happen}), ((\times, \text{night}, \_, \_) \rightarrow \text{fall})) \rightarrow \textit{when}^*$

(b) **Locational modifier**

They drove beyond where the city ends

$(\times, ((\times, \{\text{they}\}, \#\textit{Whatever}, \_) \rightarrow \text{drive}), ((\times, \{\text{the-city}\}, \_, \_) \rightarrow \text{end})) \rightarrow \textit{where}^* \cap [\text{beyond}]$

(c) **Concession modifier**

He is a teacher, although he no longer teaches

$(\times, (\{\text{he}\} \rightarrow \text{teacher}), ((\times, \text{he}, \#\textit{Whatever}, \#\textit{To-whomever}) \rightarrow \text{teach} \cap [\text{no-longer}])) \rightarrow \textit{but}^*$

(d) **Condition modifier**

If you know who did it, you should tell the teacher

$((\times, \{\text{you}\}, ((\times, \#\textit{Whoever}, \{\text{it}\}, \_) \rightarrow \text{do}), \_) \rightarrow \text{know})$
$\Rightarrow ((\times, \{\text{you}\}, \#\textit{Whatever}, \{\text{the-teacher}\}) \rightarrow \text{tell})$

(e) **Purpose modifier**

He talked to you in order to secure the account

$((\times, (\times, \{\text{he}\}, \#\textit{Whatever}, \{\text{you}\}) \rightarrow \text{talk}), ((\times, \#\textit{Whoever}, \{\text{the-account}\}, \_) \rightarrow \text{secure})) \rightarrow$
$\textit{purpose}^*$

(f) **Reason modifier**

I am in my house since I caught a cold

$((\times, (\times, \{\text{I}\}, \{\text{my-house}\}) \rightarrow \textit{where}^*), (\times, \{\text{I}\}, \{\text{a-cold}\}, \_) \rightarrow \text{catch})) \rightarrow \textit{reason}^*$

(g) **Comparison modifier**

John can speak English as fluently as his teacher can

$(\times, ((\times, \{\text{John}\}, \text{English}, \#\textit{To-whomever}) \rightarrow \text{speak}),$
$((\times, \{\text{his-teacher}\}, \text{English}, \#\textit{To-whomever}) \rightarrow \text{speak})) \rightarrow \text{as-fluent-as}$

(h) **Manner modifier**

He spent a lot of money as if he was rich

$(\times, ((\times, \{\text{he}\}, \text{money} \cap [\text{a-lot-of}], \_) \rightarrow \text{spend}), (\{\text{he}\} \rightarrow \text{rich})) \rightarrow \textit{how}^*$

10. Adverbial modifier

(a) **Adverbial modifying verb**

Ana rarely drinks coffee

$(\times, \{\text{Ana}\}, \text{coffee}, \_) \rightarrow \text{drink} \cap [\text{rarely}]$

(b) **Adverbial modifying adjective**

About 200 people came

$(\times, [\text{about } 200] \cap \text{people}, \_, \_) \rightarrow \text{come}$

(c) **Adverbial modifying adverb**

Tom is almost always busy

$\{\text{Tom}\} \rightarrow [\text{busy}] \cap [\text{almost always}]$

(d) **Negation**

Tom doesn't like Italian food

$\neg((\times, \{\text{Tom}\}, [\text{Italian}] \cap \text{food}, \_) \rightarrow \text{like})$

11. Nominal modifier

(a) **Determiner modifying a noun or noun phrase**

Some of the toys are red

$\{\text{some toys}\} \rightarrow [\text{red}]$

(b) **Noun modifying a noun or noun phrase**

Toys for children are cute

$\text{children-toys} \rightarrow [\text{cute}]$

12.	**Appositional modifier**
(a)	**Appositional modifier** Sam, my brother, arrived $((\{\text{Sam}\}, \_, \_) \rightarrow \text{arrive}) \wedge (\{\text{Sam}\} \rightarrow \{\text{my-brother}\})$

13.	**Numeric modifier**
(a)	**Numeric modifier** Sam spend forty dollars $(\{\text{Sam}\}, [40] \cap \text{dollar}, \_) \rightarrow \text{spend}$

14.	**Clausal modifier of a noun**
(a)	**Modified noun as subject** My sister has a parakeet named Cookie $((\times, \{\text{my-sister}\}, \{\text{a-parakeet}\}, \_) \rightarrow \text{have}) \wedge ((\times, \#\mathit{Whoever}, \{\text{Cookie}\}, \{\text{a-parakeet}\}) \rightarrow \text{name})$
(b)	**Modified noun as object** He is a teacher whom the students really love $(\{\text{he}\} \rightarrow \{\text{a-teacher}\}) \wedge ((\times, \{\text{the-students}\}, \{\text{a-teacher}\}, \_) \rightarrow \text{love})$

15.	**Adjectival modifier**
(a)	**Adjectival modifier** Canaries are yellow $\text{canary} \rightarrow [\text{yellow}]$
(b)	**Comparative adjective** Ana is taller than Tom $(\times, \{\text{Ana}\}, \{\text{Tom}\}) \rightarrow \text{taller}$
(c)	**Comparison "as ... as"** Ana is as tall as Tom $(\times, \{\text{Ana}\}, \{\text{Tom}\}) \rightarrow \text{as-tall-as}$
(d)	**Superlative adjective** Ana is the tallest in the group $(\times, \{\text{Ana}\}, \#\mathit{Whatever}) \rightarrow \text{taller}$ $\#\mathit{Whatever} \rightarrow \text{the-group}$

5. Discussion

Modeling a natural language with a formal language is always going to be an incomplete task. Part of the problem stems from the fact that logic formulas (in any symbolic logic) are purely declarative, while natural languages can express a variety of sentences besides declarative. It has been extensively argued that the lack of contextual or background knowledge in an artificial agent prevents any chance of communication or reasoning with unified semantics [31]. However, it seems quite evident that if artificial intelligence is going to have any chance of near-human behavior it cannot depend on non-symbolic generative models for catching the true meaning of natural language expressions.

In this paper we have shown a methodological return to the symbolic way, using linguistic analysis tools that identify the grammatical structure in a natural language sentence and reveals the various types of relations among words (dependencies, semantic role relations, etc). Such analysis provides sufficient evidence to identify concepts, instances of those concepts, properties, and relations expressed by natural language sentences, which can then be translated into NAL formulas that not only preserve the original relations, but insert them in a multi-valued, non-monotonic, and higher-order logic with flexibility enough to later perform inference tasks [32] [33].

Our approach has been to search for named entities and grammatical labels in order to define the *terms* (logical terms or concepts) on which the logical formulas will be based.

Next, we used a commonsense ontology (WordNet), to construct a minimal background context for the selected terms. Finally, we take the table of universal dependencies as the landmark reference maximizing a consistent covering of commonly used expressions and idioms, as well as their translation into NAL formulas. We would like to highlight the following linguistic/logic merits of our proposal:

- A nominal subject sentence (Examples Table 1. Nominal subject, cases (a) and (b)) gets translated to the exact same NAL formula regardless of it being in active or passive voice.
- A double object construction (Examples Table 3, case (a)) and a prepositional construction (Examples Table 7, Oblique nominal, case (c)) also get translated to the same NAL pre-defined relation formula.
- A careful use of NAL variables allow the pre-defined relations to endow its related terms with a more semantic role than their syntactic analysis would suggest. For example, the two sentences *Ana teaches Logic* and *Ana teaches the students* have exactly the same dependency parsing, but are translated to slightly different NAL formulas. The first one is translated into $(\times, \{\text{Ana}\}, logic, \#\textit{To-whomever}) \rightarrow teach$, while the second one is translated into $(\times, \{\text{Ana}\}, \#\textit{Whatever}, \{\text{the-students}\}) \rightarrow teach$.
- Adjectives are not always translated into NAL properties. When appropriate, they can also be translated into relations as can be seen in Examples Table 15, Adjectival modifier, case (b), which is consistent with [34] and [35].

Following the ideals of this research, the next step seems obvious, and by the time this paper is published this next step will already have begun: to test the translated formulas in different inference tasks and dynamically extend the required background formulas to enable conversational and common sense reasoning abilities in an artificial agent. However, since the first stage of translating natural language to NAL formulas has so many intricate details, we feel it is worth presenting it in its own dedicated paper. Undoubtedly, the task of building an artificial agent with common-sense reasoning skills is a colossal task. However, we firmly believe that the current trend of relying on generative connectionist models does not advance down the path of artificial general intelligence and fails to capture the essence of symbolic reasoning, much less common sense reasoning. That is the reason that motivates and drives this research.

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Abbreviations

The following abbreviations are used in this manuscript:

NAL	Non-Axiomatic Logic
NL	Natural language
PL	Predicate logic
AIKR	Assumption of Insufficient Knowledge and Resources

References

1. Davis, E.; Marcus, G. Commonsense reasoning and commonsense knowledge in artificial intelligence. *Communications of the ACM* **2015**, *58*, 92–103.
2. Sap, M.; Shwartz, V.; Bosselut, A.; Choi, Y.; Roth, D. Commonsense reasoning for natural language processing. Proceedings of the 58th Annual Meeting of the Association for Computational Linguistics: Tutorial Abstracts, 2020, pp. 27–33.
3. McCarthy, J. Programs with common sense, 1959.
4. Richardson, C.; Heck, L. Commonsense reasoning for conversational AI: A survey of the state of the art. *arXiv preprint arXiv:2302.07926* **2023**.
5. Davis, E. Logical formalizations of commonsense reasoning: A survey. *Journal of Artificial Intelligence Research* **2017**, *59*, 651–723.
6. McCarthy, J. *Formalizing common sense*; Vol. 5, Intellect Books, 1990.
7. McCarthy, J.; Buvac, S. Formalizing context. AAAI Fall Symposium on Context in Knowledge Representation. Citeseer, 1994, pp. 99–135.
8. Waismann, F. *Ludwig Wittgenstein and the Vienna Circle*; Basil Blackwell, 1979.
9. Wang, P. Toward a logic of everyday reasoning. *Blended Cognition: The Robotic Challenge* **2019**, pp. 275–302.
10. Wang, P. From inheritance relation to non-axiomatic logic. *International Journal of Approximate Reasoning* **1994**, *11*, 281–319.
11. Slam, N.; Wang, W.; Wang, P. An improvisational decision-making agent based on non-axiomatic reasoning system. 2014 IEEE/WIC/ACM International Joint Conferences on Web Intelligence (WI) and Intelligent Agent Technologies (IAT). IEEE, 2014, Vol. 3, pp. 360–364.
12. Han, S.; Schoelkopf, H.; Zhao, Y.; Qi, Z.; Riddell, M.; Benson, L.; Sun, L.; Zubova, E.; Qiao, Y.; Burtell, M.; et al. FOLIO: Natural language reasoning with first-order logic, 2022, [arXiv:cs.CL/2209.00840].
13. Purdy, W.C. A logic for natural language. *Notre Dame Journal of Formal Logic* **1991**, *32*, 409–425.
14. Wang, P. Natural language processing by reasoning and learning. International Conference on Artificial General Intelligence. Springer, 2013, pp. 160–169.
15. Hammer, P. English to Narsese. https://github.com/opennars/OpenNARS-for-Applications, 2020.
16. Jackson Jr, P.C. Toward human-level qualitative reasoning with a natural language of thought. Biologically Inspired Cognitive Architectures Meeting. Springer, 2021, pp. 195–207.
17. Wang, P.; Hofstadter, D. A logic of categorization. *Journal of Experimental & Theoretical Artificial Intelligence* **2006**, *18*, 193–213.
18. Wang, P. *Non-axiomatic logic: A model of intelligent reasoning*; World Scientific, 2013.
19. Gärdenfors, P.; Makinson, D. Nonmonotonic inference based on expectations. *Artificial Intelligence* **1994**, *65*, 197–245.
20. Lindes, P. Constructing meaning, piece by piece: A computational cognitive model of human sentence comprehension. PhD thesis, University of Michigan, 2022.
21. Frege, G.; et al. Begriffsschrift, a formula language, modeled upon that of arithmetic, for pure thought. *From Frege to Gödel: A source book in mathematical logic* **1879**, *1931*, 1–82.
22. Mitkov, R. *The Oxford handbook of computational linguistics*; Oxford University Press, 2022.
23. de Marneffe, M.C.; Manning, C.D.; Nivre, J.; Zeman, D. Universal Dependencies. *Computational Linguistics* **2021**, *47*, 255–308, [https://direct.mit.edu/coli/article-pdf/47/2/255/1938138/coli_a_00402.pdf].
24. Jurafsky, D.; Martin, J. *Speech and language processing: An introduction to natural language processing, computational linguistics and Speech recognition*; Prentice Hall, 1999.
25. Dan, K.; Manning, C. Accurate unlexicalized parsing. Proceedings of the 41st Meeting of the Association for Computational Linguistics, 2003, pp. 423–430.
26. Kapetanios, E.; Tatar, D.; Sacarea, C. *Natural language processing: semantic aspects*; CRC Press, 2013.
27. Finkel, J.R.; Grenager, T.; Manning, C. Incorporating non-local information into information extraction systems by Gibbs sampling. *Proceedings of the 43nd Annual Meeting of the Association for Computational Linguistics* **2005**, pp. 363–370.
28. Miller, G. WordNet: A lexical database for English. *Communications of the ACM* **1995**, *38*, 39–41.
29. Schuler, K.K. *VerbNet: A broad-coverage, comprehensive verb lexicon*; University of Pennsylvania, 2005.
30. Documentation of universal dependency relations. https://universaldependencies.org/u/dep/index.html, 2014.
31. Gärdenfors, P. The emergence of meaning. *Linguistics and Philosophy* **1993**, pp. 285–309.
32. Chabierski, P.; Russo, A.; Law, M. Logic-based approach to machine comprehension of text, 2017.
33. Barker-Plummer, D.; Cox, R.; Dale, R.; Etchemendy, J. An empirical study of errors in translating natural language into logic. Proceedings of the Annual Meeting of the Cognitive Science Society, 2008, Vol. 30.
34. Wang, P. The interpretation of fuzziness. *IEEE Transactions on Systems, Man, and Cybernetics, Part B (Cybernetics)* **1996**, *26*, 321–326. doi:10.1109/3477.485883.
35. Kamp, H. Two theories about adjectives. In *Meaning and the Dynamics of Interpretation*; Brill, 2013; pp. 225–261.