Cognitive Tools for Medical Knowledge Management

Kognitive Werkzeuge für das Medizinische Wissensmanagement

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Summary
The term cognitive tool was coined for a means especially designed to improve human cognition. Examples of cognitive tools range from simple mind maps to computer-based assistance systems. Cognitive tools can play a key role in the knowledge management process. This paper describes specific requirements for cognitive tools in a medical context, and presents an implemented framework for enabling medical knowledge management by cognitive tools. The visualization of semantic networks and the users interaction with these graphical metaphors play an important role not only in the process of authoring or knowledge externalization, but in the computer-supported application and internalization of medical knowledge, as well. The paper addresses special methodological aspects, namely: 1) the seamless integration of formal knowledge representation and informal knowledge documentation, 2) the introduction of graphical means for interacting with the medical knowledge, and 3) the mutual support of eLearning and knowledge management. The framework is applied to complementary fields: 1) a learning system for differential diagnosis in paediatrics and 2) a tool, which empowers scientific literature retrieval by a graphical visualization of concept-nets based on the Medical Subject Headings (MeSH). As a result the case studies show that a generic framework, which supports the visualization of conceptual structures and allows an easy interaction with a medical knowledge repository can successfully support very different steps of medical knowledge work and clinical decision support.

KEYWORDS
J.3 [Life and Medical Sciences], H.5 [Information Interfaces and Presentation], I.2.4 [Knowledge Representation Formalisms and Methods], knowledge management, human computer interaction, cognitive engineering, eLearning, cognitive tool, semantic modelling
1 Introduction

Medicine as a complex and multifaceted discipline is considered as an extremely knowledge-intensive domain. Due to the explosive growth of medical knowledge there is an increasing need of systematic, computer-based knowledge management (KM) in medicine.

1.1 Knowledge Management

Settled in the context of learning organizations, KM approaches have received high attention over the last decade [1] (for a severe, but inspiring criticism of the KM hype [2]). Knowledge management is concerned with the methodological and technological support of the generation, distribution, storage and use of knowledge [3].

In the field of medical informatics, process models of the flow of clinical information and the associated knowledge generation were developed early [4]. During the last years, KM-related aspects of quality management, evidence-based medicine and public health gained more and more attention [5].

The distinction between tacit and explicit knowledge [6] is one of the most influential concepts in KM. It characterizes knowledge creation and evolution by transitions between tacit and explicit knowledge (Fig. 1): Externalization: knowledge-intensive practices are explained and documented; Combination: new knowledge is created by the combination of explicit knowledge; Internalization: explicit knowledge is adopted by frequent practice, causing a significant increase of human performance; Socialization: knowledge-intensive practices are taught by doing rather than explaining.

1.2 Cognitive Tools

Cognitive tools have been defined as “physical objects made by humans for the purpose of aiding, enhancing, or improving cognition” [7]. This very wide definition includes a whole spectrum of tools, which ranges from simple diagrams to computer-based decision support systems. Cognitive tools have been studied intensively in the context of learning technology [8], where their ability to stimulate learning processes has been examined [9]. From this point of view, the above mentioned steps of knowledge internalization (learning) and externalization are interrelated: the construction and verification of explicit knowledge representations by learners supports learning processes.

Our approach focuses on a well known family of cognitive tools: the semantic networks, which are spatial representations of concepts and their interrelationships.

Semantic networks have a long history in the field of medical knowledge engineering [10]. They were criticized early for the lack of formal semantics [11]. As a consequence elaborated formal semantics have been defined for a number of medical knowledge bases, namely the class diagrams of the Unified Modelling Language (UML) or ontology diagrams as produced by ontology editors such as Protégé [12], Kaon [13], or OilEd [14].

1.3 Medical Knowledge

Medical knowledge documentation relies heavily on text, medical images, and – to a lesser degree – on audio and video data [15]. Partly this fits to the specific vagueness of medical knowledge and the importance of narrative aspects. But this kind of knowledge documentation has severe drawbacks. The algorithmic interpretation and processing of multimedia data is extremely difficult. Even more important is a second aspect: the context (and perspective) of documentation frequently differs from the application context. To give an example: diagnostic handbooks mostly follow a nosological perspective, i.e., associated facts and diagnostic criteria of a given disease are presented. During the diagnostic process, medical knowledge has to be activated from a symptomatological viewpoint: related signs and symptoms have to be identified, compared, and classified.

The fixed documentation context of multimedia data hampers a flexible knowledge combination.

Furthermore biomedical research and evidence-based medicine reveal more and more exact factual knowledge of high clinical relevance. This kind of knowledge can be formally represented (e.g. by metabolic pathways or clinical pathways).

1.4 Objective

In many cases, semantic networks are an adequate means for representing this kind of medical knowledge. Even simple inferences based on these networks (e.g. following causal associations between pathophysiological states or linking a symptom to all associated diagnoses) constitute a valuable support
for medical professionals. A fixed documentation context is avoided. Furthermore, the network metaphor activates and facilitates the exploration and communication of medical knowledge.

The combination of a multimedia-based documentation and a more formal representation, processing and visualization of medical knowledge by semantic networks can serve as a cognitive tool for medical knowledge management. There is a strong need for an integrated, cooperative, and easy-to-use framework, which identifies and offers appropriate cognitive tools for supporting medical KM mainly by stimulating the steps of knowledge externalization, combination, and internalization.

2 Methods
In the following section, we first present selected issues of a framework, which meets these requirements.

2.1 Requirements

2.1.1 Support of cooperation Medical knowledge evolves in communities of practice. It is an emergent property, which slips the control of single individuals [16]. Hence, KM is a cooperative effort. A framework designed to support KM in medicine essentially has to enable and improve communication and cooperation during a continuing process of knowledge creation. The following requirements address these aspects:

Resource Integration – Cognitive tools for medical KM should provide a transparent integration of the existing infrastructure for knowledge work in the medical domain, namely: international classifications (e.g. ICD) online databases (e.g. Medline, Entrez), support for medical language processing (UMLS, SNOMED), collections of guidelines, and the growing number of biomedical ontologies.

Cooperation platform – Cognitive tools should be seamlessly integrated in a framework, which provides a computer supported cooperative work (CSCW) functionality and therefore enables direct communication between the participants (such as informal comments, discussion or email contact).

Central repository – Cognitive tools should be connected to a central repository, where explicit knowledge can be stored and retrieved.

Versioning support – Knowledge externalization by a cognitive tool is an evolutionary process. A version control system should track the modifications of the knowledge repository and analyze differences.

2.1.2 Knowledge representation Knowledge representation in the context of medical knowledge management primarily aims at knowledge externalization. Hence, a complete operationalization is neither intended nor necessary. On the contrary, the framework should provide the following means for bridging the gap between human knowledge explication and formal knowledge representation:

Informal documentation – Many medical procedures, the characteristics of medical images or the narrative aspects of a patient's history are adequately represented by multimedia data [15]. Formal and informal means of knowledge representation or documentation have to be integrated.

Weak schemata – Research on medical cognition yields that medical knowledge can be constructed as a hierarchically organized system of concepts [13; 14], but there is evidence that the organizing principle is not primarily that of a class-subclass or class-instance relationship [20]. Instead, constructs that intermediate between individual observations and more abstract concepts, play a central role in the clinical decision making [21]. Cognitive tools should therefore avoid a strict separation of a schema (class) level and an instance level.

Incremental formalization – The knowledge repository should be able to document steps of the process of knowledge externalization at any degree of formalization and grant traceability [17].

Cognitive adequacy – Cognitive tools are meant to be fully compatible with human understanding. Medical professionals should be able to interpret, control and eventually criticize the externalized medical knowledge.

2.1.3 Knowledge processing It is commonly accepted that sound algorithmic knowledge processing is only feasible for formalized models. Knowledge processing can be applied to check the consistency of a model, to infer new conclusions, or to let a model exhibit a behaviour, which is analogous to real world situations. The differing competencies of human experts and knowledge processing applications have to be carefully combined which is the concern of the following requirements:

Transparency – Cognitive tools should improve human cognition and not substitute it. A medical professional should be able to keep track of the knowledge processing.

Interactivity – Cognitive tools should offer a way of exploring operational models of medical knowledge in order to grant the opportunity to detect consequences and possible short-comes.

Complementarity – Medical expertise is associated with differential use of reasoning strategies [22] which corresponds to the general concept of bounded rationality [23]. Therefore, cognitive tools should not be limited to only one inference mechanism, but provide an opportunistic mix of inference types.

Soundness – A sound calculus based on formal logics is a prerequisite of secure knowledge processing.

2.1.4 User interfaces The knowledge presentation and access by an adequate user interface is not just a fancy add-on. Following the
cognitive tool perspective, it is an integral part of the approach. Visual metaphors and intuitive means of interaction are indispensable for enabling efficient knowledge work. Recent results in the field of user-centered system design have to be employed to improve cognitive integration:

**Recognition** – Knowledge presentation has to generate visual representations which can be recalled deliberately and recognized by the user in order to grant orientation and to enable learning.

**Activation** – The representation of a problem affects the cognitive work which is needed for its solution [24]. The visual presentation and the graphical metaphors should be appropriate to activate human cognition.

**Facilitation** – The use of a cognitive tool should add as less new cognitive load as possible to the medical professional. The following three items address this in detail: 1) Simplicity: A cognitive tool should not distract the user from his working with model components, which have a clear semantics in the domain of interest. 2) Fluid interaction: Traditional graphical user interfaces expose the user to continual interruptions to their flow of activity (e.g. when new windows pop up). The tracking of GUI states binds cognitive capacity. The fluid interaction paradigm [25] tries to avoid discontinuities in the states of the user interface. 3) Zoomable knowledge access: There should be a smooth transition between different levels of detail. A zoomable access provides a means for a fluid interaction. By simple zooming in an information space the user accesses the relevant detailed information without losing contact to the surrounding context [26].

2.2 The cognivis.m framework

**2.2.1 System architecture** The cognivis.m (cognitive visualization in medicine) framework was implemented in order to meet the above requirements. It aims at an integrated in order to meet the above requirements. It aims at an integrated framework was implemented to improve cognitive integration:

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2.2.2 Graph-based presentation

The cognivis.m framework visualizes different kinds of semantic networks (see Section 1.2), including causal networks, metabolic pathways, medical classifications, mereologic networks, decision trees, and clinical pathways. A graph editor is the primary user interface, by which the central knowledge repository can be maintained and accessed.

The semantic networks bridge the gap between ad hoc knowledge documentation and a formal representation format. Additionally they are easy to understand and can be manipulated by humans. Hence, they support incremental formalization and meet the requirements of cognitive adequacy.

The user interaction is almost exclusively based on direct manipulation of the graph; context menus provide the necessary functionality. Apart from exploring the network users can construct graph templates in order to formulate queries (this functionality is still at an early stage).

Primarily the visualization relies on tree- and network-shaped representation of graphs. The nodes and edges change their shape and color when the user interacts with the diagram. In addition to that, an
alternative visualization for generic and partitive relations can be chosen, which uses nested groups. The editor integrates multiple perspectives on a given semantic net, which are simultaneously updated: an overview, multiple tree views, and a central structure browser.

The graph layout is generated automatically by a set of layout algorithms. The algorithms are capable of a deterministic layout calculation, which fulfills the requirement of a reliable presentation. User interactions, that change the semantic network are supported by an incremental graph layout and morphing between two different states of the network.

Texts and pictures are equally presented as nodes of the network. Their content can be accessed by simply zooming in. When a user retrieves or selects an area or a single node, smooth visual transitions preserve the awareness of the former location.

2.2.3. Hybrid Knowledge repository
In order to enable a seamless and easy integration of existing medical classifications and ontologies, the formal knowledge representation is separated from the central knowledge repository of the cognivis.m framework. The repository is built on a very simple data model of typed graphs:

The repository uses a standard database system to store graph data

\[ g = (\mathcal{G}, \mathcal{T}, \mathcal{N}, \mathcal{E}, \mathcal{R}) \in \mathcal{G} : \]

\[ = \phi(\mathcal{N}) \times \phi(\mathcal{E}) \times \mathcal{T} \times \mathcal{R} , \]

where:

\[ \mathcal{G} := \text{Set of Graphs}, \]
\[ \mathcal{T} := \text{Set of Nodetypes}, \]
\[ \mathcal{N} := \text{Set of Nodes}, \]
\[ \mathcal{E} \subseteq \mathcal{N} \times \mathcal{N} := \text{Set of Edges}, \]
\[ \mathcal{R} := \text{Set of Edgetypes}, \]
\[ t : \mathcal{N} \rightarrow \mathcal{T} := \text{Assignment of Nodetypes}, \]
\[ r : \mathcal{E} \rightarrow \mathcal{R} := \text{Assignment of Edgetypes}, \]
\[ h : \mathcal{T} \rightarrow \mathcal{T} := \text{Assignment of Super-type}, \]
\[ \phi(\mathcal{M}) \text{ denotes the power set of set } \mathcal{M} \].

Additionally multimedia data can be stored and linked to the graph nodes.

A set of basic graph-based retrieval operations is defined in terms of database queries and available for the access and maintenance of the knowledge repository. More advanced graph algorithms can be applied on previously retrieved subgraphs by a separate graph processor.

Formal knowledge representation is downstream. The graphs with typed edges can be transformed in concept descriptions of a description logics (DL) and processed by a DL-Reasoner.

The advantage of this approach is that the integration of existing medical classifications and ontologies and the process of transforming an informal documentation into a formal representation can be performed incrementally within the framework.

2.2.4 Weak Schemata
The approach avoids a strict distinction between schema and instance even in the case of formally represented knowledge. In terms of knowledge representation a formal cognivis.m model resides only at the terminological level (T-Box) and has no assertional level (A-Box).

An entity in the domain of interest is represented by a concept. Concept definitions are formally expressed by a description logic (DL) [27].

For example:

\[ \text{herpes simplex } \sqsubseteq \text{viral disease } \sqcap \exists \text{hasSymptom.eczema} \]

states that herpes simplex is a viral disease and that an eczema has to be present in a case of herpes simplex. In terms of predicate logics this reads as:

\[ \forall x: \text{herpes simplex}(1)(x) \rightarrow \text{viral disease}(1)(x) \land \exists y: \text{hasSymptom}(2)(x,y) \land \text{eczema}(1)(y) \]

Additionally one can express, e.g., the requirement, that everything associated with a disease by an hasSymptom-Relationship has to be a symptom:

\[ \text{disease } \sqsubseteq \text{medical entity } \sqcap \forall \text{hasSymptom.symptom} . \]

If a concept cannot be classified under the concept symptom, but is associated by hasSymptom to a special disease, the definition of this disease will be rejected by the satisfiability check. This is basic description logics. Nevertheless, it is worth to note that the above all-quantified role restrictions can compensate for the lack of a separate schema by establishing internal consistency constraints.

2.2.5 Technical issues
The implementation of the cognivis.m framework is based on Java Technology (Java 5, Java 2 Platform Enterprise Edition, Swing, Java Database Objects).

Actually, the persistence layer uses the relational database system MySQL, but the object-oriented DBMS Fastobjects has been in use as well.

For graph layouts, we employed Touchgraph [28] and yFiles [29]. Racer [30] is used as the DL-Reasoner.

3 Proof of concept
3.1 Case study: Datamed
The objective of the project Datamed was to develop an ontology-based information system on viral diseases in paediatrics. Primarily, the system addresses learners, but it can serve as an electronic reference manual as well.

During the acquisition process of the Datamed model, two physicians and a computer scientist worked together as a modelling team. They identified the necessary conceptual constructs and built a compact model following the cognivis.m approach.

Multimedia elements and literature references are directly linked to the model. They illustrate and justify statements of the model, and...
hence improve the traceability of the modelling process. The acquisition of inferences started by the elicitation of questions, followed question abstraction and arrived at a set of generic queries defined on the model repository (Fig. 3). As an example: The user can now initiate an operation, which continuously expands, rearranges, and recolours a network that shows the context of a given disease. The operation results in displaying and highlighting the differential diagnoses of the given disease with the differing and corresponding symptoms. The Datamed model includes a relevant part of the SNOMED nomenclature.

Additionally Datamed comes with a different page-oriented web-based user interface (Fig. 4), which is generic in the sense that it adapts automatically to new or changed domain models.

3.1.1 Lessons learned At present, the Datamed repository contains 549 concepts, 16 relation types, and 1,041 associations.

During the first phase of the project, a standard UML-editor has been used as an acquisition tool. The model was defined by UML class diagrams and imported by an XMI interface. The modelling team appreciated the simple visual metaphor of the class diagrams and the possibility of working consistently on subdiagrams of the whole model. Apart from the modelling team (see above), two independent physicians working in different departments and a group of five medical students continuously gave feedback in a process of formative evaluation. The analysis of the short-comings of the modelling tool led to the development of the cognivis.m editor.

3.2 Case study: MeSHView

The objective of the MeSHView project is to improve bibliographic research in the Medline-database by visual access to the Medical Subject Headings (MeSH), the controlled vocabulary used for keyword indexing of the Medline bibliographic database.

The cognivis.m editor is applied to visually compose bibliographic queries based on MeSH terms. Re-
searcher, medical professionals, and students can browse and zoom the large and complex MeSH structure visually (Fig. 5). This results in 1) enabling fluid interaction to a certain degree, and 2) an improved presentation of the overall structure of the MeSH.

In addition to that, the MeSH keywords of the result set of a given query are presented in the context of the MeSH hierarchy and linked to the elements of the result set.

By modifying the graph, users can give relevance feedback, explore the result set and modify the primary query (Fig. 6). The project is still at an early stage, therefore results of a systematic evaluation are not yet available.

### 3.2.1 Lessons learned

The case study shows that our approach can be applied to extensive models: The MeSH 2005, which has been integrated to our framework, contains 41,063 terms. There have been no major problems during the interactive, incremental expansion of large graphs, when exploring the model, but we had to split the overview graphs of the MeSH for performance reasons: actually each MeSH Category is presented as a separate overview.

For MeSHView we could take advantage of the separation between the data representation at the persistence level and the logical interpretation of the data by the DL-reasoner. The MeSH data could be easily imported to the cognivis.m framework at the persistence level.

### 3.3 Evaluation

The cognivis.m framework is not yet in routine use, therefore we can not present results of a summative evaluation based on log-statistics or an outcome study. On the other hand the formative evaluation of the case studies was an important aspect of the implementation process.

Cognitive walkthrough techniques [31] have been applied in order to evaluate the usability with respect to given tasks (e.g. comparison of differential diagnoses or selecting relevant papers from an result set of a Pubmed-query). Additionally thinking-aloud protocols [32; 33] of two small groups of potential users (3 and 5 persons, respectively) have been analysed. The results continuously led to improvements of the framework.

We received informal feedback from a total of five different user groups: clinicians (two persons), medical students (five persons), participants of a medical course (eighteen persons), students of medical informatics (six persons), and the modelling team of the Datamed project (three persons). Only very few difficulties with the application of the cognivis.m functionality to
browsing and retrieval tasks within the Datamed and MeSH network were reported. These difficulties were caused by the fact that some tools, which had been exclusively offered by context menus, could not be found easily enough. All users expressed a high satisfaction with the knowledge visualization and considered it as very helpful for maintaining orientation.

4 Discussion
The cognivis.m framework aims at an integrative support of medical KM, which is not limited to the support of authoring and knowledge elicitation. As a major difference to existing knowledge acquisition environments and ontology editors (e.g. Protégé [12], Kaon [13], or OilEd [14]) the framework can be equally used for the construction of user interfaces of services based on a given central knowledge repository (i.e. support for explorative learning, diagnostic decision support).

As a major result of the case studies, our framework provides the necessary flexibility and an adequate pool of generic functionality to be applicable to a broad range of KM-related application scenarios.

In the first part of this paper we present central requirements for an integrative support of medical KM based on the concept of cognitive tools:

With respect to the first groups, addressing the concern of a collaborative platform, cognivis.m actually meets all of the requirements except one: the framework enables resource integration by a flexible and simple relational import format, it provides a central repository for the representation and documentation of knowledge, which integrates versioning support. The integration of existing medical classifications and terminologies is a difference to some general purpose frameworks, but Protégé – as it emanated from the context of medical knowledge engineering – integrates, e.g., a tab, by which the Unified Medical Language System can be accessed.

Only the integration of CSCW functionality, which aims at a cooperation platform, is yet at a preliminary and rudimental stage. Compared to this, even Protégé, as one of the most important knowledge acquisition environments for the medical domain, lacks of a fully-fledged support of a collaborative knowledge elicitation, which would include versioning support and integrated CSCW functionality.

The next group of requirements addresses the problem of an adequate support for the externalization of medical knowledge. Our approach especially focuses on the integration of formal knowledge
representation and informal knowledge documentation, which successfully serves as a base of incremental formalization. Cognivis.m systematically smooths the transitions between an informal knowledge documentation (e.g. by multimedia objects) and a formal one. Unlike knowledge acquisition methodologies as, e.g., CommonKADS [38], we do not aim at a progressive knowledge formalization, but at a seamless integration of different formats of explicit knowledge. Protégé, Kaon, OilEd, and similar approaches do not sufficiently support this concern. The Media Slot Widget of Protégé allows the inclusion of video and audio files, but multimedia data are not seamlessly integrated in the knowledge presentation layer as it is the case in cognivis.m. Brain-storming or mind-mapping tools often provide an adequate integration of multimedia, but lack of more formal means of knowledge representation.

Practically all frame-based knowledge engineering environments (including Protégé) are built on the distinction between concept and instance or between a schema level and an assertional level. While of cause they can be applied to the acquisition of very detailed domain models exclusively on the basis of concepts, the explicit support and methodology of weak schemata is a characteristic trait of the cognivis.m approach.

Although the cognitive adequacy of a cognitive tool is difficult to prove, results of cognitive science in medicine [21; 22] back our graph-based approach.

Soundness is granted in cognivis.m by applying a representation format and inference procedure based on description logics. Sound knowledge processing is the base of the above mentioned knowledge engineering platforms, too. The requirements of transparency, interactivity, complementarity are met by our framework, when it is applied to the construction of service-oriented user interfaces for applications, which are based on the central knowledge repository. Such services enable the user to explore represented or documented knowledge. The cognitive workflow is uniformly supported by navigating, searching, zooming, extending, pruning, and merging semantic networks. In contrast to this, the existing knowledge engineering environments are not suitable as modular components of end-user applications.

There are many tools for ontology visualizations (for an overview see [34]), e.g., the ontology browser of the Kaon environment [13], Jambalaya [35], OntoViz [36], Isaviz [37]. In contrast to our approach, they focus on the process of ontology acquisition and maintenance. They provide means for consistency checking or a visual control of schemata and instances. Knowledge delivery or decision support are out of scope, where they are a central concern in cognivis.m.

The reduction of the cognitive load by an appropriate knowledge presentation is a major concern of our approach. It fits with the aim of presenting knowledge in a form that stimulates further knowledge externalization, combination and internalization. The application of deterministic and incremental layout algorithms, which are included the yFiles-package, enables a reliable recognition of graphically presented knowledge. Activation and facilitation is equally achieved by the graph-based interaction approach.

We do not intend to substitute established knowledge engineering tools (e.g., Protégé, Kaon, OilEd) or methodologies. On the contrary, by applying standards like OWL or XMI, they can be integrated into the framework.

One of the most exciting challenges is to employ our framework to track human knowledge processing in the fields of medical information retrieval, learning, problem solving, and the integration of knowledge sources. We hope to observe and identify patterns of usage, that will lead to detailed recommendations on how to improve the support for cooperative knowledge work in medicine.

5 Conclusion

To the best of our knowledge, the combination of the following three aspects is unique to our approach: 1) the support of weak schemata modelling, 2) the predominant role of (fluid) interaction on graph visualizations, 3) the uniform framework for authoring (knowledge externalization) and knowledge delivery. We will further improve the support of open and standardized data exchange formats.

References


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