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Analysis of Subordinate Clauses in Arabic by using Applicative Combinatory Categorial Grammar

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ABSTRACT

The model of Applicative Combinatory Categorial Grammar (ACCG) [1] [2] [3] [4], which employs combinators and reduction mechanisms derived from combinatory logic, constitutes an effective applicative system for handling various types of propositions, whether simple or complex, in certain languages.

ACCG is a system that transforms concatenated expressions in natural language into applicative expressions that provide a functional-semantic interpretation for verifying sentence structure. The objective of this study is to analyze subordinate clauses in Arabic using the ACCG framework.

Keywords: AI, NLP, categorial grammar, combinatory logic, linguistics, syntactic, semantic, subordinate clauses in Arabic.

1- INTRODUCTION

The syntactic analysis of sentences has undergone several stages, beginning with [5], who proposed a unidirectional system, followed by the bidirectional system introduced by [6], and culminating in the model developed by [7], which was enriched through the introduction of axioms and theorems. It is important to note that early ideas concerning the notion of type can be traced back to the work of [8], and subsequently to [9], particularly in relation to semantic analysis.

Syntactic categories (noun, adjective, verb, etc.) are analyzed as functional types within the framework of type theory developed by [10]. Since certain syntactic analyses require the composition and transformation of types, formal correspondences have been established between categorial grammar and combinatory logic, as developed by [11]. These formalisms enable the execution of syntactic analyses and the resolution of related structural problems. The relationships between these frameworks have been further explored in models such as Universal Applicative Grammar (UAG) [12], Applicative and Cognitive Grammar (ACG) [13], Combinatory Categorial Grammar (CCG) developed by [14] [15] [16][17], and Applicative and Combinatory Categorial Grammar (ACCG) [2][18][19].

ACCG forms a bridge between different levels of analysis in natural languages, linking syntagmatic sentence organization with logical analysis. This representation corresponds to an applicative decomposition in which operators of various types are applied to operands. Accordingly, ACCG is conceived as a system of functional types associated with the grammatical categories of a language.

Several sentence types have been analyzed using the ACCG model across different languages, including Arabic, particularly in the works of [20], [21], [22], [23], and [24]. This article focuses specifically on the analysis of subordinate clauses in Arabic, following a general presentation of the ACCG model.

2- THE STRUCTURE OF THE SENTENCE IN ARABIC:

The structure of sentences in Arabic differs from that of many Indo-European languages. Arabic is written and read from right to left (Semitic languages) and traditionally comprises two principal sentence types: the verbal sentence

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(Verb–Subject–Object) and the nominal sentence (Subject–Predicate) [25]. The verbal sentence represents the primary context in which subject–verb agreement is realized, whereas in nominal sentences, the predicate provides information about the subject.

Arabic allows for multiple syntactically distinct sentences that convey the same meaning. Consider the English sentence: *"Mohamed wrote the lesson."*

Note: To facilitate the processing and analysis of sentences in arabic, it was deemed useful to start from left to right.

a) كتب محمد الدرس arabic sentence
kataba Mohamadu ālddarsa Transcription
wrote Mohamed the lesson Gloss
Mohamed wrote the lesson translation

b) محمد كتب الدرس/
mohamedu kataba ālddarsa
Mohamed wrote the lesson
Mohamed wrote the lesson

c) كتب الدرس/
kataba ālddarsa
wrote the lesson
He wrote the lesson
He remplace the subject (agent) invisible *Mohamed*

The following three sentences (a, b, and c) have the same meaning. The first sentence is a verbal sentence, meaning it begins with a verb. The verb *kataba* (*wrote,* كتب) is followed by the subject *mohamadu* (*Mohamed*, محمد), where *Mohamed* is a proper noun, and then by the direct object *ālddarsa* (*the lesson,* الدرس/). The second sentence (b), however, is a nominal sentence, meaning it begins with a noun, *mohamadu* (*Mohamed,* محمد), followed by the verb *kataba* (*wrote,* كتب), and ends with the direct object *ālddarsa* (*the lesson,* الدرس/). The structure of sentence (c) is a verbal sentence: the verb *kataba* (*wrote,* كتب) is followed directly by the direct object, while the subject is implicit (invisible subject or agent).

The hidden or invisible subject is neither spoken nor written, but is implicitly present in the meaning. It is indicated in the grammatical analysis by the expression: "*hidden pronoun whose meaning is…*" in order to complete and clarify the sentence's syntactic structure. It corresponds to the third-person singular personal pronoun, in this case *huwa* (*He*). This type of sentence is common in Arabic.

3- APPLICATIVE AND COMBINATORY CATEGORIAL GRAMMAR

ACCG conceptualizes conceptualizes languages as systems for organizing linguistic units (words, morphemes, lexical units, etc.) some of which function as operators while others function as operands [18].

A canonical correspondence is established between the combinatory categorial rules developed by Steedman and the combinatory logic of Curry. The application of these combinatory categorial rules requires the introduction of one or more combinators at specific positions within the syntagmatic chain.

Analysis and processing within the ACCG framework are carried out in two stages:

- The verification of the correct syntactic connection with the progressive introduction of the combinatory at very precise positions in the syntagmatic chain of the application representation.

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- The use of the applicative rules (reduction, simplification) of the combinatory (in the sense of Curry) which will be eliminated in the expression obtained in order to construct a normal form, that is to say an applicative expression.

Furthermore, their application and combinatorial rules allow for a quasi-incremental left-to-right analysis.

We first present the ACCG framework, followed by a brief introduction to combinators and the associated rules of combination and application. The model is then applied to carefully selected examples.

3.1- SYSTEM TYPES:

The ACCG model employs the same application rules as simple categorical grammars. The syntactic reduction system contains:

1. Two construction operators of type: \ (left reduction) and / (right reduction).
2. Basic types are composed of a finite set of primitive syntactic types:

   S (*sentence*), sentence type

   N (*noun*), nominal syntagm type

   N*, complete nominal syntagm type

For more details regarding the syntactic types of linguistic units, see [4].

Descles and Biskri adopted Steedman's notation for compound types:

X/Y: is an operator that is applied to the right of an operand of type 'Y' to form a new expression of type 'X'.

X\Y: is an operator that is applied on the left to an operand of type 'Y' to form a new expression of type 'X'.

We can define an infinite set of composite types: X/Y (read: X over Y) and X\Y (read: X under Y), which represent operators applied to left or right operands.

The system components can be basic types and/or derived types:

- Basic types are types;
- If X and Y are types, then Y\X and Y/X are types;

A linguistic unit u which is of type X, will be noted "[u :X] ".

The ACCG rules applied for the Arabic language are the same as those used by Biskris and Desclés.

Lowercase letters represent semantic interpretation and uppercase letters represent syntactic types.

[X/Y :*u1*] + [Y :*u2*]

---------- > right simplification rules (Forward Applicative rule)

[X :*u1u2*]

[Y :*u1*] + [X\Y :*u2*]

---------- > left simplification rules (Backward Applicative rule)

[*u2u1* :X]

In this notation, the symbol "+" indicates concatenation. The premises of each rule are concatenations of linguistic units with oriented types considered to be operators or operands.

The notation 'S/N' (more generally 'X/Y') is interpreted as the function-oriented type 'X/Y' of an operator that is applied to an expression of type 'Y' to form a new expression of type 'X'.

The correct syntactic connection is verified by successively simplifying the categories to arrive at a simple category of the form S or N*.

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3.2- THE APPLICABLE COMBINATORIAL RULES

We now present the ACCG rules employed in this article. Functional composition is linked to combinator **B**, type change is linked to combinator **C*** (Steedman denotes as **T**), and functional substitution is associated with combinator S.

a- Functional composition rules:

The principle is interpreted as follows: A linguistic unit of syntactic type X/Y or X\Y can be combined with another unit of syntactic type Y/Z or Y\Z. The result is a composite linguistic unit of type X/Z or X\Z.

[X/Y : *u1*]+[Y/Z : *u2*] [X/Y : *u1*]+[Y\Z : *u2*]

----------**>B** ----------**>Bx**

[X/Z : (**B** u1 u2)] [X\Z : (**B** *u1 u2*)]

[Y\Z : *u1*]+[X\Y : *u2*] [Y/Z : *u1*]+[X\Y : *u2*]

----------**<B** ----------**<Bx**

[X\Z : (**B** *u2 u1*)] [X/Z : (**B** *u2 u1*)]

b- The rules of distributive composition, also referred to as functional substitution, are presented here for illustrative purposes only. They were originally proposed by [26].

[(X/Y)/Z : *u1*]+[Y/Z : *u2*] [X/Y)\Z : *u1*]+[Y\Z : *u2*]

----------**>S** ----------**>Sx**

[X/Z : (**S** *u1 u2*)] [X\Z : (**S** *u1 u2*)]

[Y\Z : *u1*]+[(X\Y)\Z : *u2*] [Y/Z : *u1*]+[(X\Y)/Z : *u2*]

----------**<S** ----------**<Sx**

[X\Z : (**S** *u2 u1*)] [X/Z : (**S** *u2 u1*)]

c- Type raising rules:

Type raising enables operands to function as operators, thereby allowing them to combine with other operators:

[X : *u*] [X : *u*]

----------**>T** ----------**>Tx**

[Y/(Y\X) : (**C***u*)] [Y/(Y/X) : (**C***u*)]

[X : *u*] [X : *u*]

----------**<T** ----------**<Tx**

[Y\(Y/X) : (**C***u*)] [Y\(Y\X) : (**C***u*)]

3.3- STRUCTURAL REORGANIZATION:

When there is a blockage in the application of the rules, an "intelligent" step back is necessary, hence the "structural reorganization"[2]. The principle consists of decomposing the already constructed constituent into two components. This feedback requires us to modify the structure in such a way that we isolate an entity whose syntactic type can combine with that of the remaining entity (see the analysis of example d).

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The decomposition is performed using two rules:

[X :(*u1u2*)]	[X :(*u1u2*)]
---------- > **Dec**	---------- <**Dec**
[X/Y : *u1*]+[Y : *u2*]	[*u2* :Y]+[X\Y : *u1*]

We read these rules as follows :

- For (**dec<**): If we have an applicative structure (*u1 u2*) of type X, with *u1* of type X/Y and *u2* of type Y, then we can construct a new concatenated construction formed from the two categories *u1* :X/Y and *u2* :Y.
- For (**dec>**): If we have an applicative structure (*u1 u2*) of type X, with *u1* of type X\Y and *u2* of type Y, then we can construct a new concatenated construction formed from the two categories *u2* :Y and u1 :X\Y.

These two rules allow us to construct a concatenated arrangement of the operator/operand structure resulting from the reorganization operation.

4- COMBINATORIAL LOGIC:

Combinatory logic, as developed by [11], is based on abstract operators known as *combinators*, which make it possible to construct complex operators from elementary or compound ones.

The integration of combinators into categorial grammar frameworks led to the development of ACCG, which is grounded in the operator–operand principle.

Each combinator is associated with an inference rule for introduction or elimination, as in Gentzen calculus [27] [4]. The action of these combinators is described in the rules of β-introduction for introducing combinators and β-reduction for eliminating them.

We present the two combinators **B** and **C**$_*$, used in our system, as well as their β-reduction rules: the combinator B :

Bfgx ---------- > f(gx)

The C* combinator (type raising (type change)). It was proposed by Lambek [13] in his analysis of pronouns:

C$_*$xy ---------- > yx

5- PROCESSING AND ANALYSIS USING THE ACCG APPLICATION:

5.1- PROCESSING SIMPLE SENTENCES:

We will apply the previous rules to representative sentences and, to simplify the notation, we will replace '+' with a space for concatenation.

To clarify the analytical procedure and the application of combinators, we begin with an English sentence in order to facilitate understanding of the system's functioning.

Exemple:

Mohamed wrote the lesson

1- N* : *Mohamed* (S\N*)/N*: *wrote* N*/N: *the* N:*lesson*

2- S/(S\N*) : (**C**$_*$*Mohamed*) (S\N*)/N*: *wrote* N*/N: *the* N:*lesson* (>**T**)

3- S/N* : (**B**(**C**$_*$*Mohamed*) *wrote*) N*/N: *the* N:*lesson* (>**B**)

4- S/N : (**B**(**B**(**C**$_*$*Mohamed*) *wrote*)*the*) N:*lesson* (>**B**)

5- S : (**B**(**B**(**C**$_*$*Mohamed*) *wrote*)*the*) *lesson* (>**B**)

The sentence is syntactically well-formed, since it is of type S. We now move on to the reduction phase:

6- S : (**B**(**C**$_*$*Mohamed*) *wrote*) (*the lesson*) (**B**)

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7- S : (**C****Mohamed*) (*wrote* (*the lesson*)) (**B**)

8- S : (*wrote* (*the lesson*)) *Mohamed* (**C***)

The analysis of the preceding sentence is conducted in two successive phases: in the first phase (steps 1, 2, 3, 4, and 5), we employ to verify whether the sentence is syntactically well-formed (S or N*) or not. In the second phase (steps 6, 7, and 8), we construct the application representation after reducing the combinators.

In the first phase, the sentence analysis proceeds through the following steps: In the first step, we assign each linguistic unit its syntactic type, where the subject *Mohamed* takes the type N*. The verb "*worte*" expects a direct object (*the lesson*) of type N* to its left and a subject (*Mohamed*) of type N* to its right. Thus, the syntactic type of the verb is (S\N*)/N*. For the article (*the*), we assign it N*/N and expect a nominal syntagm (*lesson*) of type N to its right.

The second step, a type change with the introduction of the combinator **C***, gives us S/(S\N*): (**C****Mohamed*). In the third step, we combine S/(S\N*): (**C****Mohamed*) with the verb (S\N*)/N*: "wrote" using the Forward combination rule (**>B**). We continue the analysis until we obtain S.

The second phase of the sentence analysis concerns the application of the β-reduction rule of combinators **B** and **C*** to obtain the following applicative system: (*wrote* (*the lesson*)) *Mohamed* as an operator/operand of the linguistic units: where the operator *written* is applied to the operand *the lesson* to form the predicate (*wrote* (*the lesson*)), the whole will be applied to *Mohamed*.

After dealing with an example in English, we move on to analyzing its translation into Arabic.

We begin with sentence analysis (a) in Arabic:

a) *kataba* *mohamadu* *āl* *ddarsa*

1- (S/N*)/N* : *kataba* N*: *mohamadu* N*/N :*āl* N:*ddarsa*

2- (S/N*)/N* : *kataba* S\(S/N*): (**C*** *mohamadu*) N*/N :*āl* N:*ddarsa* (**>T**)

3- S/N* : (**B**(**C*** *mohamadu*) *kataba*) N*/N :*āl* N:*ddarsa* (**<Bx**)

4- S/N : (**B**(**B**(**C*** *mohamadu*) *kataba*) *āl*) N:*ddarsa* (**>B**)

5- S : (**B**(**B**(**C*** *mohamadu*) *kataba*) *āl*) *ddarsa*) (>)

The sentence is syntactically well-formed, since it is of type S. We move on to the reduction phase:

6- S : (**B**(**C*** *mohamadu*) *kataba*) (*āl* *ddarsa*) (**B**)

7- S : (**C*** *mohamadu*) (*kata*ba (*āl* *ddarsa*) (**B**)

8- S : (*kata*ba (*āl* *ddarsa*) *mohamadu* (**C***)

Sentence (a) is a verbal sentence beginning with the transitive verb *kataba* (*wrote*), that is, a predicate which expects two arguments on the left, the subject *mohamadu* (*Mohamed*) of type N* and the direct object which contains the article *āl*(*the*) of type N*/N and *ddarsa* (*lesson*) of type N. The verb must therefore receive the categorical syntactic type (S/N*)/N*.

As we mentioned earlier, the analysis process involves the following steps:

Step 1: Assigning types to each linguistic unit.

Step 2: A type change is performed to construct the operator (**C****mohamadu*) from the subject *mohamadu* (*Mohamed*).

Step 3: A compound is made between (**C****mohamadu*) and the verb *kataba* (*Wrote*), forming the complex predicate (**B**(**C****mohamadu*) *kataba*).

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Step 4: Similarly, a compound is made between (**B**(**C****mohamadu*) *kataba*) and the article *āl* (*the*), again forming a more complex predicate ((**B**(**C****mohamadu*) *kataba*)*āl*).

Step 5: After left simplification, we obtain ((**B**(**C****mohamadu*) *kataba*)*āl*)*ddarsa*. The resulting syntactic type is S, so the sentence is syntactically correct.

Steps 6 and 7: We apply the β-reduction rule of combinator **B**.

Step 8: After applying the β-reduction rule of combinator **C***, we obtain an operator/operand order of the linguistic units of the initial utterance: the operator *kataba* (*wrote*) is applied to the operand (*āl ddarsa*) (*the lesson*). The result, *kataba* (*āl ddarsa*) (*wrote* (*the lesson*)), is a new operator that will be applied to the operand *mohamadu* (*Mohamd*) to obtain the applicative expression (*kataba* (*ddarsa āl*)) *mohamadu* – (*wrote* (*the lesson*)) *Mohamed*).

Now we move on to the analysis of sentence (b) in Arabic:

b) *mohamadu kataba āl ddarsa*

1- N*: *mohamadu* (S/N*)/N* : *kataba* N*/N :*āl* N:*ddarsa*

2- S/(S/N*): (**C*** *mohamadu*) (S/N*)/N* : *kataba* N*/N :*āl* N:*ddarsa* (>**Tx**)

3- S/N* : (**B**(**C*** *mohamadu*) *kataba*) N*/N :*āl* N:*ddarsa* (>**B**)

4- S/N : (**B**(**B**(**C*** *mohamadu*) *kataba*) *āl*) N:*ddarsa* (>**B**)

5- S : (**B**(**B**(**C*** *mohamadu*) *kataba*) *āl*) *ddarsa*) (>)

The sentence is syntactically well-formed, since it is of type S. We move on to the reduction phase:

6- S : (**B**(**C*** *mohamadu*) *kataba*) (*āl ddarsa*) (**B**)

7- S : (**C*** *mohamadu*) (*kata*ba (*āl ddarsa*) (**B**)

8- S : (*kata*ba (*āl ddarsa*) *mohamadu* (**C***)

Similarly, after applying the rules, we arrive at the same application system: (*kata*ba(*āl ddarsa*) *mohamadu*.

Finally, we will address sentence (c) in Arabic:

This last sentence has the same meaning as sentences (a) and (b), meaning that the lesson will be written in all three cases, but in (a) and (b) the subjects are apparent, whereas in (c) the subject (agent) is implicit (hidden or invisible).

c) *kataba āl ddarsa*

1- (S/N*)/N* : *kataba* N*/N :*āl* N:*ddarsa*

2- (S/N*)/N : (**B***kataba*)*āl* N:*ddarsa* (>**B**)

3- S/N* : (**B** *kataba āl*) *ddarsa* (>)

In step 3, we note that the analysis did not lead to S even though sentence (c) is syntactically correct, leading to a deadlock. To resolve this issue, we introduce the symbol (A), which represents the agent invisible only during processing.

c') *kataba* (*A*) *āl ddarsa*

1- (S/N*)/N* : *kataba* N*: (*A*) N*/N :*āl* N:*ddarsa*

2- (S/N*)/N* : *kataba* S\(S/N*): (**C*** (*A*)) N*/N :*āl* N:*ddarsa* (>**T**)

3- S/N* : (**B**(**C*** (*A*)) *kataba*) N*/N :*āl* N:*ddarsa* (<**Bx**)

4- S/N : (**B**(**B**(**C*** (*A*)) *kataba*) *āl*) N:*ddarsa* (>**B**)

5- S : (**B**(**B**(**C*** (*A*)) *kataba*) *āl*) *ddarsa*) (>)

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The sentence is syntactically well-formed, since it is of type S. We move on to the reduction phase:

6- S : (**B**(**C**$_*$ (*A*)) *kataba*) (*āl ddarsa*) (**B**)

7- S : (**C**$_*$ (*A*)) (*kata*ba (*āl ddarsa*) (**B**)

8- S : (*kata*ba (*āl ddarsa*) (*A*) (**C**$_*$)

After removing the introduced symbol (*A*), we obtain the following application expression:

(*kataba* (*āl ddarsa*)) (wrote (the lesson)).

5.2- ANALYSIS OF A COMPLEX SENTENCE:

5.2.1- SENTENCE CONTAINING AN ADVERB:

Among the complex sentences, an example is given of a sentence that contains an adverb.

d) محمدُ	ذهب	مسرعا	arabic sentence
mohamadu	*dahaba*	*mosri/an*	Transcription
Mohamed	*went*	*quickly*	Gloss
Mohamed went quickly			translation

where : محمدُ : *mohamadu*, *Mohamed* is the subject of the sentence.

ذهب : *dahaba, went* is the verb.

مسرعا : *mosri/an, quickly* is the adverb.

1- N* : *mohamadu* S/N* :*dahaba* (S/N*)\(S/N*) :*mosri/an*

2- S/(S/N*) : (**C**$_*$*mohamadu*) S/N* :*dahaba* (S/N*)\(S/N*) :*mosri/an* (>**Tx**)

3- S : (**C**$_*$*mohamadu*)*dahaba* (S/N*)\(S/N*) :*mosri/an* (>)

From this point onward, direct progression is no longer possible, and it is necessary to move to a decomposition in order to continue the analysis:

4- S/(S/N*) : (**C**$_*$*mohamadu*) S/N*: *dahaba* (S/N*)\(S/N*) :*mosri/an* (>**Dec**)

5- S/(S/N*) : (**C**$_*$*mohamadu*) S/N*: (*mosri/an dahaba*) (<)

6- S : (**C**$_*$*mohamadu*) (*mosri/an dahaba*) (>)

The sentence is syntactically well-formed, since it is of type S. We move on to the reduction phase:

7- S : (*mosri/an dahaba*) *mohamadu* (>)

In the first step of this analysis, a syntactic type is assigned to each linguistic unit. In the second step, a type change is performed, followed by a left application rule. From step 3 onward, no rule is possible between S and (S/N*)\(S/N*). We then proceed to a decomposition in step 4, which gives us two parts: the first part is S/(S/N*): (**C***mohamadu*) (*Mohamed*) and the second part is S/N*: *dahaba*(went). In step 5, we apply a left application rule between S/N*: *dahaba*(*went*) and (S/N*)\(S/N*):*mosri/an* (*quickly*). In step 6, we have a right application rule. The resulting syntactic type is S, so the sentence is syntactically well-formed; we can now move on to the reduction phase.

Finally, in step 7, a reduction rule for the combinator **C**$_*$ is applied. We obtain an applicative expression in the form of an operator applied to an operand, where *mosri/an* (*quickly*) is an adverb that functions as an operator applied to the operand *dahaba* (*went*). The set (*mosri/an dahaba*) (*quickly went*) then constitutes a complex operator that is again applied to the operand *mohamadu* (*Mohamed*) to form the applicative expression:

(*mosri/an dahaba*) *mohamadu*((*quickly went*) *Mohamed*).

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5.2.2- SENTENCE CONTAINING RELATIVE PRONOUNS (SUBORDINATE PROPOSITIONS (CLAUSES) IN ARABIC)

The relationship between two propositions is important. Subordination is a syntactic dependency relationship between linguistic units. The subordinate proposition always depends on another proposition, called the main proposition. According to [28], relative pronouns are treated as operators that link the subordinate proposition to the main proposition.

In principle, a relative proposition in arabic is formed around the following three elements:

1- The antecedent, which is a definite or indefinite noun (However, there are relative proposition without an antecedent).

2- Relative pronoun: is a noun used with what follows it to describe and specify a referent; for example**:** *ālady* (*that, who, which..,* الذي) for masculine referents**,** *ālaty* (*that, who, which..,* التي) feminine referents**,** *man* (*that, who..,* من) for persons and *maā* (*that,* ما) and *āay* (*that,* أي) for non-human referents**.**

3- A relative proposition. This is the sentence that follows the relative pronoun to define it, complete its meaning, and clarify what it signifies. According to Fleisch [25], the relative proposition in Arabic and the attributive adjective have the same syntactic status. The attributive adjective is placed after the noun it modifies and agrees with it in gender, number, and case; similarly, the relative follows what is called its antecedent [25].

Regarding relative propositions, Arabic grammarians have established a number of specific conditions [29]:

- A verbal or nominal sentence
- A pseudo-sentence (prepositional or adverbial complement).
- It must include a revenant, esteemed, or equivalent.

In Arabic, the revenant is an element belonging to the relative proposition. It agrees in gender and number with the antecedent. It constitutes the fundamental linking element between the two propositions. This differs from some other languages where the relative proposition may not have a subject or object.

[28] states that subordination is achieved by applying a subordination constructor to two simple propositions. For example, the following propositions:

علي بنى البيت

/aliyun *banaī* ālbayta

Ali built the house

And

محمد سكن البيت

mohamadu sakana ālbayta

Mohamed lived in the house

can be performed by the relative pronoun :

الذي ālady *who*

The resulting proposal is as follows :

علي	بنى	البيت	الذي	سكنه	محمد
/aliyun	banaī	ālbayta	ālady	sakanahu	mohamdun
Ali	built	the house	who	lived in	Mohamed

Ali built the house who Mohamed lived in

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The verification of syntactic dependency relations between linguistic units in arabic remains relatively limited compared to other languages. Here, we propose a syntactic analysis of relative propositions using the ACCG model. To study more precisely the different syntactic dependency relations between the relative proposition and the main proposition, we have selected the following propositions:

1- ذهب الذي يحب ال قراءة
dahaba *ālady* yuhibu *āl qiraā/ta*
went who loves reading
The one who loves reading went

2- جاء الذي في ال دار
ǧaā/ *ālady* fy āl daāri
came who in the house
The one who was in the house came

3- اخذ محمدُ ما علي ترك ـه
āhada *mohamadu* *maā* */aliyu* *taraka* *hu*
took *Mohamed* *what* *Ali* *left* *him*
Mohamed took what Ali left

4- اخذ محمدُ ما في ال دار
āhada *mohamadu* *maā* *fy* āl daāri
took Mohamed what in the house
Mohamed took what was in the house

5- اشترى محمدُ كتاب ال الذي يحب ـه علي
āištarà *moḥamadu* āl kitaāba *ālady* yuḥibu *ḥu* */aliyun*
Bought Mohamed the book which love him Ali
Mohamed bought the book that Ali loves.

6- اخذ محمدُ كتاب ال الذي في ال قسم
āhada *moḥamadu* āl kitaāba *ālady* fy āl qismi
took Mohamed the book which in the classroom
Mohamed took the book that was in the classroom

7- مرَّ محمدُ بـ الذي نصح ـه علياً
mara *moḥamadu* *bi* *ālady* nasaḥa hu */aliyun*
passed Mohamed by who advised him Ali
Mohamed passed by the one whom Ali advised

8- الذي نجح ذكي

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ālady naǧaḥa *d*akiyun

who *succeed* *intelligent*

The one who succeeded is intelligent

9- ما عند محمد ثمين

maā */inda* *moḥamdin* *t*amynun

what *with* *Mohamed* *precious*

What Mohamed has is precious

In the preceding examples, there are propositions that are introduced by an antecedent and propositions that are not. For example, relative propositions (8) and (9) do not have an antecedent.

According to the arabic grammarians [29] and based on grammatical categorization, a relative pronoun can be assigned a syntactic type according to its position in the sentence. This means that it has a grammatical function like any other noun (it can be a subject, direct object, adjective, etc.). In examples (1) and (2) : *ālady* yuhibu *ālqiraā/ta* (*who loves reading*), and *ālady* fy āldaāri (*who was in the house*) Relative pronouns function as subjects, respectively intransitive verbs *d*ahaba(*went*) and ǧaā/ (*came*). Note in exemple (1) that the relative pronoun is followed by a verbal sentence: yuhibu *ālqiraā/ta* (*he loves reading*). However, in sentence (2), the relative pronoun is followed by a prepositional phrase: fy āldaāri (*in the house*).

In exemples (3) and (4), *maā /aliyu tarakahu* (*what Ali left*) and *maā fy* āldaāri (*what was in the house*), relative pronouns function as object complements.

The relative pronouns in the preceding sentences function as an operator acting in place of a noun constructor. In example (1), if we replace *ālady yuhibu ālqiraā/ta* (*who loves reading*) with a noun like *mohamadu* (*Mohamed*), the sentence will be as follows: *d*ahaba *mohamdun* (*Mohamed went*).

However, in example (5), *ālady yuḥibuḥu /aliyun* (*that Ali loves*), the relative pronoun functions as an adjective modifying the noun *ālkitaāba* (*the book*). Thus, post-nominal modifier constructor. In other words, *ālaādi yuḥibuḥu /aliyun* (*that Ali loves*) is an operator applied to the operand *ālkitaāba* (*the book*). The verb *āištarà* (*bought*) is a transitive verb followed by the subject *mohamadu* (*Mohamed*).

For the relative propositions in examples (8): *ālady naǧaḥa* (*The one who succeeded*) and (9): *maā /inda moḥamdin* (*what Mohamed has*), these (that is, the relative pronoun *ālady* (*who*) followed by the verb *naǧaḥa* (*succeeded*), and the relative pronoun *maā* (*what*) followed by the prepositional phrase */inda moḥamdin* (*Mohamed has*)) function as nouns. In case (7): *ālady nasaḥahu /aliyan* (*the one whom Ali advised*), the relative proposition functions as a complement introduced by the preposition *bi*(*in*).

Relative propositions can function as operators applied to operands in an application system, hence the need to use ACCG to perform syntactic checking of subordinate proposition(clauses). First, we assign a syntactic category (syntactic type) to each linguistic unit, and then we proceed with the checking.

1- [dahaba] S/N* [*ālady*] N*/S [yuhibu] (S/N*)/N* [*āl*] N*/N [*qirā/ta*]N

2- [*ǧaā/*]S/N* [*ālady*]N*/(N*\N*) [*fy*](N*\N*)/N* [āl]N*/N [daāri]N

3- [*āhada*](S/N*)/N* [*mohamadu*]N* [*maā*]N*/S [*/aliyu*]N* [*taraka*](S/N*)/N* [*hu*](S/N*)\((S/N*)/N*)

4- [*āhada*] (S/N*)/N* [*mohamadu*]N* [*maā*]N*/(N*\N*) [*fy*](N*\N*)/N*)] āl[N*/N [daāri]N

5- [*āištarà*](S/N*)/N* [*moḥamadu*]N* [āl]N*/N [kitaāba]N [*ālady*](N*\N*)/S [yuḥibu](S/N*)/N* [*hu*](S/N*)\((S/N*)/N*) [/aliyun]N*

6- [*āhada*](S/N*)/N* [*moḥamadu*]N* [āl]N*/N [kitaāba]N [*ālady*] (N*\N*)/(N*\N*) [*fy*](N*\N*)/N*) [āl]N*/N [*qismi*]N

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7- [*marra*]S/N* [*moḥamadu*]N* [*bi*]((S/N*)\(S/N*))/N* [*ālad̲y*]N*/S [nasaḥa](S/N*)/N* [*hu*](S/N*)\((S/N*)/N*) [/aliyun]N*

8- [*ālady*]N*/S [na*ğaḥa*]S/N* [*d̲akiyun*]N*\N*

9- [*maā*]N*/(N*\N*) [*/inda*](N*\N*)/N* [*moḥamdin*]N* [*t̲amynun*]N*\N*

We are particularly interested here in the syntactic types assigned to relative pronouns:

For example (1), *ālady* (*who*) is considered a noun constructor followed by a verbal phrase to which the type N*/S is assigned. The set *ālady yuhibu ālqirā/ta* (*who loves reading*) functions as a subject and constitutes an operand of the operator *dahaba*(*go*).

In example (2), the relative pronoun *ālady* (*who*) functions as a noun constructor and acts as an operand with respect to the operator, the verb *ğaā/* (*came*). However, it is followed by the preposition *fy* (*in*), which is assigned the category (N*\N*)/N*. Thus, the relative pronoun acts as a noun constructor whose syntactic category is N*/(N*\N*).

In example (3), the sentence begins with the transitive verb *āh̲ada* (*take*), which has the syntactic type (S/N*)/N*, followed by the subject *mohamadu* (*Mohamed*), which has the syntactic type N*. The object complement *maā /aliyu tarakahu* (*what Ali left*) is a relative proposition containing the relative pronoun *maā* (*what*), which acts as a noun constructor. This constructor is followed by the sentence *tarakahu /aliyu* (*Ali left*), which has the syntactic type S. Therefore, the relative pronoun *maā* (*what*) has the category N*/S.

In example (4), the structure is similar to that of example (3), except that the object complement *maā fy āldaāri* (*what in the house*) contains a relative proposition in the form of a prepositional phrase *fy āldaāri* (*in the house*). The preposition *fy* (*in*) is represented by the category (N*\N*)/N* and *āldaāri* (*the house*) by N*, and finally the relative pronoun, which functions here as a noun constructor, will have the category N*/(N*\N*).

In example (5), the sentence begins with the transitive verb *āištarà* (*bought*), which is assigned the category (S/N*)/N*, followed by the subject *mohamadu* (*Mohamed*) of category N*. The object complement *ālkitaāba ālady yuḥibuḥu /aliyun* (*The book what Ali loves*) begins with *ālkitaāba* (*the book*), of syntactic type N*, followed by the adjective *ālady yuḥibuḥu /aliyun* (*what Ali loves*). The latter contains the relative pronoun *ālady* (*what*), which acts as a back modifier constructor, followed by the phrase *yuḥibuḥu /aliyun* (*Ali loves*), of category S. Thus, the relative pronoun *ālady* (*what*) has the category (N*\N*)/S.

Regarding example (7), the verb *marra* (*passed*) is an intransitive verb of category S/N*, followed by the subject *mohamadu* (*Mohamed*) of type N*. The relative pronoun *ālady* (*whom*) is preceded by the preposition *bi* (*by*), to which is assigned the type ((S/N*)\(S/N*))/N*, and followed by the phrase *nasahahu /aliyun* (*Ali advised him*) of category S. Therefore, the categorical type N*/S is assigned to the relative pronoun.

In examples (8) and (9), the relative propositions have no antecedent. In example (8), the relative pronoun *ālady* (*who*) functions as a noun constructor, followed by the phrase *nağaḥa* (*he succeeded*) with an implied (hidden) subject. The relative pronoun takes the type N*/S. Similarly, in example (9), the relative pronoun *maā* (*what*) acts as a noun constructor of type N*/(N*\N*), followed by an adverbial of place */inda* (*with*) of type (N*\N*)/N*, and *maā /inda* (*what with*) will have the category N*/N* followed by *moḥamdin* (*Mohamed*) of type N*.

In summary, the relative pronoun plays different roles that allow us to categorize the following syntactic types:

The role of the relative pronoun	The type of relative proposition	Syntactic type of the relative pronoun	Example number
Subject	Sentence	N*/S	(1)
	Prepositional phrase	N*/(N*\N*)	(2)
Complement	Sentence	N*/S	(3)

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	Prepositional phrase	N*/(N*\N*)	(4)
Adjective	Sentence	(N*\N*)/S	(5)
	Prepositional phrase	(N*\N*)/(N*\N*)	(6)
Prepositional phrase	Sentence	N*/S	(7)
A noun at the beginning of the sentence	Sentence	N*/S	(8)
A noun at the beginning of the sentence	A circumstantial complement of place	N*/(N*\N*)	(9)

Analyzing sentences using the ACCG model involves two successive phases:

- In the first phase, we apply the application rules (see paragraph 3.1) to check whether the sentence is syntactically correct or not.
- In the second phase, we construct the application representation after the reduction of the combinators (see paragraph 4). In this presentation, the application order of the linguistic units corresponds to that of the operators followed by their operands.

In some cases, during the analysis of arabic sentences, a state of blockage is reached in the first phase, which necessitates a reduction of the combinators.

Now we move on to analyzing the different situations of the relative pronoun:

Case 1: the relative pronoun acts as the subject and the relative proposition is a verbal phrase

(1) dahaba *ālady* yuhibu *āl qiraā/ta*

In this example, the relative proposition *yuhibu ālqirā/ta* (*he loves reading*) contains an implicit (hidden) subject, which will henceforth be represented by (*A*) with syntactic type N*, which will be removed after reduction:

1- S/N*: dahaba N*/S :*ālady* (S/N*)/N*: yuhibu N*: *A* N*/N: *āl* N: *qirā/ta*

2- S/S: (**B**dahaba *ālady*) (S/N*)/N*: yuhibu N*: *A* N*/N: *āl* N: *qirā/ta* (>**B**)

3- S/S: (**B**dahaba *ālady*) (S/N*)/N*: yuhibu S\(S/N*): (**C**$_*$*A*) N*/N: *āl* N: *qirā/ta* (<**T**)

4- S/S: (**B**dahaba *ālady*) S/N*: (**B**(**C**$_*$*A*) yuhibu) N*/N: *āl* N: *qirā/ta* (<**Bx**)

5- S/N*: (**B**(**B**dahaba *ālady*) (**B**(**C**$_*$*A*) yuhibu)) N*/N: *āl* N: *qirā/ta* (>**B**)

6- S/N: (**B**(**B**(**B**dahaba *ālady*) (**B**(**C**$_*$*A*) yuhibu)) *āl)* N: *qirā/ta* (>**B**)

7- S: (**B**(**B**(**B**dahaba *ālady*) (**B**(**C**$_*$*A*) yuhibu)) *āl) qirā/ta* (>)

The sentence is syntactically well-formed, since it is of type S. We can proceed to the reduction phase:

8- S: (**B**(**B**dahaba *ālady*) (**B**(**C**$_*$*A*) yuhibu)) (*āl qirā/ta*) (**B**)

9- S: (**B**dahaba *ālady*) ((**B**(**C**$_*$*A*) yuhibu) (*āl qirā/ta*)) (**B**)

10- S: dahaba (*ālady* ((**B**(**C**$_*$*A*) yuhibu) (*āl qirā/ta*))) (**B**)

11- S: dahaba (*ālady* ((**C**$_*$*A*) (yuhibu (*āl qirā/ta*)))) (**B**)

12- S: dahaba (*ālady* (yuhibu (*āl qirā/ta*))*A*)) (**C**$_*$)

By removing (A), we obtain the applicative form: dahaba (*ālady* (yuhibu (*āl qirā/ta*))) *went*(*who*((*loves*) *reading*)) :

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- The operator *yuhibu* (*loves*) is applied to the operand (*āl qirā/ta*) (*reading*), to form a new operand (*yuhibu* (*āl qirā/ta*)) (*loves reding*).
- The operator *ālady* (*who*) is applied to this new operand which is (*yuhibu* (*āl qirā/ta*)) (*loves reading*), to form a new more complex operand (predicate), (*ālady* (*yuhibu* (*āl qirā/ta*))) (*who*((*loves*) *reading*).
- Finally, the operator *dahaba* (*went*) will be applied to the complex operand (*ālady* (*yuhibu* (*āl qirā/ta*))) (*who*((*loves*) *reading*), to form the applicative system *dahaba* (*ālady* (*yuhibu* (*āl qirā/ta*)))

Case 2: the relative pronoun acts as a subject and the relative proposition is a prepositional complement: (2) *ǧaā/ ālady fy* āl daāri

1- S/N* : *ǧaā/* N*/(N*\N*) : *ālady* (N*\N*)/N* : *fy* N*/N : *āl* N : daāri

2- S/(N*\N*) : (**B***ǧaā/ ālady)* (N*\N*)/N* : *fy* N*/N : *āl* N : daāri (>**B)**

3- S/N* : (**B**(**B***ǧaā/ ālady*)*fy*) N*/N : *āl* N : daāri (>**B**)

4- S/N : (**B**(**B**(**B***ǧaā/ ālady*)*fy*) *āl*) N : daāri (>**B**)

5- S : (**B**(**B**(**B***ǧaā/ ālady*)*fy*) *ā*l) daāri (>)

The sentence is syntactically well-formed, since it is of type S, we can move on to the next phase, in this case, reduction:

6- S : (**B**(**B***ǧaā/ ālady*)*fy*) (*ā*l daāri) (**B**)

7- S : (**B***ǧaā/ ālady*) (*fy* (*ā*l daāri)) (**B**)

8- S : *ǧaā/* (*ālady* (*fy* (*ā*l daāri))) (**B**)

Case 3: the relative pronoun functions as a direct object and the relative proposition is a nominal sentence: (3) *āhada mohamadu maā /aliyu taraka hu*

1- (S/N*)/N*:*āhada* N*:*mohamadu* N*/S:*maā* N*:*/aliyu* (S/N*)/N*:*taraka* (S/N*)\((S/N*)/N*):*hu*

2- (S/N*)/N*:*āhada* S\(S/N*): (**C***mohamadu) N*/S:*maā* N*:*/aliyu* (S/N*)/N*:*taraka* (S/N*)\((S/N*)/N*):*hu* (<**T**)

3- S/N*: (**B**(**C***mohamadu) āhada*) N*/S:*maā* N*:*/aliyu* (S/N*)/N*:*taraka* (S/N*)\((S/N*)/N*):*hu* (<**Bx**)

4- S/S: (**B**(**B**(**C***mohamadu)āhada*) *maā*) N*:*/aliyu* (S/N*)/N*:*taraka* (S/N*)\((S/N*)/N*):*hu* (<**Bx**)

5- S/S: (**B**(**B**(**C***mohamadu)āhada*) *maā*) S/(S/N*): (**C***/aliyu*) (S/N*)/N*:*taraka* (S/N*)\((S/N*)/N*):*hu* (<**Tx**)

6- S/(S/N*): (**B**(**B**(**B**(**C***mohamadu)āhada*) *maā*) (**C***/aliyu*)) (S/N*)/N*:*taraka* (S/N*)\((S/N*)/N*):*hu* (>**B**)

If we perform the composition S/(S/N*): (**B**(**B**(**B**(**C***mohamadu)āhada*) *maā*) (**C***/aliyu*)) with (S/N*)/N*:*taraka* , we obtain: S/N*: (**B**(**B**(**B**(**B**(**C***mohamadu)āhada*) *maā*) (**C***/aliyu*))*taraka*). It is not possible to combine the result obtained with (S/N*)\((S/N*)/N*):*hu*. To solve this problem, we must first combine (S/N*)/N*:*taraka* with (S/N*)\((S/N*)/N*):*hu*.

7- S/(S/N*): (**B**(**B**(**B**(**C***mohamadu)āhada*) *maā*) (**C***/aliyu*)) S/N* : (*hu taraka*) (<)

8- S : (**B**(**B**(**B**(**C***mohamadu)āhada*) *maā*) (**C***/aliyu*)) (*hu taraka*) (>)

The sentence is syntactically well-formed, since it is of type S. We now move on to the reduction phase:

9- S : (**B**(**B**(**C***mohamadu)āhada*) *maā*) ((**C***/aliyu*) (*hu taraka*)) (**B**)

10- S : (**B**(**C***mohamadu)āhada*) (*maā* ((**C***/aliyu*) (*hu taraka*))) (**B**)

11- S : (**C***mohamadu*) (*āhada* (*maā* ((**C***/aliyu*) (*hu taraka*)))) (**B**)

12- S : (*āhada* (*maā* ((**C***/aliyu*) (*hu taraka*)))) *mohamadu* (**C***)

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13- S : (*āḥaḍa* (*maā* ((*hu taraka*) */aliyu*))) *mohamadu* (**C***)

Case 4: the relative pronoun acts as a direct object and the relative proposition is a prepositional phrase: (4) *āḥaḍa mohamadu maā fy* āl daāri

1- (S/N*)/N*:*āḥaḍa* N* :*mohamadu* N*/(N*\N*) :*maā* (N*\N*)/N* :*fy* N*/N :*āl* N :daāri

2- (S/N*)/N*:*āḥaḍa* S\(S/N*): (**C***mohamadu*) N*/(N*\N*) :*maā* (N*\N*)/N* :*fy* N*/N :*āl* N :daāri (**<T**)

3- S/N*: (B (**C***mohamadu*) *āḥaḍa*) N*/(N*\N*) :*maā* (N*\N*)/N* :*fy* N*/N :*āl* N :daāri (**<Bx**)

4- S/(N*\N*): (**B**(B (**C***mohamadu*) *āḥaḍa*) *maā*) (N*\N*)/N* :*fy* N*/N :*āl* N :daāri (**>B**)

5- S/N*: (**B**(**B**(B (**C***mohamadu*) *āḥaḍa*) *maā*) *fy*) N*/N :*āl* N :daāri (**>B**)

6- S/N: (**B**(**B**(**B**(B (**C***mohamadu*) *āḥaḍa*) *maā*) *fy*) *āl*) N :daāri (**>B**)

7- S: (**B**(**B**(**B**(B (**C***mohamadu*) *āḥaḍa*) *maā*) *fy*) *āl*) daāri (>)

The sentence is syntactically well-formed, since it is of type S, so we move on to the reduction phase:

8- S: (**B**(**B**(B (**C***mohamadu*) *āḥaḍa*) *maā*) *fy*) (*āl* daāri) (**B**)

9- S: (**B**(B (**C***mohamadu*) *āḥaḍa*) *maā*) (*fy* (*āl* daāri)) (**B**)

10- S: (B (**C***mohamadu*) *āḥaḍa*) (*maā* (*fy* (*āl* daāri))) (**B**)

11- S: (**C***mohamadu*) (*āḥaḍa* (*maā* (*fy* (*āl* daāri)))) (**B**)

12- S: *āḥaḍa* (*maā* (*fy* (*āl* daāri)))) *mohamadu* (**C***)

Case 5: the relative pronoun functions as an adjective and the relative proposition is a verbal phrase: (5) *āištarà moḥamadu* āl kitaāba *ālaḍy* yuḥibu *hu* /aliyun

1- (S/N*)/N* :*āištarà* N* : *moḥamadu* N*/N : *āl* N : kitaāba (N*\N*)/S : *ālaḍy* (S/N*)/N* :yuḥibu (S/N*)\((S/N*)/N*) : *hu* N* : /aliyun

2- (S/N*)/N* :*āištarà* S\(S/N*) : (**C***moḥamadu*) N*/N : *āl* N : kitaāba (N*\N*)/S : *ālaḍy* (S/N*)/N* :yuḥibu (S/N*)\((S/N*)/N*) : *hu* N* : /aliyun (**<T**)

3- S/N* : (**B** (**C***moḥamadu*) *āištarà*) N*/N : *āl* N : kitaāba (N*\N*)/S : *ālaḍy* (S/N*)/N* :yuḥibu (S/N*)\((S/N*)/N*) : *hu* N* : /aliyun (**<Bx**)

4- S/N : (**B**(**B** (**C***moḥamadu*) *āištarà*) *āl*) N : kitaāba (N*\N*)/S : *ālaḍy* (S/N*)/N* :yuḥibu (S/N*)\((S/N*)/N*) : *hu* N* : /aliyun (**>B**)

5- S : (**B**(**B** (**C***moḥamadu*) *āištarà*) *āl*) kitaāba (N*\N*)/S : *ālaḍy* (S/N*)/N* :yuḥibu (S/N*)\((S/N*)/N*) : *hu* N* : /aliyun (**>B**)

6- S : (**B**(**B** (**C***moḥamadu*) *āištarà*) *āl*) kitaāba (N*\N*)/S : *ālaḍy* S/N*: (hu yuḥibu) N*: /aliyun (>)

7- S : (**B**(**B** (**C***moḥamadu*) *āištarà*) *āl*) kitaāba (N*\N*)/N* : (**B** *ālaḍy* (hu yuḥibu)) N* : /aliyun (>)

8- S : (**B**(**B** (**C***moḥamadu*) *āištarà*) *āl*) kitaāba N*\N* : ((**B** *ālaḍy* (hu yuḥibu)) /aliyun) (>)

No further simplification rules can be applied: the solution consists of applying a reduction rule to the combinator **B**. We then obtain:

9- S : (**B** (**C***moḥamadu*) *āištarà*)(*āl* kitaāba) N*\N* : ((**B** *ālaḍy* (hu yuḥibu)) /aliyun) (**B**)

10- S/N* : (**B**(**C***moḥamadu*) *āištarà*) N*: (*āl* kitaāba) N*\N*: ((**B***ālaḍy*(hu yuḥibu))/aliyun)(**>Dec**)

11- S/N* : (**B** (**C***moḥamadu*) *āištarà*) N*: (((**B** *ālaḍy* (hu yuḥibu)) /aliyun) (*āl* kitaāba)) (<)

12- S : (**B** (**C***moḥamadu*) *āištarà*) (((**B** *ālaḍy* (hu yuḥibu)) /aliyun) (*āl* kitaāba)) (>)

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The sentence is syntactically well-formed, since it is of type S, so we move on to the reduction phase:

13- S : (**C****moḥamadu**) (*āištarà* (((**B** *ālad̲y* (hu yuḥibu)) /aliyun) (*ā*l kitaāba))) (**B**)

14- S : (*āištarà* (((**B** *ālad̲y* (hu yuḥibu)) /aliyun) (*ā*l kitaāba))) *moḥamadu* (**C**\)

15- S : (*āištarà* ((*ālad̲y* ((hu yuḥibu) /aliyun)) (*ā*l kitaāba))) *moḥamadu* (**B**)

Discussion of this analysis:

In step 1, a syntactic type is assigned to each linguistic unit. In step 2, a type change is applied to the unit moḥamadu (Mohamed), followed by a composition rule in step 3 between S\(S/N*): (C*moḥamadu) (Mohamed) and (S/N*)/N*: āištarà(bought). In step 4, another composition rule is applied between (**B** (**C***moḥamadu)āištarà) ((**B** (**C***Mohamed)bought)) and N*/N: āl(the). In step 5, by applying a right simplification rule, we obtain (**B**(**B** (**C***moḥamadu) āištarà) āl) kitaāba((**B**(**B** (**C***Mohamed) bought) the) book).

In step 6, we obtained S/N*: (*hu yuḥibu*)(*him love*), by applying a right simplification rule between (S/N*)/N*: *yuḥibu*(*love*) and (S/N*)\((S/N*)/N*): *hu*(*him*).

In step 7, after applying the composition rule between (N*\N*)/S: *ālady*(*that*) and S/N*: (*hu yuḥibu*) (*him love*), we obtain: (N*\N*)/N*: (**B** *ālady* (*hu yuḥibu*)) ((**B** *that* (*him love*))).

Step 8, after a left simplification, we obtain: N*\N* : ((**B** *ālady* (*hu yuḥibu*)) */aliyun*) (((**B** *that* (*him love*)) *Ali*)).

After step 8, no simplification rule can be applied, even decomposition is impossible; we are faced with a deadlock. The only solution is to apply a reduction rule from combinator **B** to S: (B(B (**C****moḥamadu**) *āištarà*) *āl*) *kitaāba*((**B**(**B** (**C****Mohamed**) *bought*) *the*) book), which will result in, S : (**B** (**C****moḥamadu**) *āištarà*)(*ā*l kitaāba) ((**B** (**C****Mohamed**) *bought*) (*the* book)).

In step 10, we can now apply the decomposition rule on the left, obtaining the two types S/N*: (**B** (**C****moḥamadu**) *āištarà*) ((**B** (**C****Mohamed**)*bought*)) et N*: (*ā*l kitaāba)(the book).

A left simplification rule is possible in step 11, between N*: (*ā*l kitaāba)(*the book*) et N*\N*: ((**B** *ālad̲y* (hu yuḥibu)) /aliyun) (((**B** *that* (*him* love)) Ali)), hence : N*: (((**B** *ālad̲y* (*hu* yuḥibu)) /aliyun) (*ā*l kitaāba))((((**B** *that* (*him* love)) Ali) (*the* book))).

In step 12, after applying the right simplification rule, we obtain a sentence of type S. The sentence is therefore well-formed. We then proceed to the reduction phase in order to obtain the applicative form of the operator/operand type: (*āištarà*((*ālad̲y*((*hu* yuḥibu) /aliyun)) (*ā*l kitaāba))) *moḥamadu*((*bought*((*that*((*him* love) Ali)) (*the* book))) *Mohamed*).

Case 6: the relative pronoun functions as an adjective and the relative proposition acts as a prepositional complement: (6) *āḥad̲a moḥamadu ā*l kitaāba *ālad̲y fy ā*l *qismi*

1- (S/N*)/N* : *āḥad̲a* N* :*moḥamadu* N*/N :*ā*l N :kitaāba (N*\N*)/(N*\N*) :*ālad̲y* (N*\N*)/N*) :*fy* N*/N :*ā*l N :*qismi*

2- (S/N*)/N* : *āḥad̲a* S\(S/N*) : (**C****moḥamadu**) N*/N :*ā*l N :kitaāba (N*\N*)/(N*\N*) :*ālad̲y* (N*\N*)/N*) :*fy* N*/N :*ā*l N :*qismi* (>**T**)

3- S/N* : (**B**(**C****moḥamadu**)*āḥad̲a*) N*/N :*ā*l N :kitaāba (N*\N*)/(N*\N*) :*ālad̲y* (N*\N*)/N*) :*fy* N*/N :*ā*l N :*qismi* (<**Bx**)

4-S/N*: (**B**(**B**(**C****moḥamadu**)*āḥad̲a*)*ā*l) N :kitaāba (N*\N*)/(N*\N*) :*ālad̲y* (N*\N*)/N*) :*fy* N*/N:*ā*l N :*qismi* (>**B**)

5- S : (**B**(**B**(**C****moḥamadu**)*āḥad̲a*) *ā*l) kitaāba (N*\N*)/(N*\N*) :*ālad̲y* (N*\N*)/N*) :*fy* N*/N :*ā*l N :*qismi* (>)

6- S : (**B**(**B**(**C****moḥamadu**)*āḥad̲a*) *ā*l) kitaāba (N*\N*)/N* : (**B***ālad̲y fy*) N*/N :*ā*l N :*qism* (>**B**)

7- S : (**B**(**B**(**C****moḥamadu**)*āḥad̲a*) *ā*l) kitaāba (N*\N*)/N : (**B**(**B***ālad̲y fy*)*ā*l) N :*qismi* (>**B**)

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8- S : (**B**(**B**(**C***moḥamadu*)*āḥaḍa*) *ā*l) kita*ā*ba N*\N* : ((**B**(**B***ālaḍy fy*)*ā*l)*qismi*) (**>**)

No rule can be applied anymore: the solution consists of applying a reduction rule to combinator **B**. We then obtain:

9- S : (**B**(**C***moḥamadu*)*āḥaḍa*) (*ā*l kita*ā*ba) N*\N* : ((**B**(**B***ālaḍy fy*)*ā*l)*qismi*) (**B**)

10- S/N* : (**B**(**C***moḥamadu*)*āḥaḍa*) N* : (*ā*l kita*ā*ba) N*\N* : ((**B**(**B***ālaḍy fy*)*ā*l)*qismi*) (**>Dec**)

11- S/N* : (**B**(**C***moḥamadu*)*āḥaḍa*) N* : (((**B**(**B***ālaḍy fy*)*ā*l)*qismi*) (*ā*l kita*ā*ba)) (**<**)

12- S : (**B**(**C***moḥamadu*)*āḥaḍa*) (((**B**(**B***ālaḍy fy*)*ā*l)*qismi*) (*ā*l kita*ā*ba)) (**>**)

The sentence is syntactically well-formed, since it is of type S, so we move on to the reduction phase:

13- S : (**C***moḥamadu*) (*āḥaḍa* (((**B**(**B***ālaḍy fy*)*ā*l)*qismi*) (*ā*l kita*ā*ba))) (**B**)

14- S : (*āḥaḍa* (((**B**(**B***ālaḍy fy*)*ā*l)*qismi*) (*ā*l kita*ā*ba))) *moḥamadu* (**C***)

15- S : (*āḥaḍa* (((**B***ālaḍy fy*) (*ā*l *qismi*)) (*ā*l kita*ā*ba))) *moḥamadu* (**B**)

16- S : (*āḥaḍa* ((*ālaḍy* (*fy* (*ā*l *qismi*))) (*ā*l kita*ā*ba))) *moḥamadu* (**B**)

Case 7: The relative pronoun plays the role of a complement introduced by a preposition:

(7) *marra moḥamadu bi ālaḍy* nasaḥa *hu* /aliyun

1- S/N*:*marra* N*: *moḥamadu* ((S/N*)\(S/N*))/N*:*bi* N*/S:*ālaḍy* (S/N*)/N*: nasaḥa (S/N*)\((S/N*)/N*):*hu* N*:/aliyun

2- S/N*:*marra* S\(S/N*): (**C***moḥamadu*) ((S/N*)\(S/N*))/N*: *bi* N*/S: *ālaḍy* (S/N*)/N*: nasaḥa (S/N*)\((S/N*)/N*): *hu* N*:/aliyun (**<T**)

3- S: (**C***moḥamadu*) *marra* ((S/N*)\(S/N*))/N*: *bi* N*/S: *ālaḍy* (S/N*)/N*: nasaḥa (S/N*)\((S/N*)/N*): *hu* N*:/aliyun (**<**)

4- S: (**C***moḥamadu*) *marra* ((S/N*)\(S/N*))/S: (**B***bi ālaḍy*) (S/N*)/N*: nasaḥa (S/N*)\((S/N*)/N*): *hu* N*:/aliyun (**>B**)

5- S: (**C***moḥamadu*) *marra* ((S/N*)\(S/N*))/S: (**B***bi ālaḍy*) S/N*: (*hu* nasaḥa) N*:/aliyun (**<**)

6- S: (**C***moḥamadu*) *marra* ((S/N*)\(S/N*))/N*: (((**B***bi ālaḍy*) (*hu* nasaḥa)) N*:/aliyun) (**>B**)

7- S/(S/N*): (**C***moḥamadu*) S/N*:*marra* (S/N*)\(S/N*): (((**B***bi ālaḍy*) (*hu* nasaḥa)) /aliyun) (**>Dec**)

8- S/(S/N*): (**C***moḥamadu*) S/N*: ((((**B***bi ālaḍy*) (*hu* nasaḥa)) /aliyun) *marra*) (**<**)

9- S: (**C***moḥamadu*) ((((**B***bi ālaḍy*) (*hu* nasaḥa)) /aliyun) *marra*) (**>**)

The sentence is syntactically well-formed, since it is of type S. We move on to the reduction phase:

10- S: ((((**B***bi ālaḍy*) (*hu* nasaḥa)) /aliyun) *marra*) *moḥamadu* (**C***)

11- S: (((*bi* (*ālaḍy* (*hu* nasaḥa))) /aliyun) *marra*) *moḥamadu* (**B**)

Le système obtenu est un système applicatif de type opérateur/opérande, où ((*bi* (*ālaḍy* (*hu* nasaḥa))) /aliyun) (((*by* (*whom* (*him* advised))) Ali)) est un opérateur appliqué à l'opérande *marra(passed*) qui est un verbe.

Case 8: the relative pronoun functions as a noun and the relative proposition is a verbal phrase:

(8) *ālady* na*ǧ*a*ḥ*a *ḍakiyun*

In this example, the relative proposition *naǧaḥa* (*he succeeds*) contains an implicit (hidden) subject which will be represented by (*A*) and removed at the end after reduction; this invisible agent has the syntactic type N* :

1- N*/S: *ālady* S/N* : na*ǧ*a*ḥ*a N*: *A* N*\N*: *ḍakiyun*

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2- N*/N*: (**B***ālady* naǧaḥa) N*: *A* N*\N*: *ḏakiyun* (>**B**)

3- N*: ((**B***ālady* naǧaḥa)*A*) N*\N*: *ḏakiyun* (>)

4- N*: *ḏakiyun* ((**B***ālady* naǧaḥa)*A*) (<)

The sentence is syntactically well-formed, since it is of type N*. We move on to the reduction phase:

5- N*: *ḏakiyun* (*ālady* (naǧaḥa *A*)) (**B**)

By removing (*A*: wichis the invisible agent), we obtain the application form: *ḏakiyun*(*ālady* (naǧaḥa)) (*intelligent(who (he succeeded*))

Case 9: the relative pronoun functions as a noun and the relative proposition is a prepositional phrase: (9) *maā /inda moḥamdin ṯamynun*

1- N*/(N*\N*) :*maā* (N*\N*)/N* :*/inda* N* : *moḥamdin* N*\N* :*ṯamynun*

2- N*/N* : (**B** *maā /inda*) N* : *moḥamdin* N*\N* :*ṯamynun* (>**B**)

3- N* : ((**B** *maā /inda*) *moḥamdin*) N*\N* :*ṯamynun* (>)

4- N* : *ṯamynun* ((**B** *maā /inda*) *moḥamdin*) (<)

The sentence is syntactically well-formed, since it is of type S. We move on to the reduction phase:

5- N* : *ṯamynun* (*maā* (*/inda moḥamdin*)) (**B**)

The relative pronoun *maā*(*what*), is an operator applied to the operand of the prepositional group */inda moḥamdin*(*Mohamed has*) to obtain the result (*maā* (*/inda moḥamdin*)) (*What* (*Mohamed has*)). The predicate *ṯamynun* (*precious*) acts as an operator applied to the operand (*maā* (*/inda moḥamdin*)) (*What* (*Mohamed has*)) to form the applicative expression: *ṯamynun* (*maā* (*/inda moḥamdin*))(*precious* (*What* (*Mohamed has*))).

4. CONCLUSION

Despite the numerous studies and searches devoted to sentence structure analysis, arabic remains relatively less studied than other languages within the frameworks of categorical grammars and combinatorial logic. Among the works employing the ACCG model, we may cite, for example: [30], [21], [20], [31], [32], [33], [34] and [35].

Syntactic analysis is carried out in two phases, the first phase involves the application of simplification rules (type change, composition, and left and right simplification), and the second phase consists in applying reduction rules for the combinators C* and B.

However, a difficulty arises with certain subordinate clauses (see cases 5 and 6), where, after the application of some simplification rules in the first phase, no further simplification rule can be applied. To address this issue, a reduction rule associated with combinator B is applied. This allows the simplification process to continue until completion, thereby enabling the transition to the second phase.

For subordination, both constructions (before and after the relative pronoun) are based on the principle that two linguistic expressions are linked by an operator (relative pronoun). Indeed, relative pronouns function as operators that apply to linguistic units in order to construct more complex linguistic structures. Ultimately, this leads to an applicative system based on the ACCG model, which can be applied to both simple and complex sentences.

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