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An image-based reasoning model for rock interpretation

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Abstract

Expert reasoning about the contents and history of specimens presented visually cannot be purely symbolic: relating observed features to the terms that might be present in a textbook, symbolic statement of knowledge is not straightforward, and experts often also use abstract visual concepts, not present in textbooks, to marshal their basic observations. The paper describes an approach to symbolically organizing such visual reasoning, with the help of "knowledge graphs" and "visual chunks", and furthermore expressing the reasoning in a pattern-matching process described as a problem-solving method. The approach is illustrated for the petrographic interpretation of oil-reservoir rocks and implemented as a software architecture.

1 Introduction

Interpretation of images is a common reasoning activity in many domains. For example, X-ray interpretation in industry or medical domains, evaluation of natural resources for agriculture from satellite images, interpretation of chemical structures in microscopic images in the pharmaceutical industry, and of human diseases in biochemical assays via microscopic image analysis, and so on. Our own example is the task of interpreting oil-reservoir rocks in petroleum exploration. The challenge for our analysis is the effective modeling of the visual knowledge that experts apply, both quantitatively and qualitatively, to evaluate the potential of a geological unit as an oil reservoir.

According to [Harmon and Sawyer, 1990], interpretation means analysis of data to determine their meanings. However, according to [Abel, 2001], image interpretation deals with the matching of more abstract and diagnostic visual features than geometric data. The geometric features can not be used on their own to produce relevant inferences. In this paper, we justify the assumption that these abstract types of visual knowledge are essential to produce solutions to a problem of rock interpretation.

The rock interpretation problem studied here is concerned with the seeking of reasonable explanation for the formation process of a sedimentary rock, in the domain of sedimentary petrography. It is carried out by the analysis of the relationship of rock features that are discerned in a naked-eye analysis under an optical microscope. These features, collected by some visual pattern-matching process, are selected/combined – using what was described by [Nonaka, 1994] as tacit knowledge – and only afterwards named and organized for incorporation into an explicit body of knowledge. The aim of this exercise is to propose a reasoning model characterized by the use of visual knowledge to obtain rock interpretations. This reasoning model is presented mainly as a problem-solving method (PSM) [Gómez-Pérez and Benjamins, 1999]. A PSM describes the reasoning process of a knowledge-based system (KBS) in an implementation-independent way, specifying the knowledge and data required by an inference process at a more abstract and structured level. This reasoning pattern is modeled by i) a competence specification related to the solution of a task, ii) an operational specification described by high-level modeling primitives and iii) requirements/assumptions of the method in terms of domain knowledge. We have developed the rock interpretation PSM accordingly, which allows us to explain the way that knowledge and data are employed to solve a problem of image-based rock interpretation. This method produces rock interpretations from rock descriptions matched through the use of visual knowledge structures associated with schemata of interpretation.

The method is supported by symbolic descriptions of visual aspects of a rock sample. For example, the bitmap file of an image is not the input to the inference process; rather, our modeling view makes use of a textual approach to image analysis, as opposed to numeric

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approaches oriented towards geometric (color, size, texture) feature-based image representations. This textual description closely related to an image follows a symbolic ontology, which is formed by primitive concepts of rock (for example: "siderite" as "constituent name", "booklet" as "habit", and so on), where this symbolic labeling is used to specify rock features that have been determined visually.

The paper presents the process of rock interpretation modeling in terms of knowledge structures, which are defined and used to describe the rock interpretation PSM. The PSM is then described as a software architecture for interpretation supported by integrated knowledge and data components. Finally, the rock interpretation PSM is compared with other approaches.

2 Rock Interpretation Modeling

Any systematic knowledge engineering process that develops KBSs must include models of reasoning, such as PSMs. But KBS development methodologies, e.g. CommonKADS [Schreiber *et al.*, 1999] and PROTEGE [Grosso *et al.*, 1999], provide only limited support for building new reasoning patterns for particular domain applications. These methodologies emphasize the adaptation of already-defined methods, giving little attentions to the development of PSMs from the ground up. However, the literature presents several approaches that can be viewed as PSM development methodologies, for example: [Wielinga *et al.*, 1998; Fensel and Motta, 2001]. We have drawn on these approaches to model the new rock interpretation PSM.

This PSM relies on the important assumption that rock features taken individually by the user can help only weakly the extraction of more semantic and useful inferences in rock interpretation. That interpretation uses more abstract and cognitive structures of visual knowledge, here acquired and modeled as visual chunks [De Groot, 1965; Abel, 2001]. The chunks are most conveniently associated with geological interpretations using knowledge graphs [Leão and Rocha, 1990].

A knowledge graph (K-graph) can be understood as a schema for rock interpretations, having great expressivity and bigger granularity when compared to other formalisms that associate items of evidence with hypotheses, such as production rules or Bayesian nets. The K-graph is a tree where a) the root node represents the interpretation hypothesis and b) the leaf nodes represent visual chunks identified by the experts in the image of rock as pieces of evidence necessary to support the interpretation. Each interpretation is associated in the K-graph with a threshold value that represents the minimum amount of evidence needed to indicate it. The leaf nodes can be combined to increase the influence and the certainty of the interpretation stated.

We have modeled 6 K-graphs, expressing 6 possible interpretations of the "diagenetic environment in oil-reservoir rocks". For instance, the "Continental Meteoric Eodiagenesis Under Dry Climate Conditions" interpretation hypothesis was modeled as a root node, requiring an interpretation certainty (a threshold) of 6. This K-graph has 7 leaf nodes (each of our graphs has 5 to 7 nodes) to represent the following visual chunks: "Silcrete", "Sulphate", "Calcrete", "Dolocrete", "Dolomite", "Infiltrated Clays" and "Iron oxide/ hydroxides". A K-graph model has the role of describing this knowledge of visual chunks, which we consider to be fundamental for image-based problem-solving.

A visual chunk translates expert knowledge for driving useful inferences about rock images as described by geologists at novice or intermediate levels of expertise. This chunking assumption underpins the definition of more semantic methods of interpretation, as well as the adaptation of this visual knowledge to computational constraints. It has also the important role of connecting the expert-level knowledge - the tacit knowledge represented as visual chunks - to novice-level knowledge, represented by the simplified rock concepts associated with geometric features. Figure 1 shows that only the combination of rock features seen by an expert in an image of a rock can lead to a rock interpretation.

An AND/OR tree of visual chunks is built from rock concepts describing visual rock features. These rock concepts are grouped together with AND operators, forming an AND relationship. OR operators also can be used, meaning that at least one rock feature needs to be found in a matching analysis process. The tree describes how rock concepts are logically combined, to form evidence for an interpretation. Visual chunks have been introduced as a new type of concept, defined as an aggregation of rock concepts representing visual geometric features which can be specified in the domain ontology. This explicit adaptation process can connect basic geometric rock concepts at the user level to abstract concepts at the expert level, to make possible the inference steps in the interpretation method.

Our visual chunks modeled in K-graphs were associated with significance indexes (here represented by weights). For example, the leaf nodes on the "Continental Meteoric Eodiagenesis Under Dry Climate Conditions" K-graph have visual chunks/weights such as: "Silcrete" (weight 6), "Sulphate" (weight 6), "Calcrete" (weight 5) (Figure 2). An interpretation can only be reached when the combination of significance indexes of observed visual chunks has reached the threshold associated with it.

A rock interpretation PSM (e.g. Figure 3) is composed of (1) knowledge roles, which are entities associating objects applied by the inference with the objects of the domain ontology, (2) inference steps, which transform objects to develop the reasoning, and (3) the expected flow of inference.

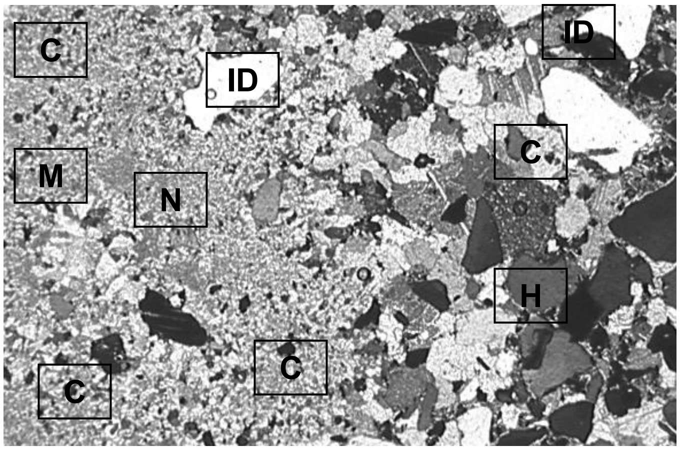

Figure 1 – The rock features C – Calcite, ID – Intergranular Displacive, M – Massive, N – Nodules and H – Heterogeneous seen in a microscope image of a sample are combined in a visual chunk labeled “Calcrete” to indicate a rock interpretation.

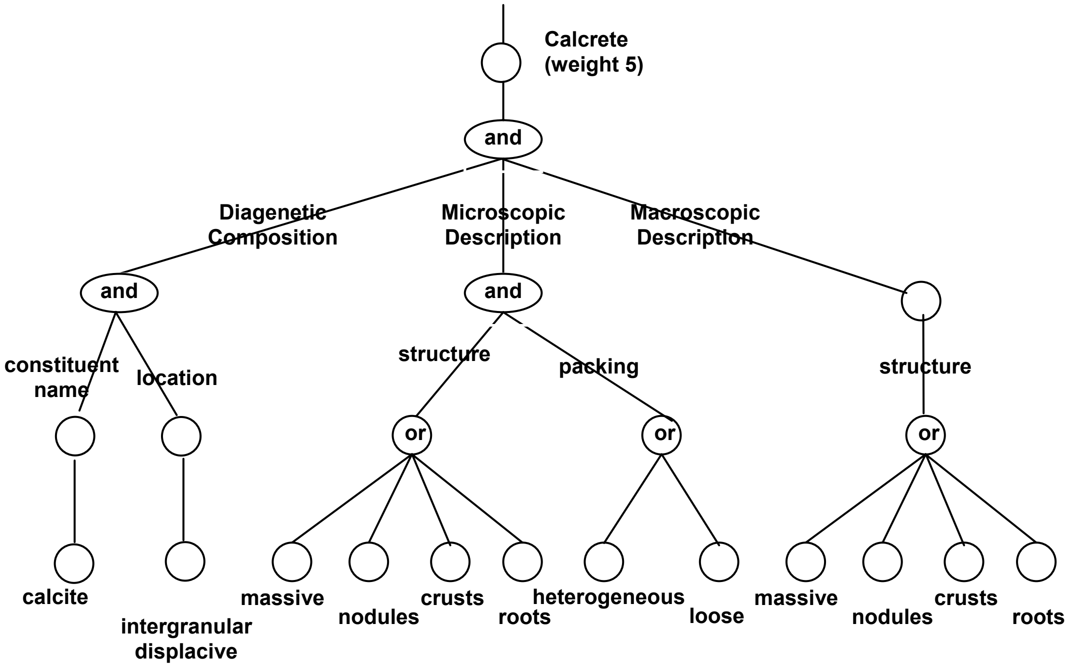

Figure 2 – The Calcrete visual chunk and its set of logical relationships with geometric rock features.

The rock interpretation PSM has knowledge roles defined as K-graphs, visual chunks, image description and solutions. The inference steps are *select*, to specify visual chunks or K-graphs; *match*, to compare visual chunks with rock features in the problem; and *specify*, to find possible solutions supported by the visual knowledge. The rock interpretation PSM is able to specify solutions from an image description of rock matched through the use of visual chunks associated with schemata of rock interpretation. This basic competence notion is complemented by assumptions about what domain knowledge is required by the method. An assumption that can be described, for example, is related to the association of K-graphs and visual chunks. Any association of visual chunks for interpretations relies on the availability of relevance indices (e.g. weights and thresholds) between them, which can model a way of increasing the certainty of solutions and the belief in a rock interpretation.

The rock interpretation PSM is mainly guided by a pattern-matching process of visual chunks against an image description. But additional search tactics can be used to increase the certainty of an interpretation hypothesis indicated by a K-graph and supported by the visual chunks that are matched. An image is described through basic concept-attribute-value triples (C-A-Vs) of an instance of a rock sample. The reasoning can be developed either driven by hypothesis (starting with a selected K-graph) or by data (starting from some observed evidence). In a data-driven inference, a set of visual chunks is logically matched against the C-A-Vs mentioned in an image description. The visual chunks that match are considered as "activated". Visual chunks are only activated when a minimal logical set of C-A-Vs is found in an image description. The activated visual chunks are used to select other K-graphs that include the same visual chunk, which in their turn are used to select new visual chunks, with the aim of confirming a hypothesis of interpretation. This process is repeated for as long as K-graphs and visual chunks remain to be analyzed, and while visual chunks remain to be matched, over the entire knowledge base. A solution is indicated if some K-graph has sufficient confirmation indicated by a set of activated chunks, considering the weights and threshold values. The solutions comprise the matched K-graphs and the whole set of visual chunks activated.

Using the "Continental Meteoric Eodiagenesis Under Dry Climate Conditions" K-graph as an example, the visual chunks "Silcrete" and "Sulphate" can be selected initially (the visual chunks with the largest weights). The set of logical combinations of C-A-Vs of these visual chunks is then matched against the image description. If one of these visual chunks is activated, the other chunks "Calcrete", "Dolocrete", "Dolomite", etc, are also selected. This process can increase the certainty about this K-graph currently taken as hypothesis. The new set of selected visual chunks is analyzed, and the certainty of this K-graph is thereby strengthened. Finally, the "Continental Meteoric Eodiagenesis Under Dry Climate Conditions" solution is indicated by the confirmed K-graph and by the activated visual chunks. As exemplified for this K-graph, the inference process is also repeated over the 6 others "diagenetic environments" modeled, according to their respective K-graphs and visual chunks.

3 The Implementation

Reasoning patterns can be implemented using different software components, such as logic systems, numerical systems, symbolic systems, database systems, web components, etc. We detail the implementation of the rock interpretation PSM using a software architecture for interpretation, which is a specification of knowledge and data software components. The challenge for this architecture is the integration of symbolic and database components, dealing with storage and querying over a large volume of knowledge and data, in addition to the reasoning resources for interpretation.

The components of the architecture are: interpretation engine – which translates inference steps into knowledge/ data requests, and carries out the task of parsing symbolic knowledge or data structures used to represent the inference steps of the rock interpretation PSM (This engine also has the role of analyzing the inference knowledge, such as visual chunk weights and interpretation thresholds, according to the interpretation criteria.); query engine – which supplies the interaction between the interpretation engine and the database components, writing and running queries automatically, according to the knowledge/data requests that are sent by the interpretation engine; database components – supported by a relational database system, which has schemata for a repository of rock descriptions and a repository of inferential knowledge about rock interpretation, here modeled as K-graphs and visual chunks. This architecture is also supported by i) an image-description model mapped to an entity-relationship model, producing a database schema to store rock descriptions and ii) inferential knowledge (K-graph and visual chunk models) mapped to an entity-relationship model, producing a database schema for storage of the concepts and relationships of the inferential knowledge used in the rock interpretation.

The operation of the "interpretation architecture" (Figure 4) is as follows. When an interpretation request is received (I), the interpretation engine loads the mapping between knowledge and data models (II). The working memories (WMs) are organized as symbolic data structures according to these mappings, because the inferential knowledge is stored in the main memory during the interpretation. The query engine also employs these mappings, using them to produce queries (in SQL), which allow the integration of the knowledge and data components defined in the architecture. Next, the query engine receives knowledge requests (III). These requests are parsed and knowledge queries (IV) are serviced in the database of inferential knowledge. This process is repeated until the query engine has completely loaded every knowledge structure of interpretation in the knowledge WM (V - VIII). Then, the interpretation engine parses these structures (VI), starting a sequence of data requests to the query engine (VII). The query engine parses the data requests and runs the resulting description queries on the database of application data (IX). The application data about rock samples are gradually queried and stored in the data WM by the query engine (X - XI). The interpretation engine parses these data about rock samples (XII) regarding the interpretation structures stored in the knowledge WM (VI), trying to match an interpretation indicated by K-graphs and visual chunks. The overall interpretation process is controlled by a symbolic algorithm of interpretation, which is implemented in the interpretation engine. This algorithm can run the inference steps described in the rock interpretation PSM, managing the main requirements of the process of image-based interpretation. Finally, if an interpretation has been reached by the analysis of inferential knowledge modeled, it will be returned by the interpretation component (XIII).

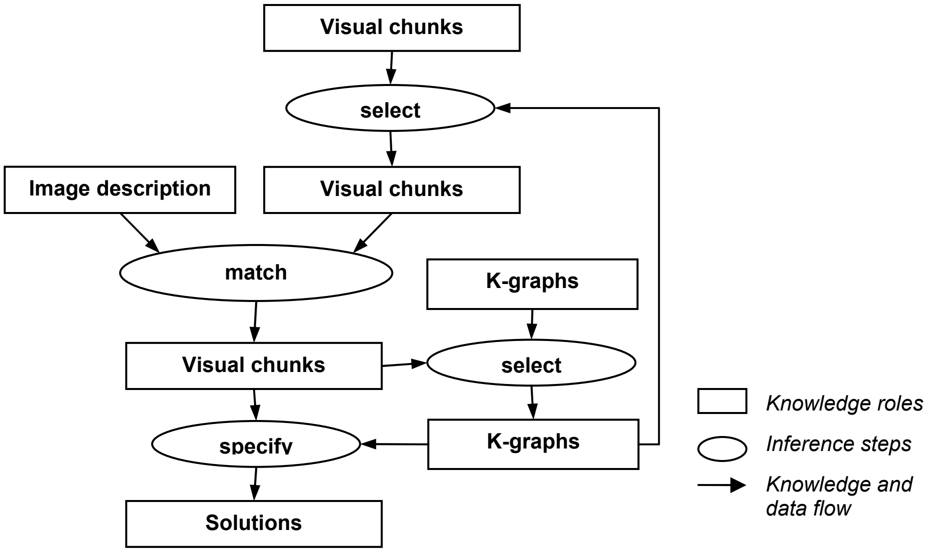

Figure 3 – The rock interpretation problem-solving method.

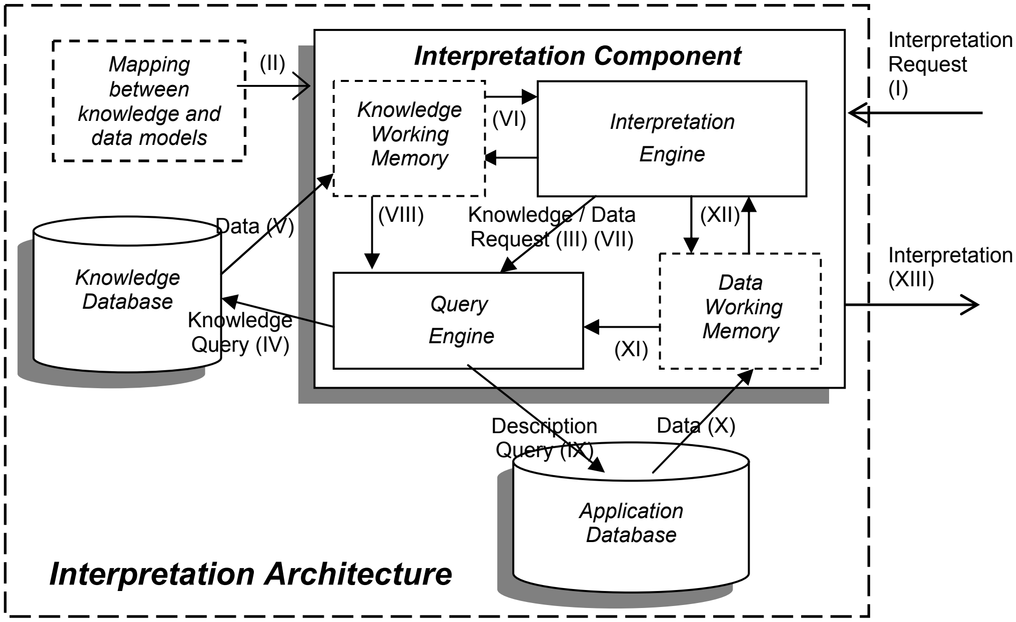

Figure 4 – The software architecture for interpretation: the integration of knowledge and data components to carry out rock interpretation.

The software architecture for interpretation is understood as a practical validation of a PSM of rock interpretation, allowing explicit manipulation of knowledge and data requirements that are abstracted in method patterns. This architecture has been used as a reasoning component of an oil-reservoir application [Abel, 2001].

4 Discussion

According to [Schreiber *et al.*, 1999], classification is concerned with establishing the correct class for an object using the object characteristics, e.g. (in geology) classification of minerals in a rock. According to [Clancey, 1985], the heuristic classification problem is concerned with abstract observations, which are sometimes used in place of simplified observations to generate hypotheses. Here, too, rock interpretation is mainly based on qualitative abstractions (sets of visual factors associated with each other and understood together) taken as observations, which can be used to specify interpretations. But the rock interpretation is not a class of some well-defined interpretation; nevertheless, we can still find solutions supported by visual aspects that can produce a weaker outcome, e.g. a merely "acceptable" interpretation.

According to [Benjamins and Jansweijer, 1994], the goal of diagnosis is to find solutions that explain both the initial and any additional observations. Diagnostic PSMs are firstly based on fault models, or models of abnormal behavior (mainly defined from fault diagnosis in technical systems). Data about the abnormal behavior guides the reasoning and search to reach the solution of the problem. In contrast to that, the rock interpretation process tries to explain some observations, but there are no fault models to support these interpretation processes. Furthermore, the observations are not monotonic data in the interpretation process, but more abstract information, here defined as visual chunks. Rock interpretation also raises issues about management of certainty, very common in medical problems but weakly described in diagnostic methods.

The assessment problem described in [Schreiber *et al.*, 1999] proposes a category for a case, based on a set of domain-specific norms. The rock interpretation PSM can be characterized as a similar problem, because it is based on a case of image description and norms modeled as K-graphs and visual chunks. The challenge for a rock interpretation PSM comparing with assessment method is to consider explicitly an image-based reasoning process of interpretation, establishing the assumptions and requirements that arise from *visual* knowledge modeling. Understanding the chunking process as a simple analysis of interpretation norms also does not take into account many cognitive aspects that are involved in this process of interpretation. We expect to be able to explore these aspects by trials of our newly-derived PSMs on further instances of oil-reservoir interpretation.

5 Conclusion

This essay can be considered as a first step towards the development of a knowledge-based approach for the handling of problems of image interpretation, primarily in the petrographic domain, but it also outlines an approach to modeling of reasoning that can be reused in other domains where application of visual knowledge is the key activity. The rock interpretation PSM is a step in the development of a PSM library for knowledge-based interpretation of images, which can decrease the development effort of KBSs for oil-reservoir applications.

References

[Abel, 2001] M. Abel. Estudo da perícia em petrografia sedimentar e sua importância para a engenharia de conhecimento. Programa de Pós-Graduação em Computação – II/UFRGS, Porto Alegre, 2001.

[Benjamins and Jansweijer, 1994] R. Benjamins and W. Jansweijer. Toward a competence theory of diagnosis. IEEE Expert, 9:43-52, October 1994.

[Clancey, 1985] W. J. Clancey. Heuristic classification. Artificial Intelligence, 27(3):289-350, 1985.

[De Groot, 1965] A. D. De Groot. Thought and choice in chess. The Hague, Mouton, 1965.

[Fensel and Motta, 2001] D. Fensel and E. Motta. Structured development of problem-solving methods. IEEE Transactions on Knowledge and Data Engineering, 13(6):913-932, November/December, 2001.

[Gómez-Pérez and Benjamins, 1999] A. Gómez-Pérez and R. Benjamins. Overview of knowledge sharing and reuse components: Ontologies and problem-solving methods. In Proceedings of the IJCAI-99 Workshop on Ontologies and Problem-Solving Methods (KRR5), pages 1.1--1.15, Stockholm, Sweden, August 1999.

[Grosso *et al.*, 1999] W. E. Grosso, H. Eriksson, R. W. Fergerson, J. H. Gennari, S. W. Tu, M. A. Musen. Knowledge Modeling at the Millennium. Technical Report SMI-1999-0801, Stanford Medical Informatics, 1999.

[Harmon and Sawyer, 1990] P. Harmon and B. Sawyer. Creating Expert-systems for Business and Industry. John Wiley & Sons, New York, 1990.

[Leão and Rocha, 1990] B. Leão and A. Rocha, 1990. Proposed methodology for knowledge acquisition: a study on congenital heart disease diagnosis. Methods of Information in Medicine, 29:30-40, 1990.

[Nonaka, 1994] I. Nonaka, 1994. The dynamic theory of organizational knowledge creation. Organization Science, 5(1):14-37, February 1994.

[Schreiber *et al.*, 1999] G. Schreiber, H. Akkermans, A. Anjewierden, R. Hoog, N. Shadbolt, W. van de Velde, B. Wielinga. Knowledge engineering and management. The MIT Press, Cambridge, Massachusets, 1999.

[Wielinga *et al.*, 1998] B. J. Wielinga, J. M. Akkermans and G. Schreiber. Competence theory approach to problem solving method construction. International Journal of Human Computer Studies, 49(4):315-338, October 1998.