Cognitive Elements in Forming and Understanding Sentences

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Abstract

A new approach to resolving ellipses in geometric texts is described. This approach covers: constructing cognitive schemes of geometric configurations, formulating the rules of converting the complete sentences to their elliptical variants, and the reverse transformations. The cognitive schemes are understood as the syntactic synonyms of sentences describing planimetric configurations. They are represented by the drawing and NL-texts generated on the principle of combining the noun, verb, and prepositional phrases corresponding with both fragments of schemes and expressions in real geometric texts. The possible equivalent transformations of sentences are also considered. More generally, we may consider creating the cognitive schemes and their descriptions as modeling the processes of generating the texts of planimetric tasks. This approach is evolving in an automated system of solving school geometry tasks.

Keywords

Cognitive approach, resolving ellipses, planimetry, cognitive scheme, sentence transformation, generative grammar, natural language processing

1. Introduction

An integrated intelligent system to solve natural language planimetric tasks is considered. The destiny of the system is to serve for training schoolchildren in the domain of Euclidean geometry. The cognitive approach proposed can be a first step to automated analyzing plane geometry texts and, in perspective, to a cognitively controlled parsing. The system embodies some intellectual characters: it contains and uses the problem domain knowledge (plane geometry), it has a natural language interface, linguistic translator, solver, and graphical module for displaying and explaining the results. The solver of the system works based on heuristic search for solution [1]. Visualization in this system is aimed at showing as much as possible all the stages of the system's functioning and giving in the "point and click" manner explanations about the content and genesis of any element of the drawing. Drawing the conditions of geometrical tasks is a key problem in the system (for students too).

The difficulty in analyzing and understanding the text is induced by various reasons. Some difficulties are caused, first, by a vague text language that is not logically and linguistically clear. Secondly, these difficulties are induced by the necessity to attract general geometric knowledge related to objects and relationships in the texts of tasks. Thirdly, some difficulties are explained by the need to choose from several building options, or to formulate additional considerations (conditions) for drawing. The latter circumstance requires the involvement, in the process of drawing, various assumptions and logical conclusions. The idea of involving cognitive graphics and relations pre-formed in the system to overcome the above difficulties has been advanced in [2, 3]. Another difficulty is the ellipticity of the texts. This paper is concerned with the possibilities of applying a cognitive approach to resolving ellipses in the plane geometry texts.

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2. Classification of ellipses in plane geometry tasks

To study the typology of ellipses, we used a body of texts containing more than 1000 planimetric tasks from various handbooks and sources.

The following types of ellipses are revealed [3]: ellipses with dash "–" Type 1.A: ellipses with skipped predicate and Type 1.B: ellipses with skipped verb; ellipses without "–" Type 2: ellipses with skipped verb, noun, pronoun, or predicate. In general, most sentences contain several types of ellipses or/and a number of ellipses of the same type. In what follows, we shall consider ellipses only of Type 1.A and Type 1.B. Consider the selected types of ellipses in terms of their properties and structure. The texts of tasks are given fragmentary and their translation in English has only illustrative character (in the real translation into English texts, the dash can be absent).

The examples of ellipses of Type 1.A.:

В треугольнике ABC даны R и r – радиусы описанной и вписанной окружностей. A_1, B_1, C_1 – точки пересечения биссектрис треугольника ABC с описанной окружностью. In triangle ABC there are given R and r – the radii of the circumscribed and inscribed circles. A_1, B_1, C_1 – the intersection points of the bisectors of triangle ABC with the circumscribed circle.

Основания перпендикуляров, опущенных из B и D на AC – M и N. The bases of perpendiculars dropped from B and D to AC – M and N.

Доказать, что середины сторон треугольника, основания высот и середины отрезков высот от вершин до точки их пересечения лежат на одной окружности – «окружности девяти точек» (*задача Эйлера*). Prove that the midpoints of arbitrary triangle's sides, the grounds of three heights and the middles of the three segments connecting the orthocenter with the vertices of the triangle all lie on the same circle – "the circle of nine points" (Euler's task).

Дан треугольник ABC, D – произвольная точка плоскости. A triangle ABC is given, D – an arbitrary plane point.

Докажите, что: а) всякая трапеция, вписанная в окружность, равнобедренная; б) *всякий параллелограмм, вписанный в окружность, – прямоугольник*; в) *всякий ромб, вписанный в окружность, – квадрат*. Prove that: (a) every trapezium, inscribed in a circle, is isosceles; b) every parallelogram inscribed in a circle – a rectangle; c) every rhombus inscribed in a circle – a square.

Среди точек данной прямой L найти такую, что сумма расстояний от неё до двух данных точек A, B – минимальная; Among the points of a given straight line L, to find such a point that the sum of distances from it to two given points A, B – minimal.

Structural components of these ellipses are Noun Phrase (NP) and Prepositional Phrase (PP). Revealing the NPs and PPs, for example, is realized in the system OntoIntegrator [4] in the project on creating World Digital Mathematical Library – WDML.

Consider this type of ellipses in detail:

a) < NP > < – > < Designation(s); b) < Designation(s) > < –> < NP >; c) < NP > < – > < NP >; d) <NP> < – > <PP> (Center of circle – inside a quadrangle; C – between A and F); e) < NP > < – > <a property expressed by adjective>.

If NP begins with a noun in nominative case of singular or plural number, then we can use more simple forms of a) and b): a*) designation(s) – object(s); б*) object(s) – designation(s).

The cases c) and d) in plane geometry tasks are relatively rare (at least in the task corps we are considering). Let's call the type T1.A "the denotational type of ellipses", understanding the term "denotation" in an extensional sense (including the propositional function). In cases a), a*), b), b*, c, d the sign « – » can be replaced by one of the forms of verb "to be": IS or ARE. In case e), the dash can be replaced by the forms of verb "to be" or eliminated.

The type 1.B is known as the verb phrase ellipsis (the VPE). This type of ellipses is also divided into subclasses: with only one dash (Class 1) and with several dashes replacing the same verb (Class 2).

Examples of the ellipses of Class 1:

Дана окружность и точки P и Q внутри неё. Построить вписанный в эту окружность прямоугольный треугольник, у которого один катет проходит через точку P, а другой – через точку Q. There are given a circle and two points P and Q inside it. Build a right triangle inscribed in this circle so that one leg of it passes through point P and the other – through point Q.

One of the methods for resolving ellipses of Class 1 in the texts of planimetric tasks has been described in [3]. But the approach considered in this work does not cope with ellipses of Class 2.

Example of ellipses of Class 2:

Внутри квадрата $A_1A_2A_3A_4$ *взята точка P. Из вершины* A_1 *проведена прямая, перпендикулярная к прямой* A_2P*, из вершины* A_2 *– к прямой* A_3P*, из вершины* A_3 *– к прямой* A_4P *и из вершины* A_4 *– к прямой* A_1P; Inside a square $A_1A_2A_3A_4$ a point P is taken. From vertex A_1, it is drawn a line perpendicular to line A_2P, from vertex A_2 – to line A_3P, from vertex A_3 – to line A_4P, and from vertex A_4 – to line A_1P.

Despite the fact that the problems of resolving ellipses are widely discussed theoretically, most of works only address to a special type of ellipses, namely the VPE, and more often for English language [5, 6, 7, 8, 9]. In English, the VPE is usually associated with an auxiliary verb without a verb phrase. The structure of the VPE consists of two parts standing in a sentence on the right and left of the "dash". An example: "one had the power of the Sun, the other – the Moon". To resolve the multiple VPE ellipses, a new method is advanced in [10]. An example of multiple ellipsis is: "the prices growth amounted to 11.9% in 2003, in 2009 – 4.4 %, in 2014 – 7.5%.

It should be noted that the question of how to restore the complete structure of elliptical part of a sentence has not been fully solved in the conventional approach based on syntactical-semantic parsing sentences. Linguists have already realized the restriction of this approach to resolving ellipses in which syntax is separated from semantics [11]. In [12], a key problem of cognitive view on resolving ellipses is stated: understanding ellipsis does not mean that we first have to restore it, and then to turn to understanding the whole sentence. In fact, understanding the sentence also entails understanding the ellipsis in it.

3. Cognitive approach to resolving ellipses

Our cognitive approach to resolving ellipses rests on the following assumptions:

- Cognitive models of geometric configurations are seen as syntactic-synonymous mappings of sentences;
- Cognitive processes of designing and understanding sentences are interconnected with one another;
- Understanding sentences is based on knowing how sentences are formed (generated);
- Sentences of Class 1 and Class 2 imply the same processes of generation.

Studying elliptical sentences, we assume some hypotheses about cognitive operations produced mentally when generating elliptical sentences:

- **Hypothesis 1**: Repeated actions are described within the same sentence.
- **Hypothesis 2**: The complete sentence describes some cognitive (imaginable) geometric situation.
- **Hypothesis 3**: The complete sentence is mentally transformed into an incomplete (elliptical) one.
- **Hypothesis 4**: The transformation mentioned above is based on some cognitive operations performed mentally by a certain algorithm in the process of generating incomplete sentence.

We need now to introduce the concept of context for words in texts. We mean the term "context of a word" not as "accessibility" or "dedication" [13], but as a zone of action of the word, that is, a fragment of the text in which we are talking about some object or action already mentioned, or/and the situation expressed by this word. The inclusion relationship is realized between the contexts of words.

We are now equipped to formulate some cognitive Rules 1-5 of transforming a complete sentence into an elliptical one:

1. If the designation of an object is introduced in a sentence, then further in this sentence it can be used only this designation without the name of object;
2. If the designation of a figure is introduced in a sentence, then further in this sentence it can be used this designation without mention of the name of the figure (in the scope of this figure's context);
3. If an action over (with) several objects is meant, then after the description of this action over (with) the first object in a sentence, further this action over (with) other objects can be described without copying the name of this action (the verb is skipped);

4. An object can be expressed by its Noun Phrase, it implies the permission of missing (skipping) in a sentence the common (repeated) fragment of the Noun Phrases when describing similar objects;
5. A verb can enter its Verb Phrase, it implies that if one and the same repeated action is described many times in a sentence and it has several repeated arguments, then these arguments (or their fragments) can be skipped.

Let's take a look at how these rules work in the tasks.

Task 1. *A trapezium ABCD with the base AD is given. The bisectors of external angles at vertices A and B intersect in point P, and at vertices C and D – in point Q.*

In the second sentence, the part of the NP "the bisectors of external angles" and the verb "intersect" are omitted; Rule 4 and 3 were applied.

Task 2. *In a right triangle ABC, the height CK is drawn from the vertex of the right-angle C and in the triangle ACK – the bisector CE.*

In this sentence, the verb with a part of its phrase is skipped by Rule 5. The context of triangle ABC includes the contexts of "height" and "the right-angle C", and the context of "triangle ACK". The context of "triangle ACK" includes the context of "bisector CE" and "the vertex of right-angle C". The context of action "is drawn" covers the entire sentence.

Task 3. *Denote the bases of perpendiculars dropped from point A to the given lines by M and N, but the bases of perpendiculars dropped from point B – by K and L.*

Action "to drop perpendicular" has two arguments: "from a point" and "to a line". When the perpendicular is dropped from the second point B, the argument "to the given lines" is implied being the same and, by this reason, it is skipped by Rule 5.

4. Resolving ellipses of Class 1 and Class 2 based on syntactic-cognitive approach

The cognitive rules of transforming complete sentences into elliptical ones formulated above can be used in an inverse process to restore elliptical sentences. In this process, the following steps are required: revealing the structure of word's contexts; revealing all the complete phrases (NPs, VPs, PPs) and incomplete ones; revealing, in complete phrases, the candidates to be inserted in the elliptical parts of phrases using the reversed variants of Rules 1-5; inserting the candidates found in the previous step into incomplete phrases and constructing the syntactical tree with the links between phrases.

For example, Rule 5 reversed is:

"If, after the complete description of an action, the verb with some arguments is omitted in the subsequent descriptions, then you can assume that the missing part is a copy of the corresponding text from the complete previous description of the action".

As an instance, consider a task from the Polish mathematical Olympiads:

"*В окружность вписан четырехугольник ABCD, прямые AB и CD пересекаются в точке E, прямые AD и BC – в точке F.* Quadrangle ABCD is inscribed in a circle, straight lines AB and CD intersect in point E, straight lines AD and BC – in point F.

The context of the word "quadrangle" embraces the whole sentence; straight lines AB, CD, AD, and BC are included in the context of "quadrangle" (both its sides and segments lying on their extensions); the context of the verb "intersect" is the sub-context of the "quadrangle" and embraces lines AB, CD, AD, and BC. The verb "intersect" contains two PPs as its arguments: "in point E" and "in point F". Since we have the context of only one verb, it is possible to assume that the expression "in point F" is the second argument (indirect object) of this verb.

The context of the word is a more complex concept than the concept of projection in the generative grammar, in which phrases are often referred to as projections [14, page 162]. The word "projection" is used in the generative grammar with the meaning of "spreading." Within one sentence, we shall assume that the "context of a word" is "all the phrases functionally related to this word", in particular cases, it coincides with the meaning of projection. But the context has two aspects – grammatical and semantic (geometric, in this case). The verb "intersect" geometrically implies that there is an intersection point of lines. The structure of the sentence can be presented as follows (Figure 1).

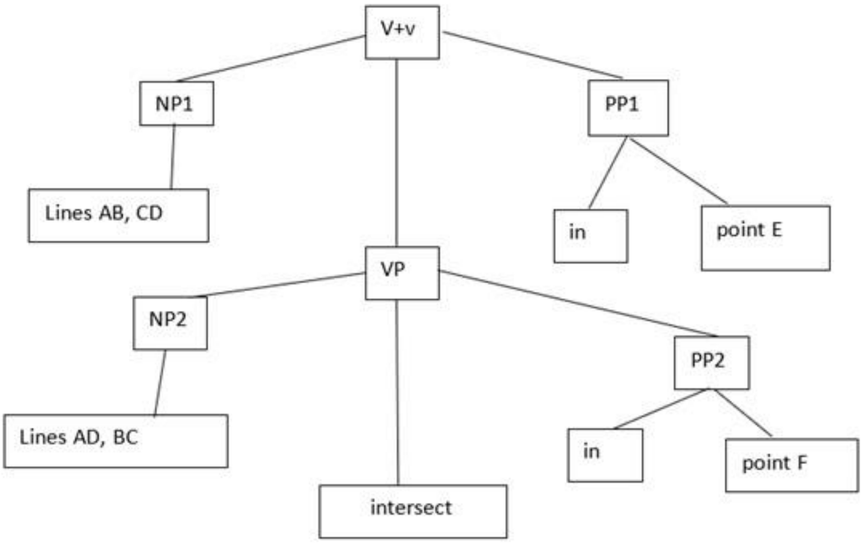

Figure 1: The structure of the sentence

A few words about the syntax scheme: it is formed in the spirit of the minimalism of the generative grammar. When building a bottom-up tree, we can add not only new elements, but also add repeatedly (reconnect) existing ones. Nothing in the generative grammar excludes this possibility and it is not only possible, but also necessary to use [14, p. 134].

There are no templates for building phrases, and the phrase's specificator can be empty [14, p.136]. When there are several copies of a single item (element) in the syntax tree, the lowest one is believed to be the first to join. This is commonly referred to as **an external connection,** and all subsequent connections – as **internal connections**. V + v shows that the verb has been copied [14, p.136-137].

Revealing phrases as a fundamental step of reconstruction ellipses is based on our confidence that they underlie the cognitive processes of sentences' generating in human mind.

It seems reasonable to assume that this approach is also true not only in geometry.

Class 2's ellipses are resolved likewise Class 1's ellipses.

The verb in this case has several repetitive similar arguments, as in the task: *inside a square $A_1A_2A_3A_4$, a point P is taken. From vertex A_1 it is drawn the line perpendicular to line A_2P, from vertex A_2 – to line A_3P, from vertex A_3 – to line A_4P, and from vertex A_4 – to line A_1P.*

5. The role of cognitive schemes in understanding texts of plane geometry sentences

The process of binding objects extracted from the tasks' texts is supported by creating cognitive models of objects and relationships between them. Therefore, the cognitive schemes will combine three components: semantic component in the form of specific relationships between objects (typical geometric situations); syntactical component associated with the semantic component, on the one hand, and with the corresponding natural language description, on the other hand; visual component in the form of image of the corresponding geometric situation. All the graphic representations of cognitive structures are supported by interactive visualization [15].

We also assume that the cognitive schemes correspond to the profound structures of geometrical situations outlined in the tasks' texts and define the structures of the noun phrases (NPs), prepositional phrases (PPs), and verb phrases (VPs) in the description of these situations. The cognitive approach deals with modeling processes occurring in human brain during generating sentences to describe geometric structures to be analyzed. To compare the generated cognitive scheme descriptions with the analyzed input task's texts we need to perform their equivalent transformation (among them, converting to elliptical forms). Analyzing the text of a task will be considered successful if this text coincides with a converted description of the cognitive scheme.

5.1. Equivalent transformations of cognitive model descriptions

We now give some examples of equivalent transforming the NPs and VPs of the word “bisector”. The examples of the bisector’s NP are: bisector of an angle; bisector of a given angle; bisector of angle A in triangle ABC; bisector of inner angle of a triangle; bisector of acute angle in a rectangular triangle; bisectors AK and BL of triangle ABC; bisectors of angles A and B of a convex quadrangle ABCD; bisectors of angles at the base of isosceles triangle; bisectors of angles adjacent to one side of parallelogram; the continuation of bisector of a triangle; bisector coming from a vertex of inscribed triangle; in triangle ABC, bisector of angle A; in a parallelogram, bisectors of its four inner angles.
Most often we have the following common scheme consisting of the nested NPs of angle from which a bisector is drawn and a geometric figure to which the angle belongs: (NP_{bis}: bisector (NP_{angle}: angle (NP_{fig}: geometric figure))).

In some cases, the NP of a figure is transformed into prepositional phrase and precedes the NP of bisector. Such information structure of sentence tells us that the expressions “in triangle ABC” or “in parallelogram” represent the theme (topic) of the sentence [13], i.e., the whole sentence is associated with a certain figure – triangle or parallelogram. In our understanding, this structure gives the context of sentence. With the point of view of generative grammar, this means the possibility to move or to copy these expressions inside the sentences and to insert them in the NPs of various elements of triangle or parallelogram without breaking (disturbing) the sentence’s content. Thus, the fragment “in triangle ABC, bisector of angle A” can be transformed into “bisector of angle A in (of) triangle ABC”. The expression “bisectors of angles at the base of an isosceles triangle” can be transformed into several equivalent expressions: “bisectors of angles in an isosceles triangle at its base”; “bisectors of angles in an isosceles triangle at the base of this triangle”; “in an isosceles triangle, the bisectors of angles at the base”. The sentence “bisectors of angles adjacent to one side of parallelogram” can be transformed as follows: “in parallelogram, bisectors of angles adjacent to one side”. The expression “bisector coming from the vertex of angle” is equivalent to “bisector of angle” and, by this reason, “bisector coming from a vertex of inscribed triangle” can be transformed to “bisector of one angle of (in) the inscribed triangle”.

Let's now turn our attention to the consideration of the VPs with the word "bisector(s)”. There are objectively, in the cognitive field of geometry, some generalized patterns of action (and the VPs) that can generate lines or be performed on them: (line) perpendicular (line); (line) is drawn from (point) to (line, point) in (figure); (line) divides (line) into (segments) in (ratio); (line) cuts (line) at (point of intersection) into (segments); (lines) intersect at (point); (point) is taken on (line); (line) lies on (line); (lines) generate/form (figure) by their intersections.

Examples of the VPs with “bisector” in planimetric tasks are: in triangle ABC**,** bisector BD of the external/internal angle B is drawn; prove that the center O of the circle inscribed in triangle ABC divides the bisector AA_1 in the ratio; point P lies on the bisector of an angle with vertex C; the continuation of the bisector of angle B of triangle ABC intersects the circumscribed circle at point M; prove that in triangle ABC bisector AE lies between median AM and height AH.

The equivalent transformation described above can be applied to NPs entering VPs (as constituents of it). For example, we have: (NP_{bis}: bisector of angle A of triangle ABC) is perpendicular (NP_{med}: median drawn from the vertex B). The expression “of triangle ABC” can be transformed into the PP “in triangle ABC” and this new expression can be removed to the beginning of the sentence: in triangle ABC, (NP_{bis}: bisector of angle A) is perpendicular (NP_{med}: median drawn from the vertex B). Since in the original sentence the context of "triangle ABC" includes the contexts of “median” and “the vertex B”, this movement does not disrupt the relationship between the contexts and the meaning of the whole sentence.

Equivalent transformations of sentences take place on the interface between semantics and syntax [13].

5.2. Sentence's analysis when constructing cognitive schemes

Consider the sentence: "the bisectors of angles A and B of convex quadrilateral ABCD intersect at point M, the bisectors of angles C and D – at point N".

Separate (one possibility would be to use the key words) the cognitive scheme of "convex quadrilateral" in the collection of cognitive schemes generated in advance. Construct a convex quadrilateral ABCD.

By the words «bisectors of angles A and B», separate the cognitive scheme "drawing of bisector of an angle" and construct bisectors of angles A and B in quadrilateral ABCD. The intersection point of bisectors occurs in the cognitive scheme and the following description has been added: «the bisectors of angles A and B intersect at point X». The analysis of sentence allows us to denote point X by M: «the bisectors of angles A and B intersect at point M».

By analogy with the above consideration, we add to the cognitive scheme the bisectors of angles C and D and the description «the bisectors of angles C and D intersect at point X». According to the rule 3 of the elliptic sentence generation, if the verb is repeated, then it can be missed in the second and subsequent analogical using it; we shall get a new converted sentence with ellipsis: «the bisectors of angles C and D – at point X». Comparing this fragment with the corresponding fragment in the original sentence allows us to denote point X by N.

Consider the following sentence: Three squares are inscribed into triangle ABC: one square has two vertices lying on the side AC, the other – on BC, the third – on AB.

To create the cognitive scheme (Figure 2) for the whole sentence we use the cognitive schemes «triangle» and «to inscribe a square into a triangle». When creating the complete cognitive scheme, its description is generated incrementally:

"in triangle ABC, three squares are inscribed:
one\ the first square is inscribed into triangle ABC;
the second\ the other square is inscribed into triangle ABC;
the third square is inscribed into triangle ABC;
two vertices of one\ the first square lie on the side AC of triangle;
two vertices of the second\ the other square lie on the side BC of triangle;
two vertices of the third square lie on the side AB of triangle".

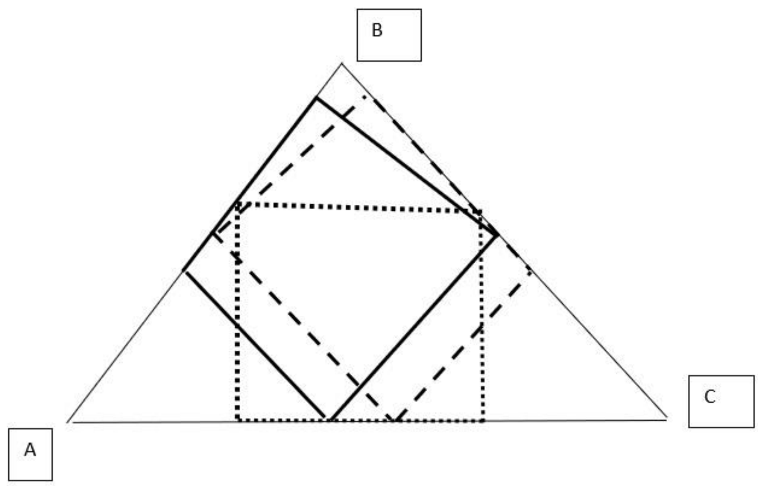

Figure 2. Cognitive scheme for three inscribed squares

The expression "vertices of the square" can be transformed into "the square has the vertices" and "lie on" – into lying on". And after applying this transformation to three previous sentences we obtain:

"one\ the first square has two vertices lying on the side AC of triangle;
the second\ the other square has two vertices lying on the side BC of triangle;

the third square has two vertices lying on the side AB of triangle".

Since the same action is performed three times, the verb "has" is missed for second and third squares and replaced by"–". It is possible to miss the words "of triangle" because the action enters the context of it and the word "square" in the second and third previous sentences. We can also miss the repeated part of the NP of "vertices" (two vertices lying on the side). Finally, the description of cognitive situation is converted as follows: "One square has two vertices lying on the side AC, the other – on BC, the third – on AB".

The omission of the word "square" is based on referential identities [16]. The omission of the words "two vertices" is associated with constructing the squares inscribed in a triangle: any inscribed square has two vertices on one side of the triangle.

Consider the sentence: "Inside a square $A_1A_2A_3A_4$, a point P is taken. From vertex A_1 it is drawn the line perpendicular to line A_2P, from vertex A_2 – to line A_3P, from vertex A_3 – to line A_4P, and from vertex A_4 – to line A_1P".

The complete text describing the cognitive scheme for this sentence will be the following: "inside a square $A_1A_2A_3A_4$, a point P is taken. From vertex A_1, it is drawn the line perpendicular to line A_2P, from vertex A_2, it is drawn the line perpendicular to line A_3P, from vertex A_3, it is drawn the line perpendicular to line A_4P, and from vertex A_4, it is drawn the line perpendicular to line A_1P".

The cognitive scheme will combine the following cognitive models: "construct a square and take an arbitrary point inside it"; "drop the perpendicular from a point to a straight line". The elliptical variant of this sentence is obtained with the use of Rule 5.

Undoubtedly, the realization of cognitive schemes is always more difficult than we have described in our schematic examples. The problems of identical transformations of sentences are thoroughly investigated in [16]. The conjunction reduction of ellipses in Russian language is also considered in [16]. But it takes more efforts to develop the cognitive approach to resolving ellipses.

6. Conclusion

A cognitive approach to the analysis of task texts in planimetry is proposed. The concept of cognitive scheme as syntactic-semantic equivalent of task's text has been introduced. It is important in our approach to associate basic cognitive schemes with the NPs, VPs, PPs that are structural elements of sentences. The rules of cognitive transformation of full sentences into elliptical ones (design of ellipses) have been formulated. Some rules for equivalent transformations of the NPs and VPs in plane geometry sentences based on geometric semantics, including the process of movement and transformation of the PPs, have been considered. The concept of the context of word is used. Examples of cognitive-driven analysis of sentences in the texts of planimetric tasks when resolving ellipses based on a cognitive approach are considered.

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