Natural Language Processing and Coq : a case-study

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***Abstract*—This paper presents a case-study devoted to the formalization of sentence frames in the Coq system. We instanciate these frames for performing a semantic analysis of simple sentences. In particular, we rely on a hierarchy of types for type-checking the conceptual well-formedness of sentences. To do that, we investigate how to exploit the particular features of the Coq type system in order to take advantage of this elegant unifying framework for encoding the syntax-semantics interface and we show how to improve our approach for combining it with linguistic resources.**

I. Introduction

During the last fifteen years, the use of type theoretic methods for describing natural langage syntax and semantics has gained more and more popularity, resulting in the development of software relying on these methods. First, these type theoretic methods can be constantly improved with advances in the field of logic. Secondly, they depend on the developement of linguistic resources such as lexicons or dictionaries. In this context and from our point of view, the challenge for natural langage processing is twofold : the frameworks dedicated to linguistic analysis have to focus on the syntax-semantics interface ; and they have to combine linguistic resources and natural language processing programs. Among the most significant achievements, let us mention the works on categorial grammars which provide the integration of syntax and semantics in the same framework as it is described in [1] and in [2]. Moreover, categorial grammars are lexicalized that means that all items in the lexicon are typed. Thereby, although they describe syntactical rules, they also preserve the compositional aspect of Montague semantics [3]. The most well-known categorial grammars are those based on Lambek-Calculus [4]. Due to the Curry-Howard isomorphism, typed terms are proofs in logic which includes Lambek-Calculus[1]. Although many studies have already showed that it is natural to associate a syntactic term to a semantic type [9] [10] [11], our approach implemented in Coq, the Calculus of Inductive Constructions, aims to focus on the generality of definitions leading to reusable methodologies dedicated to semantic analysis of natural language. In Coq, few investigations have been performed for natural language processing. In [12], the author has developed an algorithm that produces natural language sentences from proofs described in a mathematical language. Later, for the case of categorial grammars, [13] gave a Coq formalization of the Lambek-Calculus and of an extension as multimodal grammars; they prove several theorems as completeness and consistency of multimodal logic. More recently, in [14], the authors explain how modern type theories provide a wide semantic coverage of linguistic features. Powerful typing mechanisms that have been implemented in proof systems can be employed in the field of linguistic semantics as it is described in [15] and [16]. Following these ideas, the work proposed in this paper shows how straightforwardly use specific features of Coq language for semantic analysis. It aims at showing how :

1) define formal models for representing sentences by taking advantage of the Coq type system and its particularly rich language (polymorphism, higher-order logic, coercion mechanism, module system),
2) propose natural and general specifications of sentences that can be checked for a conceptual analysis based on types,
3) take advantage of type-checking algorithms involved into the Coq system.

The paper is organized as follows. Section II briefly introduces Coq by focusing on used aspects. Section III deals with a formalization of the underlying ontology and with a semantic representation of simple sentences. In Section IV, we generalize our approach by specifying generic models for other sentences and we show how to use them. We mention in section V some tools and resources for improving our work. Then, on the conclusion, we further discuss the case-study and we highlight our perspectives.

II. An Overview of Coq

The Coq system [17] is a specification and proof system developed in the Laboratoire de Recherche en Informatique (CNRS and University of Paris-Sud) and LIX (INRIA-Futurs and Ecole Polytechnique). Coq's language relies on a higher-order typed λ-calculus, the Calculus of Constructions [18] [19] enriched with inductive and co-inductive definitions [20] [21]. Coq's logic is a constructive logic and it is based on the *propositions-as-types* correspondence, the Curry-Howard isomorphism, that states a proposition is a type and a proof is a term inhabiting this type. This correspondence provides an elegant unifying framework where type-checking is proof-checking. The Coq system is tactic oriented and it allows to interactively develop proofs. The system is organized around a small kernel (the theory) extended by libraries. Moreover, it includes many user contributions.
Coq developments can be splitted into various parameterized modules. Thus, several developments can share modules that, being compiled once and for all, are loaded fast. Moreover,

[1]There are new approaches that extend Lambek-Calculus, in particular in linear logic because it provides an efficient representation of proofs [5] [6] [7] and specific tools have been developed in this field as for example [8].

sections allow to organise modules in a structured way. In Coq, any user's term must be classified according to a type. There are two sorts of types : logical propositions are of sort $Prop$ and mathematical collections are of sort Set[2]. Polymorphic terms are parameterized with respect to terms of sort $Prop$ or Set. By defining them into a section, one can obtain reusable developments in which generic specifications has been already typed-checked. However, when instanciating these abstract specifications, types can be cumbersome. The implicit parameter mechanism allows to automatically infer arguments from the definition's context.
Moreover, Coq terms are organised according to a type hierarchy and they can be typed using the coercion subtyping system. This latter corresponds to an inheritance graph mechanism that allows to inject Coq hierarchy typed terms into another hierarchy's type. Technically, a term of type t is also of type t_1 (where t and t_1 are of types $Prop$ or Set for example) if there exists a coercion between t_1 and t, defined in Coq as :

```
Coercion c : t1 >-> t.
```

This declaration expresses the construction denoted by c as a coercion between $t1$ and t. Roughly speaking and for the need of the study, the coercion c indicates that t_1 is a subtype of t.

III. Sentence's Conceptual Analysis

A. Ontology as Concept Hierarchy

This section is devoted to the presentation of the ontology used to determine the well-formedness of sentences. Let us note that the "concepts as types" representation is largely used in the knowledge representation since it provides an appropriate interface for semantic processing.
Figure 1 presents a conceptual hierarchy which organises concepts according a world we want to refer for our study. The verification of the sentence's conceptual well-formedness will be based on this hierarchy. It describes a simple world from which it is possible to analyse the meaning of sentences. This world is organized from $animate$ and $inanimate$ notions. For example, an $animal$ is classified into the $animate$ concept while a car is $inanimate$ and can be considered as $concrete$ as well. In this tree, each node is labelled by a conceptual information that can be specified as a type. Thus, for organizing this information, it is natural to consider the subtyping principle. In typed definitions, a subtype may appear wherever an element of the super type is expected. For example, in our verb's semantic representation (Section III-B1), a type t_1 is compatible with a type t, if t_1 is a subtype of t. Consequently, a semantic representation parameterized with t will be valid for parameters of type t_1 and for all those of the lower part.
In Coq, we declare the conceptual types (all, $animate$...) as logical propositions. Then, we use the coercion mechanism for describing the relations between types, as follows :

```
Coercion animate_is_all    : animate >-> all.
Coercion animal_is_animate : animal >-> animate.
Coercion dog_is_animal     : dog >-> animal)
```

[2]Actually, this distinction is not necessary but it makes the system less confusing for the user. However, it is significant when extracting programs from proofs (a mechanism relying on the constructive aspect of Coq's logic). But this feature is not used here.

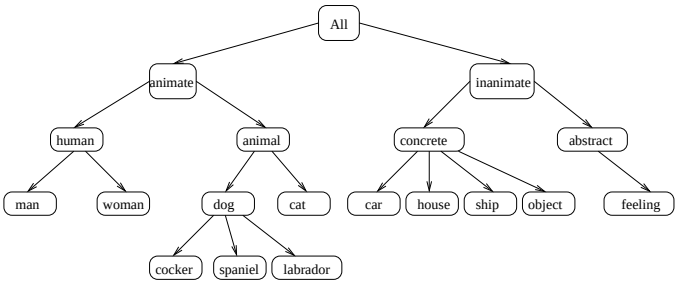

Fig. 1. A hierarchy of conceptual types

```
Coercion cat_is_animal     : cat >-> animal)
```

Each coercion creates a path between two nodes of the tree. The whole list of coercions is ordered and it defines the conceptual tree depicted in Figure 1. Coq detects ambiguous paths during the creation of the tree and, it verifies the *uniform inheritance condition* because at most one path must be declared between two nodes. Let us remark that, in Coq, the conceptual tree is straightforwardly implemented, in a natural way. Therefore, Coq automatically verifies that the hierarchy of types is well-formed. Moreover, the conceptual analysis will be parametrizable by this kind of hierarchy : in general, the ontology depends on the field under consideration and it is interesting to be able to change the ontology according the needs.

B. Coq Semantic Representation of Sentences

This section proposes a semantic formalization of simple sentences. Since a sentence is composed of elements that must be compatible with each other, we first deal with their representation and their types. In particular, we focus on the verb's description because the sentence's representation is specified according to the verb's domain of use. Then we describe a generic model for sentences which involve a verb and its subject. Finally, we show, by instanciation of the model, how sentences are represented.
The verb has a central role in the sentence, as it has been developed in the Tesnière's linguistic theory [22] which defines the valence of verbs. Let us mention that, this characterisation of sentences have been widely used in the dependency grammars as it is described in [23].

1) Lexicon of Verbs: For typing the verb's representation, we use the conceptual types described in Figure 1. For each verb, we have to choose the best label (best for the user who build the lexicon that is to say the most likely concept for the domain under consideration) which, in general, corresponds to the lower type in the hierarchy. For example, the verb $to\ bark$ can reasonably be used for all the dogs. So, it is declared in the lexicon as a logical proposition by the unary predicate $bark$ as follows :

```
Parameter bark : dog -> Prop.
```

Let us notice that verbs can have different meanings and so, different lexical entries have to be considered. Once the hierarchy of types is defined, the verbs have to be described on

these types. So, we can need to consider several declarations in Coq for the same verb. For example in french, the verb $bark$ can be used for humans : *Paul barks.* (in the sense that Paul inveighs against someone or something) is an acceptable sentence. Here, we introduce a new input in our lexicon as :

```
Parameter bark2 : human -> Prop.
```

This is not really cumbersome because dictionnaries of verbs are built from all the possible situations (see Section V) and then, the Coq representation is very concise.

2) Sentences as logical expressions: Let us consider the sentence : *A dog is barking*. It can be represented by the logical expression : $\exists x, bark(x) \wedge is\_dog(x)$ where the unary predicate is_dog characterizes the semantics of the subject dog. The following predicates introduce in Coq semantic representation for some agents used later in the paper :

```
Parameter is_animate : all -> Prop.
Parameter is_animal  : animate -> Prop.
Parameter is_human   : animate -> Prop.
Parameter is_dog     : animal -> Prop.
Parameter is_cocker  : dog -> Prop.
```

Finally, the sentence : *A dog is barking* merely can be represented in Coq as follows :

```
Definition a_dog_is_barking :=
  exists x, bark(x) /\ is_dog(x).
```

where the implicit argument mechanism automatically synthesizes the type of x as dog (from the first predicate of the definition).

3) Towards Generic Models: The kind of sentences we study is composed of a verb and a subject. In this part, we show how to generalize this kind of sentences by specifying a general frame in Coq that states : $\exists x, verb0(x) \wedge is\_something(x)$, where $verb0$ (that stands for the verb) and $is\_something$ (that stands for the subject) are polymorphic predicates respectively parameterized on $A1$ and A of sort $Prop$, with $A1$ subtype of A (to ensure the compatibility between words). The complete specification in Coq is given below, inside a section :

```
Section General_frame_v0.
     (** Local parameters of the section **)
  Variables (A A1:Prop)
            (A1A : A1 -> A).
     (** Declaration of the subtype **)
  Coercion A1A : A1 >-> A.
     (** Declaration of the predicates **)
  Variables (verb0 : A1 -> Prop)
            (is_something : A -> Prop).
     (** Definition of the generic model **)
  Definition frame_verb0 :=
     exists c, verb0 c /\ is_something c.
End General_frame_v0.
```

In the definition $frame\_verb0$, c is implicitly of type $A1$ and the coercion $A1A$ which converts the type $A1$ to A is implicitly applied on c into $is\_something(c)$. Outside the section, the local context of the definition is discharged. This means that A, $A1$, $A1A$, $verb0$ and $is\_something$ appear as parameters of the definition $frame\_verb0$.
So, $frame\_verb0$ depends on two types, on a coercion which states a subtyping relation and on two predicates which respectively stand for a verb and a subject. It is a generic representation for this kind of simple sentences due to polymorphism (from the parameters A and $A1$) and higher-order (from the $verb0$ and $is\_something$ predicates).

4) Type-checking is Well-formedness Checking: By instanciation of the generic model $frame\_verb0$, we can define the semantic representation of the sentence *A dog is barking* as :

```
Definition a_dog_is_barking :=
    (frame_verb0 dog_is_animal bark is_dog).
```

The instanciation of the parameters A and $A1$ can be omitted due to the implicit synthesis. The coercion dog_is_animal instanciates $A1A$ in the generic model ; $bark$, which is defined on dog, instanciates $verb0$ and is_dog, which is defined on $animal$, instanciates $is\_something$. So, the compatibility of words is ensured by the coercion that states dog is a subtype of $animal$.

In a similar way, the sentence *A cocker is barking* is formalized as :

```
Definition a_cocker_is_barking :=
          (frame_verb0 cocker_is_dog bark is_cocker).
```

But the checking of *A cat is barking* :

```
Definition a_cat_is_barking :=
          (frame_verb0 cat_is_animal bark is_cat).
```

is rejected by the system because the term $bark$ has type $dog \rightarrow Prop$, while it is expected from cat_is_animal (the coercion that states cat is a subtype of $animal$) to have type $cat \rightarrow Prop$.
This encoding leads to simple conceptual representation of sentences. Coq performs the type-checking of these instanciations and so, it establishes the sentence's well-formedness.

IV. Generic Models Based on Verb's use

In this section, we propose two other generic frames for representing the sentences. The first one describes sentences which are composed of a verb, a subject and a complement. The second frame defines sentences where the parameters of the verb depends on each others. This latter is interesting is the case-study because it emphasizes the dependent aspect of typing for natural language processing.

Let us consider the sentence *A woman likes cars*. In this case, the verb *to like* may be of type $animate \rightarrow inanimate \rightarrow Prop$, where $animate$ stands for the type of the subject and $inanimate$ for the type of the complement[3]. Similarly to the representation given in Section III-B, we can specify :

```
Definition a_woman_likes_cars :=
   (frame_verb1 woman_is_human
          car_is_concrete like is_woman is_car).
```

where the model $frame\_verb1$ is obtained from the generic definition depicted below :

```
Section General_frame_v1.
  Variables (A A1 B B1:Prop)
            (A1A : A1 -> A)
```

[3]But, more generally, the type of the verb *to like* in the lexicon is $animate \rightarrow all \rightarrow Prop$ because the type of the complement must be as general as possible.

```
          (B1B : B1 -> B).
  Coercion A1A : A1 >-> A.
  Coercion B1B : B1 >-> B.
  Variables (verb1 : A1 -> B1 -> Prop)
            (is_something1 : A -> Prop)
            (is_something2 : B -> Prop).
  Definition frame_verb1 :=
      exists x, exists y, verb1 x y /\
             is_something1 x /\ is_something2 y.
End General_frame_v1.
```

As in the previous frame, coercions has been defined between $A1$ and A and between $B1$ and B. The predicates $is\_something1$ and $is\_something2$ respectively stand for the subject and the complement. So the instanciation of $frame\_verb1$ is realized using the two coercions $woman\_is\_human$ and $car\_is\_concrete$, the verb $like$ and the predicates is_woman and is_car.

The second model describes a particular case where sentences are composed of a verb, a subject and a complement as well, but the typing of the verb is more binding. For example, let us consider the verb $confuse$. Only a human can $confuse$ two things that must represent the same concept in the hierarchy (for instance, a man confuse two dog breeds, two particular cars and so on ; but he cannot confuse a car and a dog). So, the type of the generic relation ($verb2$ in the here below definition) that stands for $confuse$ is $human \rightarrow A \rightarrow A \rightarrow Prop$ where A gives the general concept to be used but the two subtypes of A can be different although they are from the same concept.

This is specified in the next Coq definition inside a section :

```
Section General_frame_v2.
  Variable A A1 A2 : Prop.
  Variable A1A : A1->A.
  Coercion A1A : A1>->A.
  Variable A2A : A2->A.
  Coercion A2A : A2>->A.
  Variables (verb2 : human-> A ->  A -> Prop)
            (is_something1 : A1 -> Prop)
            (is_something2 : A2 -> Prop).
  Definition frame_verb2 : Prop :=
     exists h:human, exists a1:A1, exists a2 :A2,
     verb2 h a1 a2 /\ is_human h /\
            is_something1 a1 /\ is_something2 a2.
End General_frame_v2.
```

The two types from A are $A1$ and $A2$; the variable $verb2$ sets that the first argument is a human while the following are from A.

As already described, due to implicit synthesis, the application $(verb2\ h\ a1\ a2)$ is actually $(verb2\ h\ (A1A\ a1)\ (A2A\ a2))$, for generating the type A from $A1$ and from $A2$. The instanciation of this frame is similar to the previous paragraphs and it is not given here.

V. Tools and resources

This section briefly presents a tool for faciliting the use of our work in Coq. Really, the interface presented to the user has to hide the logical aspects of the Coq specifications which can be unsuitable for a linguistic analysis. The Figure 2 gives an overview of the application based on the Coq type-checking presented in the paper. It is not yet fully implemented but it allows to explain the motivations of our work.

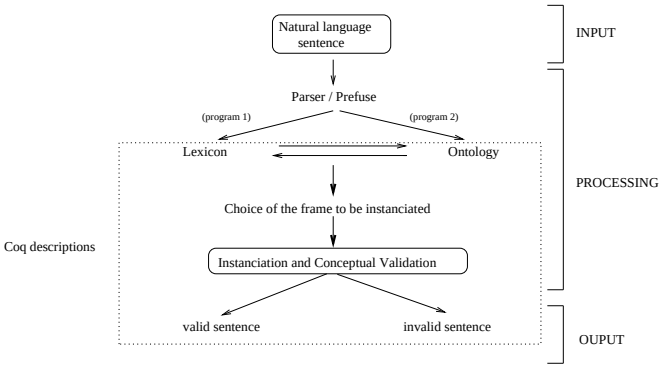

Fig. 2. Overview of the application based on a Coq analysis

The application takes as input a natural language sentence. A parser implemented in Java allows to interactively tag verbs the user wants to classify according to an ontology (as for example, the Figure 1). This classification ($program1$ in the above figure) provides a lexicon of verbs in Coq (for instance, $bark$ is tagged as $dog \rightarrow Prop$ depending on the choice of the user). The Coq description of the ontology can be automatically obtained by the $program2$ (based on the Prefuse toolkit [24]). Prefuse allows the user to graphically design its ontology without specifying Coq descriptions ; $program2$ generates the Coq file that describes the coercion between types and also the semantic predicates corresponding to the ontology ($is\_dog : animal \rightarrow Prop$ for instance). Then the user chooses the Coq generic frame to be instanciated and the conceptual validation is performed. If the representation of the sentence could be type-checked into Coq, the application outputs that the sentence is valid ; otherwise, it returns that the sentence is not valid.

This application is motivated from the fact that there are few resources in French about the semantics of words. Several linguistic resources rely on a classification of words where each class of verbs has abstract properties. In LVF[25], verbs are described as semantics classes whose scope is defined by syntax. These classes are generic and each of them gathers properties of verbs. For example, there is the class dedicated to the communication verbs. This latter is divided into 4 semantic categories :

1) human, animal (to shout, to speak)
2) human (to say something)
3) human (to show)
4) figurative sense

These categories are subdivided into syntactical sub-classes which describe the use cases of verbs (the verb can be used with a subject and a complement, it can be transitive or intransitive and so on). Several studies based on LVF have been proposed [26], [27] and [28]. and they provide many linguistic descriptions not yet taken into account in our case-study.

VI. Conclusion and Perspectives

The work presented in this paper aims at studying the capabilities of the Coq system, in the field of semantic

representation and conceptual analysis for natural language processing. The relevance of our encoding has been motivated by the particular features of the Coq system. It provides an unifying framework with a rich type system that allows to straightforwardly specify the underlying conceptual tree as well as to analyse semantic representations. In this paper we have proposed :

1) a way for describing ontologies in Coq,
2) several reusable sentence's semantic representations,
3) a sentence's conceptual analysis by instanciation process.

In particular, for this analysis, we focused on several aspects of the Coq system :

1) polymorphism : the generic models of sentences are parametrized by types and they can be reused for specifying specific sentences.
2) higher-order : it allows to take as parameters relations and so it provides a good framework for developing general definitions. From these definitions, specific sentences are derived by instanciation.
3) modularity : the development is split into several sections. This contributes to lisibility and it allows an easy reuse of libraries.
4) coercion mechanism : the hierarchy of types is easily described in Coq and it is a good way for knowledge representation based on types.
5) implicit parameters : the implicit synthesis of some parameters greatly improves the readability of the definitions.

The case study proposed in this paper is being extended to several other modules. In particular, it requires the addition of the following :

1) extension of the verb's lexicon : the lexicon takes into account around 50 verbs. We plan to use the developments of LVF mentionned in the Section V for improving the semantic analysis (by specifying classes of verbs and general models that characterize the uses of verbs).
2) representation of other sentences : once the lexicon will be extended, it will be possible to describe other generic models of sentences.
3) contextual analysis : for completing the semantic analysis, contextual representation will be necessary. This will allow to analyse texts and not just sentences.

Finally, the application depicted in the Figure 2 should be completed by adding more automatic processing : firstly, in the parser, the tagging of verbs has to be improved. This can be done using an underlying lexicon which includes linguistic properties about verbs (conjugaison patterns, lemmatization for example). Secondly, the interface between the lexicon and the ontology has to be developped. This process involves the programming of an interface that allows to manipulate verbs and concepts according to the domain of the sentences to be analysed. Thirdly, it should be relevant to give more explanation about the output when an invalid sentence has been detected. This is possible to retrieve, from the Coq system, the information about typing, in order to propose correct constructions of sentences.

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