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Computational Analogy: Some Results and Perspectives*

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1. Introduction

The Greek word analogy (gr. *analogia*) means correct corelation between two or more objects as a proportionality or correspondence. The logical reasoning by analogy is one of the most efficient means in gaining new knowledge and decision making.

The investigations on analogy in the field of artificial intelligence (AI) start at the beginning of the 60-ies, when attempts have been made to solve separate problems in this way. A specific example from this period is Evans' program, computing geometric analogies [21]. Depart from the interest towards the non-deductive methods for reasoning in AI up to the end of 70-ies, no attempts have been observed to create sufficiently universal methods and applications of analogies in AI, that could lead to the development of a separate scientific branch. The surprisingly low efficiency of these investigations can be explained finding the relation between the simplicity of formulation of the problems in the domain, and the significance of the goals, for which the reasoning by analogy is applied, and the complexity of construction of the inference mechanism, necessary for problem solving. In connection with the above said, it is necessary to explain, that the program, realizing even the simplest scheme of reasoning by analogy - usually written in Polya style [13] – is comparable by its size with the programs, realizing the most complex and universal types of deductive inference. Up to the present moment no knowledge acquisition systems have been designed, nor other types of knowledge-based systems (KBS), based on the reasoning mechanism which exceed the frames of a prototype. In connection with the difficulties of the realization, it has to be also added, that a great number of additional procedures is connected with the reasoning by analogy in AI, that are at first sight apart from the analogy, but without which the mechanism functioning becomes senseless.

The reasoning by analogy is used in machine learning and educational systems, expert systems of second generation, truth maintenance systems, decision support, case-based and other reasoning systems. If the significance of the analogies is accounted in the process of checking the inconsistency of the knowledge at incomplete problem area, then

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we cannot point any KBS, the successful functioning of which will not depend on the analogies applied. The whole variety of the types of application analogy in KBS can be divided into computational analogy and analogy, solving applied psychology problems. The second group involves methods with the main purpose to model the processes of human reasoning, while the methods from the first direction serve to apply machine algorithms in the solution of the problems in AI. The analogy is set in the centre of the investigations in the modern stage of these directions development [14, 19].

For reasoning by analogy in KBS, the scheme, represented in Fig.1, or its modification, is most often used.

Object **X** possesses features **a, b, c, d, e, f**	(I)
Object **Y** possesses features **a, b, c, d**	(II)
or: Object **Y** resembles object **X** in patterns **a, b, c, d**	(II)
Hence **Y** can possess features **e** and **f** (**hypothesis**)	(III)

Fig. 1

The process of reasoning by analogy consists in the following. After certain identity is found between the two objects – **X** and **Y**, some of the properties of object **X** (**base**) can be transferred to another object, which is the **goal of transformation by analogy**, **Y**. In case such a transformation is made on the basis of formal identity between **X** and **Y** – for example the proximity between the objects in the hierarchical network or any other – the analogy is syntactic. On the other hand, we can talk about semantic analogy in the case when the knowledge transformation is based on a detail analysis and modelling the properties of the objects.

If we consider the concept used, the methods for reasoning in computational analogy can be divided into two groups. The first one uses the apparatus of formal systems [12, 17]. The close world assumption is valid in the formal methods. The second group involves the heuristic methods [15, 20], that are most frequently realized as open systems [8]. Strategies for reasoning, that are near to the human way of reasoning in similar problems are used in them. Here the questions of method soundness, completeness and other characteristics (parameters) of the method are not proved by formal means. The above classification of the methods into formal and heuristic is conditional, since in the second group the ideas of formal logics (first order Predicate Calculus) can also be applied.

The most complete data about the application of computational analogy in KBS are given in [5], and about the types of analogies from a philosophic point of view – in [18]. The present paper unlike the existing surveys on computational analogy pays particular attention to the possibility of influencing the **direction**[1] of the analogy on the process of new knowledge formation. It also discusses other aspects of reasoning by analogy functioning, the solution of which will lead to the creation of an universal mechanism and its wide application in KBS, according to the authors' opinion.

Chapter 2 describes the characteristic features of two problem-independent methods in the domain, the authors' experimental investigations, comparative analysis and conclusions about the state of computational analogy field. Chapter 3 contains considerations about the perspective research in the field, based on our previous work, and Chapter 4 – comments and conclusions.

2. The application of analogies in research KBS

Two methods below considered possess most of the advantages and shortcomings from the scope so they are chosen as a background for the comments and ideas from chapter 3; their more detail description is given in [10].

[1] The direction of the analogy shows the purpose it is applied for: for knowledge valididty check or for eliminating the connection between the two statements, or for knowledge base (KB) completement by analogy means and others.

The methods description is constructed as follows:

I. The approach to the selection of the base for the given goal of transformation.

II. Defining the link between the objects from the base and the goal of transformation, new knowledge (hypotheses) formation in cases of identity between the objects.

III. Shortcomings of the method and/or its realization. Comparison with other methods.

In connection with the method description, it is necessary to make the following comments.

1-I. The paper studies the identity between the apriori set base and the goal of transformation by means of the formal systems. On the basis of the identity found, an attempt is made to prove the statement from the goal by transformations of the knowledge in the base, and no free (unconnected) variables remain in the transformed knowledge at that. In case there is at least one free variable, the rule considered is substituted by another one from the base; if all the rules are exhausted, the statement from the goal is rejected. The reasoning is described in terms of deduction.

1-II. The authors accept in theoretic aspect, that semantic analysis of the problem area is used in the paper suggested. The classic formal systems apparatus is used in [6], where the semantic part of the reasoning by analogy is not presented.

In [6] the base is apriori defined and the processes of selection of the base for a given goal of transformation are not investigated. The factors, leading to contradictory results are not taken in mind, which decreases the validity of the hypotheses, obtained by analogy.

1-III. In [7] an approach is suggested for the formalization of the reasoning by analogy: formal definitions, formalization in terms of automatic deduction and an applied method for logical programming. Some authors call this approach syntactic [1,3]. There exist investigations on pragmatic orientation [9,11], that differ from the above described.

The analysis of the formal methods for reasoning by analogy shows, that the application of these methods in the experimental KBS is hindered by some assumptions, characteristic for the formal systems. It is assumed in them, that all the sequences of wff are known. This assumption cannot be realized at the modern stage of AI development; the formal systems are closed, while in AI open systems are more frequently used. It is necessary to point out another shortcoming, typical for the formal methods: the assumption is made in them, that no incorrectly constructed wff or rules can exist in the process of reasoning and the questions of identification and resolving the contradictions are not considered. The shortcomings, above mentioned, can be neglected in the application of some nonclassical logical approaches and/or combined use of the formal methods and heuristic reasoning in KBS, where the heuristics is used as a superstructure above the predicate calculus of first order.

The researchers in the field of computing analogy note that most often programs are designed which work for certain examples only. The situation of designing complex, but low-efficient systems will be avoided by the apriori decomposition of the problems and the development of methods, that are not dependent on the problem area. Getner's method has to be mentioned [4] in the heuristic group and its application in SME (Structure Mapping Engine) [2]. SME realizes computing analogy in several KBS (PINEAS and others); the designers of SME think, that these KBS can be successfully applied in the cases, when distant analogies have to be found, i.e. analogies between unconnected objects or in other words "distant relatives". These analogies appear often in the systems, containing two or three independent KB.

2-I. Common predicate symbols are searched in the goal of transformation. They are also looked for in the base, after which the corresponding knowledge with equal predicate symbols are selected from KB. There come other statements together with the rule selected from KB, connected with the analogical object. We have not any information about the authors' procedure of seeking relations between the statements.

2-II. The advantages of SME are the following.

a. Means from another scientific branch are used in the investigation - cognitive psychology.

b. The knowledge from the base in SME is arbitrarily selected. There exists a special mechanism, enabling the defining of the most perspective knowledge for this goal.

c. SME operation is confirmed after a great number of tests and more than 10 examples from different problem areas. Falkenhainer has proved on the basis of the experimental data, that SME is problem independent. SME is one of the most efficient realizations of the reasoning by analogy in KBS.

An example demonstrating SME functioning is considered in [10].

2-III. SME is realized in PINEAS in LISP language. In the reports of this system it is noted, that it enables the detecting of a large number of analogies and that the results from the conclusion are close to the human way of problem resolving. Nevertheless a number of technical shortcomings are found in the selection of the new relation between the base and the goal of transformation. When complex knowledge is contained in the base or in the goal of transformation, including relations between the predicates, the algorithm for problem solving becomes inefficient, the number of the alternative solutions increasing at that and SME "falls" to evaluating the connections between all the predicates. Another shortcoming of the system is mentioned in Gentner's paper. She notes, that the plans and goals play particularly important part for the reasoning by analogy, but no means are foreseen in SME for the inclusion of similar factors. Gentner proposes to attach special pre- and postprocessors to SME for this purpose in the future. According to our opinion this will lead to a decrease in the system high speed.

As a result of the analysis of the information about the existing projects, some common advantages and shortcomings are observed for all the computing analogy methods.

The ADVANTAGES of the best representatives of the group are:

1. The methods are universal, they are realized as problem-independent systems and can be applied in specialized KBS of different types: knowledge acquisition systems, machine learning systems and others.

2. The universality of the methods above shown enables their application in combination with other approaches and in this way some of their shortcomings could be compensated.

3. The ways of knowledge transfer by analogy that are discussed serve to decrease or avoid the incompleteness in the description of the problem area of KBS. That is why the design of the methods for reasoning by analogy remains one of the priority fields in knowledge engineering. The research workers in this area of AI think [16], that each KBS will contain in the future a mechanism for reasoning by analogy.

SHORTCOMINGS:

1. Most of the existing methods check the correspondence of the hypotheses to the facts from the goal of transformation, but the hypotheses inconsistency is not analyzed. For example the inconsistency of hypotheses is checked in SME, but as far as we know, there is not any universal approach for the detection and resolving of the contradictions. This analysis in SME, applied in separate examples only and the way of human detection of the contradictions, shows unsatisfactory efficiency of the approach in this direction.

2. The methods developed are realized in the form of closed systems, in which the automatic estimate of the degree of validity of the hypotheses formed (for example, in SME), does not always guarantee the correctness of the new knowledge added.

3. Usually insufficient explanations are foreseen in the mechanism of the reasoning by analogy in these KBS, for example "Why is this processed in this way", the connections and the possible interactions between the deductive procedures of reasoning and of reasoning by analogy are not considered. It is necessary to note, that after taking into account such an interaction, the knowledge acquisition possibilities are expanded.

Some of the shortcomings above discussed are avoided in our experimental investigation. The new results obtained are shown in the next chapter.

3. Our research results and perspective investigations

As a result of the analysis of the existing applications of computing analogy, some conclusions can be done for the perspectives in this area.

Three examples of reasoning by analogy in different environments, different KB in the case, will be discussed below.

In Fig. 2 KB1 is an apriori given base, containing different rules and facts, and KB2 is the same base with new knowledge, obtained in a deductive way and KB3 - obtained with the help of reasoning by analogy. We should note that KB2 does not absorb KB3, neither the inverse is valid.

Example 1. A graphic example of the analogy functioning from Fig. 2 is discussed in Fig. 3, where F_{ij} are facts and R_k - rules.

$\{F_{11}, F_{12}, F_{14}, F_{23}\} \in KB1, \{F_{21}, F_{22}\} \in KB2, F_{23} \notin KB2$

Let us assume that the analogy confirms the validity of F_{23} and R_2 corresponds to F_{13} – then R_1 is proved. The connection between deduction and analogy is traced in the example and the consideration can be complicated taking into account the fact that in the scheme for reasoning by analogy there are often included deductive blocks as those from the example in Fig. 3. Complicating the example and the scheme for reasoning by analogy, we could follow connections of the type deduction - analogy - deduction or deduction - analogy - analogy. We have to mention that the investigation requires the use of small standard programming modules, building the mechanisms for reasoning, and in a combination with these modules more complex schemes for inference can be formed.

Fig. 4 shows the functioning of analogy similar to that in Fig. 3, but the transfer is realized from another environment (possible world 2 $\rightarrow$ possible world 1). Since here knowledge is transferred from the scope KB1, which has nothing in common with KB', the procedure will be called conditionally FAR ANALOGY.

In this case care should be taken not to transfer inconsistent or unnecessary knowledge, in other words, in these experiments the role of the block rejecting the invalid hypothethes is increased.

Example 2. In order to discuss the functioning of FAR ANALOGY, we shall consider an example with knowledge similar to that from Fig. 3, introducing significance factors for each F_{ij} from the rule body (Fig. 5), these factors K_{ij} characterizing the importance of the corresponding F_{ij} for the rule R_k. In the examplee K_{ij} =1, $K_{ij} \in [0, 1]$. Let us assume that the facts for belonging are the same as those from example 1 and $K_{23} = 0$. Then unlike example 1, in possible world 2 there is no necessity of using the analogy for proving R_1, and the rules R_1 and R_2 can be transferred to possible world 1 satisfying all the necessary correctness conditions. The example gives no idea about the different forms of FAR ANALOGY, the purpose here being another - to show the connection between different in character analogies in similar examples.

Example 3. Fig. 6 shows the same example from Fig. 5, the corresponding significance factors K_{ij} not marked on the graph. A new procedure is added in comparison with Fig. 5 - F', which is connected with F_{13} and can modify its factor K_{13} or K_{23} to a fact being investigated. Let us assume that using F' we can decrease K_{13} to near to zero value (I) or $K_{23} = 0$ (II). In this case R1 is proved by deductive means, since not altering the validity of F_{13} or F_{23}, its role in the proof of R1 falls to near to zero value; in other words this fact becomes insignificant, its significance becomes zero, while the significance of F_{21} and F_{23} increases correspondingly. When in F' reasoning by analogy is used, the procedure is called a defeasible analogy. In order to change the corresponding K_{ij} in F' the same analogies from example 1 or 2 can be used. It is not difficult to reach an opposite type of analogy F" in our experiments, contrary to the defeasible analogy when possibilities are searched not for the decrease but for the maximal increase of K_{ij}. Applying F" to F_{11}, F_{12}, F_{14} from example 3 and F' to F_{13}, we can obtain better results, both processes running parallel in time in order to give a better basis for comparison at each moment of the investigation process.

It is necessary to note that in their essence all the analogies above considered can be based on one main pocedure and the character of the concrete analogy is defined by a comparatively small "meta-procedure" (Fig. 7). For example, we have traced the behaviour of the analogies from Fig. 2-6, using a scheme from Fig. 1. According to us the relation between the roles in the deductive inference is the greatest for the first analogy (Fig. 2, 3), and unexpectedly high validity of the information is obtained for the one represented in Fig. 6.

The problem-independent KBS, in which all the procedures (reasoning by analogy, deductive reasoning, knowledge inconsistency test, interface, other procedures can also be added), are independent and can interfere, have promising future. Investigations of a prototype of a similar system have been realized at the Institute of Information Technologies, its functioning being connected with the following specifics:

* The analogies have been applied for solving problems, in which the validity estimates of the statements from the problem formulation are investigated. For example "the person tested is ill of angina" or "the reason for the failure in the operation of a cutting instrument is its bad completing", or statements from other domains. The experiments for checking the statements validity, using analogies, show that in the solution of a similar type new results are obtained not only when the problem formulation is investigated, but at any other statement, connected with the given formulation G. Let us assume, that problem G is solved after applying the deduction and a set of statements is formed, connected with G: S_1, S_2, ..., S_n. Then the use of analogies expands the knowledge connected with the formulation of the problem and it can change the validity of any S_i and as a result - G. Some data have been obtained in the experiments, when the validity of G is altered not changing any of S_i and not changing the inference tree. In this case with the help of additional information, obtained by analogy, it can be proved, that the relevance of some of the S_i for the solution of the problem set falls to zero (the connection of S_i with G is defeated when the additional information is considered, while the validity of S_i is not altered, but the corresponding branch of the inference tree is pruned. The appearing changes in the

inference tree after suspending one or several S_i can finally lead to the alteration in the validity of G, because the set of statements, connected with G decreases at each elimination cycle and the total weight of the statements, confirming or rejecting G, could be altered.

* Different functioning (**direction**) goals of the analogies have been investigated: the analogy of elimination the relevance of the statements (defeasible analogy); the analogy of new knowledge gaining, the purpose of which is the completing of the KB; analogy of detecting the identity between objects from the problem domain and of taking decisions after accounting the new knowledge; analogy for "rejecting conclusion" with the purpose to reject G, forming new knowledge, which confirms "not G", where "not G" and G are mutually excluded. The problems of modelling the statements in different problems domains have been solved during the experiments. The solution of problems of another type can be principally realized without considerable alterations in the scheme for conclusion and the control superstructure, which serves for alterations in the analogies **direction**. In this aspect there will be done new research in KBS. In all the cases the scheme for conclusion, similar to the one on Fig. 1, has been applied.

* The combinations of the interactions of the type deduction-analogy-deduction, deduction-induction-analogy have been investigated and also the "isolated" application of the analogy in KBS. The most unexpected results for the expert have been obtained during the interaction of the deductive and nondeductive inference mechanisms. When solving the problems of modelling the statements the formation of set $\{S_i\}$ is admitted directly by the expert or the designer of KB. In certain cases, for example, the knowledge inconsistency test, it is necessary to apply automatic deduction inside the conclusion by analogy. For this purpose deductive conclusion with fuzzy logic elements has been used.

* Different forms of knowledge representation are investigated in connection with the functioning of the analogy inference mechanism. Exclusions of the rules play an important part in the defeasible analogy (direction of first type), in the second and third type of direction this is the knowledge representation in the hierarchical network, and in the fourth type - knowledge about statements classification (**classifiers**) and models of the objects and situations. The heuristic modelling of the problem domain is the base, on which the inconsitency test procedure is built.

* In theoretic aspect the development of perspective projects is expected in computational analogy area, that are famous from the research of the deductive direction: inheriting the properties in the hierarchical network, nonmonotonic inference schemes, default reasoning, solving problems with the elements of selftraining and other questions. The solution of these problems is considerably complicated and/or altered in reasoning by analogy.

* Promising applications of the computational analogy methods in KBS are expected, with different independent procedures for knowledge processing realized, including several types of reasoning by analogy. It is necessary to select the forms of knowledge representation in such a way, that the different independent procedures interact. A possibility is needed in the expert systems for the inference of the expert on the processes of solving the problem, forming the interactions between the different procedures in the control block (problem solver). The investigations in this direction have shown the necessity of creating a special block in the system - "Trainer", in which all the procedures should be described accompaning their mnemoscheme and different modes of operation simulated together with additional explains to the user. When an unqualified user (not an expert) operates with this system, there is a possibility to form the solver by default. The comments from the last two points are not directly connected with the mechanism of reasoning by analogy and they are not interesting in a theoretical sense for the computational analogy, but from a practical point of view these questions appear inevitably in any real KBS.

* The experiments with different applied analogies show, that there is great difference between the experimental and really functioning KBS with reasoning by analogy. The

computational analogy has its specific features, that can be explained with the following symbolic example. Let us think what the difference between a laser and a projector is? We can consider a projector, that is much more powerful than the laser, but it cannot replace the laser anyway. In a similar way, the experimental system of reasoning by analogy, that enlightens a given area, is used to get new results in theoretic aspect and to confirm those obtained up to now. In this sense, as the great number of projectors cannot replace the laser, so the large number of analogy methods cannot enligten the area investigated so well as a coordination program by different specialists in the scope. In order to pass the bound "system-prototype", it is necessary to combine the attempts in the research of different analogies for solving various types of problems in KBS and to adjust separate standards at that, which enable the combining of all the experimental results from computational analogy, obtained up to the present moment.

*Good practical results can be achieved in the future, if some common standards are developed and the attempts of large groups of specialists of different schools and regions are combined.

4. Conclusion

Some general considerations are suggested in the paper concerning the state and perspectives of computational analogy development, on the basis of the available information from the references and the investigations done. Attention has been paid to some surveys and to problems, that are still not solved or not clarified enough, one of them being the connection between analogy and other methods of reasoning, the necessary environment for the efficient functioning of KBS and others.

The possibility to get different results, using one and the same inference scheme and different superstructures, which change the analogies direction, is discussed.

The conclusion is made, that the coordinated attempts of different teams of specialists are necessary for the design of a sufficiently universal and problem-independent mechanism for reasoning by analogy in the **industrial**, not only experimental KBS.

The application of the computational analogies opens new perspectives and it can lead to new results in all the fields of AI.

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Некоторые результаты и переспективы в вычислительной аналогии

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(Р е з ю м е)

В статье рассмотрены проблемы, присущие как формальным, так и эвристическим методам вычислительной аналогии. Особое внимание уделено вопросам, которые недостаточно исследованы, например взаимосвязи между выводом по аналогии и другими методами, взаимодействующими с ним. Изучение данной взаимосвязи привело к получению следующих результатов. Изменяя конфигурацию "окружения" аналогии, можно формировать аналогии различной направленности причем используется одна и та же схема вывода по аналогии. В практическом плане сделан вывод что необходима координация усилий специалистов, работающих в данной области, для создания достаточно универсальных промышленных систем с механизмом вывода по аналогии.