25 YEARS DEVELOPMENT OF KNOWLEDGE GRAPH THEORY: THE RESULTS AND THE CHALLENGE

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Abstract. *The project on knowledge graph theory was begun in 1982. At the initial stage, the goal was to use graphs to represent knowledge in the form of an expert system. By the end of the 80's expert systems in medical and social science were developed successfully using knowledge graph theory. In the following stage, the goal of the project was broadened to represent natural language by knowledge graphs. Since then, this theory can be considered as one of the methods to deal with natural language processing. At the present time knowledge graph representation has been proven to be a method that is language independent. The theory can be applied to represent almost any characteristic feature in various languages.*

The objective of the paper is to summarize the results of the 25 years of development of knowledge graph theory and to point out some challenges to be dealt with in the next stage of the development of the theory. The paper will give some highlight on the difference between this theory and other theories like that of conceptual graphs which have been developed and presented by Sowa in 1984 and other theories like that of formal concept analysis by Wille or semantic networks.

Keywords: knowledge graph, expert system, natural language processing, conceptual graph.

1. 1982 – 1990 : The Knowledge Integration and Structuring System

Knowledge graph theory was initiated by C. Hoede, a discrete mathematician at the University of Twente and F.N. Stokman, a mathematical sociologist at the University of Groningen, both in the Netherlands. The initial idea was to use graphs, a discrete mathematical concept for which we refer to any text book on graphs, e.g. Bondy and Murty [1], as a representation of the contents of medical and sociological texts. Cumulation of the knowledge in such texts was to be carried out by constructing larger and larger graphs in such a way that the resulting structure could function as an expert system, automated search for causes, respectively as a decision support system, automated calculation of consequences. This put the focus on causal relationships. To extract these from English texts indicators like "causes" or "by" are searched for. This was investigated in particular by de Vries [2], one of the first three PhD-students in a project, proposed by Hoede and Stokman and funded by ZWO, the Dutch organization for support of pure scientific research. The other two PhD-students were Bakker [3] and Smit [4].

Choosing only one type of relationship between concepts meant that most of an analysed text was discarded. It was therefore decided to consider also a "PART OF" – relationship and a

"KIND OF" –relationship, with corresponding linguistic indicators. The latter type on one hand introduced a similarity aspect and on the other hand a kind of "IS A" – relationship, a hotly debated type of relationship, see e.g. Brachman [5].

Having made this restrictive choice, one of the participators, de Vries Robbé, a physician, started a project for himself, that led to a large project MEDES [6], *MED*ical *E*xpert *S*ystem. That system knows almost 20 types of relationships. The reason is obvious. In analyzing a medical paper one encounters various types of relationships and the chosen solution is simply to extend the set of types, indefinitely if necessary. That attitude is also the reason why semantic networks know so many types of relationships. We will see later how this problem is dealt with in knowledge graph theory.

The essential result of Bakker's thesis is the outline of KISS, the *K*nowledge *I*ntegration and *S*tructuring *S*ystem, that knows several procedures. These procedures are:

[1]. Text analysis : Mapping a text on a graph.
[2]. Construct analysis : Determining subgraphs that form a "natural" unit.
[3]. Link integration : Using a "path algebra" to derive new knowledge from the extracted knowledge. This required a *multiplication* rule for consecutive links and a *summation* rule for parallel links.

Schematically the KISS procedures can be represented as follows:
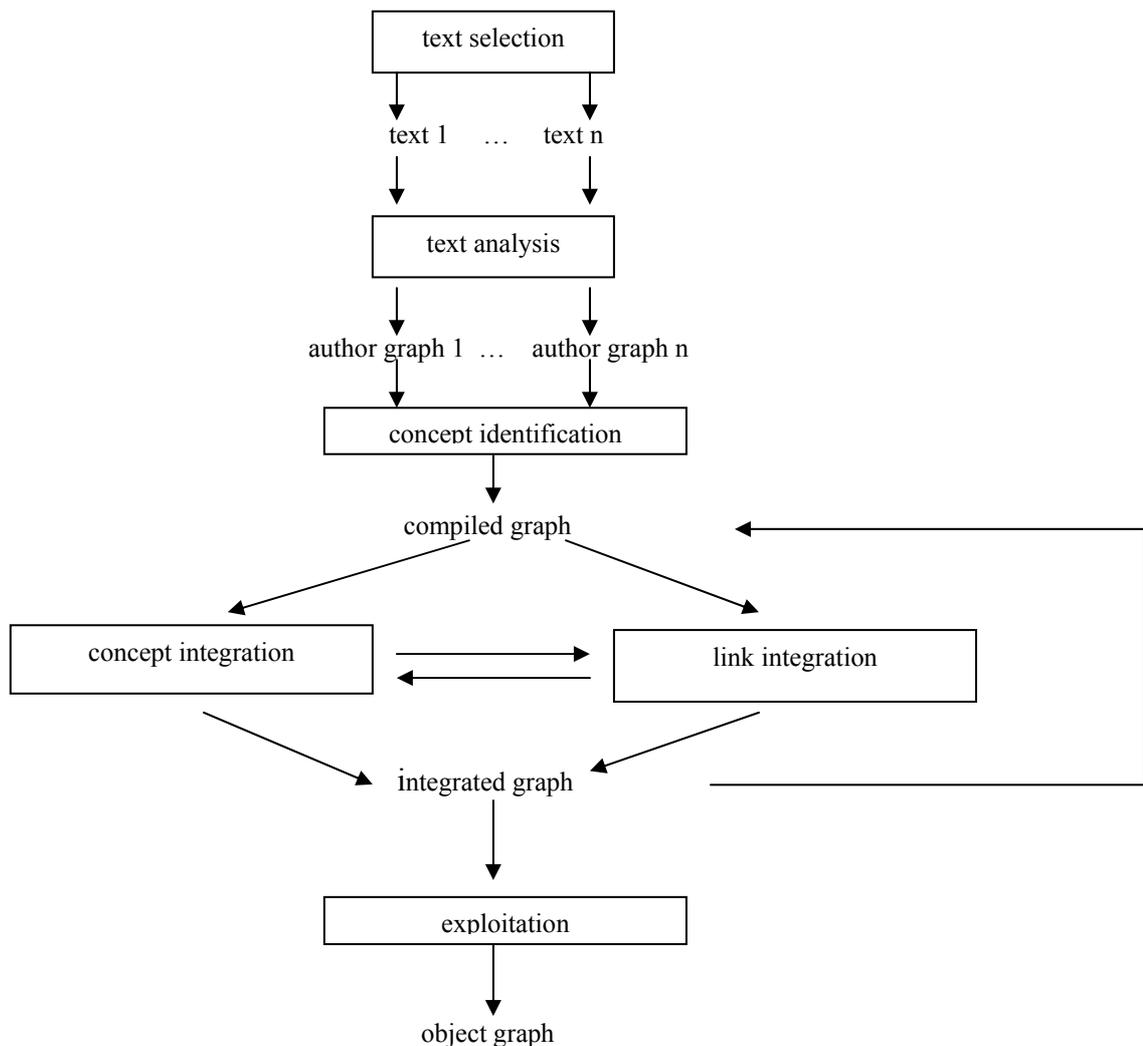
The Knowledge Integration and Structuring System (KISS)

Graph theoretically construct analysis is the most interesting procedure as it involves finding vertices with a "similar" position in the graph.

De Vries, as we already mentioned, focused on the extraction of specific types of relationships. Smit investigated the robustness of the integration process. Given an extracted graph, to what extent does the result of that process depend on the presence of a specific link? This first set of research items led to the publications [7], [8]. Meanwhile there were also some master theses related to them. We mention [9], [10], [11].

2. 1990 – 1995 : Representation of all text

From being on expert systems the focus changed to linguistical and logical aspects. Mars, a computer scientist in Twente, and Hoede were funded by a so-called "renewal fund" for a project on knowledge representation. For the mathematics group this meant that now all information contained in a text was to be represented. However, unlike in other investigations, the number of types of relationships was to be kept as small as possible. This aspect forms an essential difference with a competing system of representation of knowledge by graphs. That system is the system introduced by Sowa [12] in 1984. It was only in 1990 that the two groups became aware of each other. However, an essential difference was that for Sowa's theory of *conceptual graphs* substantial software has been developed. A more theoretical difference between knowledge graphs and conceptual graphs is that the ontology of knowledge graphs does not know any words. It literally is a theory on the *subword level*. In conceptual graph theory words are used to describe relationships between concepts, like in labels "has agent" or "has object".

The basic idea of the theory is that in the mind representation of the world is present that has a discrete mathematical nature, so can be modelled by a knowledge graph, that is called *mind graph*. The vertices of this graph correspond to somethings, the *genus* of all *concepts*. "Something" may be a perception unit, then is represented by a single token but, more generally, will be a complex structure of tokens that are linked by links of certain types. So then a subgraph of the mind graph is considered, the elements of which are "taken together" so, literally, form a concept. The first type of frame is used to indicate that the subgraph is seen as a unit. That frame may be called an AND-frame, an idea that goes back to Peirce [13] and his theory of *existential graphs*. Van den Berg [8] has shown that by introducing three other types of frames, the NEG-frame, the POS-frame, and the NEC-frame (for negation, possibility and necessity) various logical system can be represented in the formalism of knowledge graphs.

We will now focus on the 8 types of links, 3 edges and 5 arcs. For the choice of these 8 elements of the 13-elements ontology (1 token, 8 links, 4 frames) we refer to Hoede [14], where it is argued that neural networks in the brain can recognize only a restricted number of types of relationships, namely:

EQU	: equality	ORD	: ordering
SUB	: subset relationship	CAU	: causality
ALI	: alikeness	PAR	: attribute part
DIS	: disparateness	SKO	: informational dependency .

EQU, ALI and DIS are labels of edges; SUB, ORD, CAU, PAR and SKO are labels of arcs. The relationship between an element of the AND-frame and that frame as a token is said to be of type FPAR, for F(rame) (PAR)t. In the theory there are three *merological* types of relationships:

SUB : part of	PAR : attribute of	FPAR : property of.

So far no words come into consideration. They come in as names of tokens.

We will now compare the two representational systems by considering the simplified sentence "man hit(s) dog". In conceptual graph theory three vertices are used with labels man, hit and dog. This is basically the same in knowledge graph theory. Then the vertex with label " hit" is related by an arc, with label "has patient", to the vertex with label "dog" and by an arc, with label "has agent", to the vertex with label "man". The representation of the sentence in conceptual graph theory is

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In knowledge graph theory, the representation is as in the following figure

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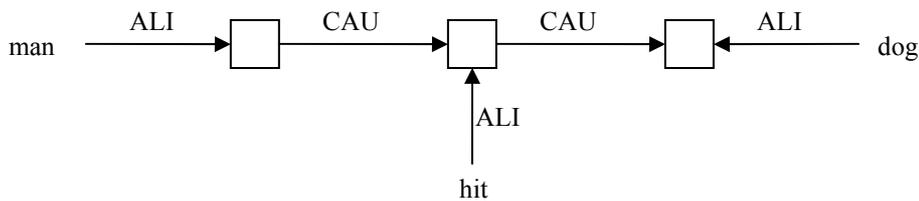
Note that the two CAU-arcs do NOT have labels on the word level. The CAU label is referring to one of the eight basic relationships we described. The words "agent" and "patient" do not occur. They correspond to certain subgraphs of the syntactical sentence graph in knowledge graph theory, the word agent having a word graph including the tokens for man and hit, the word patient having a word graph including the tokens for hit and dog, connected by SKO-arcs, as agent and patient are terms on the syntactical level. The corresponding subgraphs of the given sentence graph, now with connecting CAU-arcs, are word graphs for the words "subject" and "object", see Zhang [15] for the theory about syntactical word graph and semantical word graph corresponding to a certain word.

The important difference between conceptual graph theory and knowledge graph theory lies in the fact that in the latter the structure of the graphs determines the semantics of the words used in a sentence, whereas in the former the (assumed) semantics of the words is used to describe the sentence by a graph. It is for the same reason that in semantic networks so many relation types occur, in the form of labels of links. The ontology of knowledge graph theory is simply more basic.

Another related theory is that of Wille [16], called formal concept analysis. That theory focuses on lattice theoretical aspects of concepts in which, at the same time, intent (meaning) and extent (sets of corresponding elements) are considered. The meaning of a concept is, unlike in knowledge graph theory, not transcending the level of an enumeration of properties.

Willems [7] started the search for a universal ontology for the description of natural language, whereas van den Berg [8] showed that, by the introduction of four type of frames, all known logical systems could be described by the chosen ontology. The overall conclusion at that moment was that *all* of natural language was within reach of knowledge graph theory.

In the meanwhile Reitsma [17] used conceptual graph theory to show how one could use this type of knowledge representation to describe how, given a specification of basic elements, one could come to an implementation of a certain design. At the same time various master's theses were written, [18], [19], [20],[21],[22],[23],[24],[25].

3. 1995 – 2008 : Linguistics

The third period was dominated by linguistic aspects. It turned out that two Chinese PhD-students, Liu [26] and Zhang [15] were interested in application of the theory to Chinese. The

basic idea is that each word should have a *word graph*, expressing its meaning in the form of a knowledge graph. This led to a series of papers on word graphs, see [27], [28], [29].

This idea is not new. In fact, Ebeling [30] developed a theory of "structural linguistics", that turned out to be describable in terms of knowledge graphs. Specific features of Chinese, like that of classifiers could be described with knowledge graphs. We refer to [26]. It also turned out that particles in Japanese perfectly corresponded to the ontology of knowledge graphs, see [31]. This led, in a natural way, to the question whether all linguistic aspects were describable in terms of knowledge graphs. A first investigation of Bahasa Indonesia seems to confirms this conjecture, see [32] and [33].

A strong support for the paradigm of knowledge graph theory can be found in Chapter 8 of the book of Lyon's [34], where so-called semantic fields are discussed. We quote: "Linguistic units are but points in a system, or network, of relations; they are terminals of these relations, and they have no prior and independent existence". This remark was made in a discussion of "Structuralism", whereof de Saussure is considered to be the founder with his main work from 1916 on structural linguistics. We refer to the paper by Hoede [35] of 2005, wherein also the essential problem of translation is discussed. We give a short summary here. In knowledge graph theory translation takes place according to

(1). Sentence in language 1 → Sentence graph in language 1
(2). Sentence graph in language 1→ Sentence graph in language 2
(3). Sentence graph in language 2 → Sentence in language 2.

The first procedure is called structural parsing, see Zhang [15]. The third procedure is called uttering, for which we also refer to [36]. The main problem is (2) the transformation of the sentence graph in language 1 to a sentence graph in language 2.

The difficulty is, in a nutshell, that there is no universal one-to-one correspondence of words, like in cheap translation machines. It is not so much the problem that there are homonyms, word with more different meanings, as the problem that the word graphs for related concepts may differ in the two languages as there is indeed a substle difference in meaning. That implies that, given a sentence graph in language 1 it will have to be covered as well as possible by wordgraphs in language 2. Either not all of the original sentence graph is "brought under words" (literally!), or the sentence graph constructed may exhibit more meaning than was present in the sentence graph in language 1. In fact both may happen. These things make clear that it may be impossible to translate certain sentences in principle.

Procedure (2) has not been worked out theoretically yet.

4. Applications

In the course of time various applications of the theory were investigated, mainly in the form of master student reports. We want to mention a few of them. A typical example of applying the theory was given by Edens and Baretta [37], who analyzed a paper on the occurrence of sulphur compounds in the Dutch Wadden sea. After the extraction of the text the resulting graph was processed by KISS and two things came forward from the final graph. One was that the source of the sulphur pollution was missing, which turned out to be the city of Harlingen, and another was that the bottom underneath the aerobic and anaerobic layers was not mentioned. It turned out that the authors had forgotten to mention this too. This shows how useful a knowledge graph analysis can be.

Another example is the study and organization of electronic study books [38]. The knowledge in study books typically constitutes the material on which the theory could be applied. Yet another application field is the comparison with other representation systems, like e.g. conceptual data models [39]. The problem is always the comparison of the ontologies, which of them is more basic? An example here is the comparison of ontologies for regions. Botke and Hoede [40] compared the knowledge graph ontology with that of Randell and Cohn [41] and found out that it could express that ontology, but not the other way around.

A list of studies, mostly by students is given as references [42], [43], …, [61]. In the first period most of the student papers had a theoretical flavor. A comparison of knowledge graphs with the theory of concept lattices by de Rooy [24] is representative for the second period, where the focus shifted to linguistics. As interesting applications we should mention the modeling of eco-systems by Edens and Baretta [37], the study of printer failures by van Blanken [54] and the study of reports on natural disasters carried out by Verschut [58] for the United Nation. One of the student papers is exemplary for what we consider the highest potential of the theory. It is the study of Kramer [44] on the Rio-conference on pollution, where the opinions of different countries were extracted and presented as knowledge graphs. In the following section we will illustrate this idea for the subject biofuel.

5. The challenge

We have described how the theory of knowledge graphs has developed, but now get back to the original goal, the application of the theory to various problems. The linguistic studies could be called applications of the theory, but they themselves had a theoretical flavor. The big challenge is the development of a large software program that implements the theory. The development of an expert system like MEDES took about 50 man years, so the challenge is indeed big. A medical expert system for veterinary diseases, similar to MEDES, should get a lot of interest here.

We would like to illustrate the problems by discussing an important potential use of software, namely in the field of policy making. We considered five texts on biofuel, written by five different authors from five different perspectives. Let us look upon them as expressing "views" on the subject. What should our automated knowledge extraction system be able to do? First, the texts should be scanned automatically. Second, each text should be represented by a, huge, graph. The computer should do this automatically on the basis of a, large, lexicon of word graphs, semantical and syntactical, using the described theory of structural parsing. Third, and here the focus on policy comes in, the texts should be analyzed on the concepts, and their relationships, that stand central, i.e. are considered in all texts. Here one of the problems is to let the computer find out contradictory views. A rather technical problem is to display the extracted ideas in a good way. Drawing large graphs in a way that suits the beholder is a subject, for which regular conferences are held. Fourth, the non-common concepts refer to the specific view of the authors. For each text the concepts that do not belong to the central concepts, should be gathered in "background" graphs, that show the aspects that belong to the specific views on the subject. Especially when the texts express views of advisors who are consulted in a policy making process, both contradictory views and specific views are essential for policy making. The first indicate "where the problems are", whereas the second indicate "what is also the case and should not be forgotten". Fifth, ideally, the automated system should also produce text in which the views are combined, in a process of uttering. Sixth, utopically, this text can be translated, on the basis of knowledge graph transformation, see Section 4.

Our five texts consisted of one page each, as everything had to be done by hand. Even so it took some time to go through the procedures the computer should help us with. We did not use the full ontology of knowledge graphs either, only considered one type of link, that of "association". Our findings were the following.

1. The five texts contained 61, 75, 24, 60, respectively 23 concepts.
2. 41 concepts occurred twice or more in one of the five texts, indicating already that these contained considerable background views.
3. In order of frequency, the concepts were:

biofuel	(5)	wood	(3)
oil	(4)	animal	(3)
production	(4)	crop	(3)

sugar	(4)	technology	(3)
energy	(4)	food	(3)
biomass	(3)	price	(3)
bio-diesel	(3)	human	(3)
ethanol	(3)	generation	(3)
fuel	(3)	feedstock	(3)

Mentioned in two texts were concepts like industry, transport, plant, potential, algae.

4. Text 1 contained 40 specific concepts that turned out to form a graph with 5 components. We chose important concepts in each and found : programs, outlook, death, assistance and organizations.
5. Text 2 contained 45 specific concepts clustered in 9 components, 4 large ones on topics like: source, debate, strategy, and research.
6. Text 3 contained only 7 specific concepts in two components concerning: seed and price rises, a typically economical aspect.
7. Text 4 contained 35 specific concepts. 4 clusters appeared with chosen concepts: laboratory, non-food, alternatives and disposal problem. This latter specific view is of political nature.
8. Text 5, finally, contained 17 specific concepts, clustered in 4 subgraphs. We would summarize these as "new technological plans of the USA to find an alternative biofuel from algae".

We hope that this short survey on the outcome of our "experiment" shows that both central concepts and specific views come forward in a way that gives a policy maker support, especially concerning views that may also be taken into account. An automated analysis of this kind, if taking only small time, would be of great help in many situations.

To develop such help we plan to develop software for the KISS system. Ideally we should have:

1. A lexicon of word graphs so that an automated text analysis is possible of texts in Bahasa Indonesia.
2. A structural parsing program.
3. Software for the integration and structuring procedures.
4. Software for generating the text implied by the combined graph, or a synopsis thereof.

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