Integration of Ontologies and Knowledge from Distributed Autonomous Sources

Tina Fröhner, Matthias Nickles, Gerhard Weiß, Wilfried Brauer, Rolf Franken

In the context of open environments like the Semantic Web, Peer2Peer systems, Multiagent Systems and Semantic Grids, knowledge-based applications with multiple heterogeneous and autonomous knowledge sources have recently gained increased interest. For autonomous sources, often neither the consistency nor the reliability or the definiteness of the input knowledge can be ensured. This is why there is an increased need for theoretical frameworks and practical tools in order to enable and support the acquisition, representation and integration of such knowledge. This article provides an introduction into the issues of knowledge integration in open environments and presents a selection of outstanding approaches to these issues, focusing on ontologies and shared knowledge.

Keywords: Knowledge Management, Formal Ontologies, Information Integration, Open Systems, Semantic Web, Semantic Grid, Peer2Peer Systems, Autonomous Agents, Social AI

1 Introduction

The last few years have seen a tremendous rise of interest in distributed applications with distributed, interacting participants in so called *open environments*. Popular representatives for this sort of applications are e.g. web service based internet e-business software, *open multiagent systems*, open *Peer2Peer* systems and *Semantic Grids*. One important role of the participants (e.g. information agents, peers and web services) is to provide the application and/or their peers with knowledge, therefore we speak about *knowledge sources* in this regard henceforth.

Open environments can be characterized by the following properties:

- Relatively few access restrictions. The set of participating parties is initially often unknown and might fluctuate.

- Autonomous, heterogeneous set of participants. The participants operate independently towards their own goals. Not all relevant properties of the participants are known a priori (e.g. agent architecture, personal beliefs and goals), and their properties might be (intentionally) hidden or dynamic *(black-box character)*.

- The domain the distributed application operates on is often highly dynamic and heterogeneous. This is especially true e.g. for the Semantic Web.

- Absence of a central instance for the propagation and enactment of behavioral norms to the participants.

- A nonexistence of a commonly agreeable, single "truth".

If applications in such environments operate in a certain (common) domain - besides access and interaction protocols or the technical infrastructure - they require a shared domain semantics in order to support a mutual understanding among the distributed participants. Computational *ontologies* [3] constitute a popular response to this need. In computer science, ontologies are usually defined as formal representations of domain conceptualizations [5], focusing on consented and stable concepts. The idea behind this definition is to have a core set of statements which are usable as a vocabulary to construct concrete objects (instances) in order to model the respective domain. But this traditional definition is certainly too narrow to cover all kinds of general, stable and shared knowledge (especially in comparison to the much broader meaning the term ontology has in philosophy).

Due to the characteristics of open environments, certain issues are raised when acquiring knowledge, mostly originating from knowledge source *autonomy*: Some of the most severe problems computational approaches to knowledge management for open environments need to handle are inconsistent opinions and incompatible formalizations (cf. next section for details). Since despite (or even *because*) the research on ontologies focuses on consented, stable knowledge, in principle for ontologies the same issues as for knowledge bases arise if it comes to the integration of heterogeneous knowledge from autonomous sources. This is why we treat both ontological and instance knowledge in this text.

We refer to distributively acquired and interrelated knowledge as *integrated knowledge*. Please note that the term "integrated" does not refer to the location of the information here (for example, documents shared on a Peer2Peer network are not centralized, but none the less shared).

By no means this article is intended to be an exhaustive overview of the already quite large research field. Rather, it aims for a short, concise description of a relatively small group of formal approaches and software frameworks, selected from a larger list of similar, not necessarily "lower quality" or older approaches, in order to give a first impression of the state-of-the-art and to provide a starting point for further reading.

Also for lack of space, and because of the introductional character of this work, the fields of data mining, distributed expert systems, knowledge fusion and information integration for databases are not considered, although it is highly acknowledged that these areas are very influential in regard to the research on knowledge integration.

The reminder of this article is organized as follows: The next section states the most severe issues in contemporary knowledge integration for open environments. Section 3 introduces basic techniques for the integration of ontologies, section 4 presents selected software frameworks for knowledge integration, section 5 describes approaches to knowledge emergence, extraction and evolution, section 6 details approaches to local knowledge contexts and inconsistency perseverance, and section 7 introduces the novel concepts of Open Ontologies and Open Knowledge Bases. Section 8 concludes with some general observation regarding the future of ontology and knowledge integration.

2 Issues in Knowledge Integration for Open Environments

While the compilation, integration and sharing of information from different sources becomes more and more important, most of the contemporary formal frameworks and tools designed for the representation, acquisition and usage of distributed knowledge (especially ontologies) aim for one (however collected and compiled) consistent, coherent and monolithic knowledge (respectively ontology) base for storing this knowledge. Originating from the properties of open environments, this aim leads to several difficulties (see e.g. [6] for an exhaustive overview of integration issues).

1) Knowledge sources operating with an incompatible representation syntax or incompatible other encoding aspects.

2) Naming problems: Similar names for different knowledge facets or concepts, different names for the same facet or concept.

3) Semantical inconsistencies due to stable goal or belief conflicts of the sources (divergent *opinions*), or incompatible structures of individual ontologies or knowledge bases.

4) Incompatible background knowledge or different contexts of distributed local knowledge.

5) Heterogeneous access to the knowledge domain, heterogeneous knowledge domains.

6) Communication problems, averting agreements and coordination on/of knowledge contributions.

7) Unreliable or untrustable knowledge sources.

8) Contributions from knowledge sources conflicting with norms (e.g. laws).

9) Asynchronous dynamics of individual knowledge contributions.

10) Different scopes and viewpoints of knowledge sources, e.g. overlapping but not equivalent knowledge domains.

Basically, the following attempts to handle these issues exist: i) ignoring them, assuming they do not occur, or that they are not severe enough to justify efforts; ii) handle and resolve them, iii) handle them *without* trying to get rid of them (i.e. rather to try to co-exist with them in some intelligent way). Whereas today most of the approaches to the listed issues aim for ii) - especially those addressing syntactical issues and misunderstanding, as 1) and 2) - it becomes more and more obvious, that in certain cases a dissolution of these issues is impossible, or the dissolution would require disproportional measures that would therefore lead to severe restrictions on the software applicability. This is mainly true for the issues 3-9), whereas the other conflicts at least theoretically can be resolved. For example, semantically heterogeneous knowledge contributions might have their origin in divergent world views of the knowledge sources; an alignment of these world views, establishing fully mutual agreement, would - if practicable at all - lead to a loss in source autonomy and therefore decreasing the flexibility and robustness of the application.

Despite the possible infeasibility of resolving some or all of the above issues, and the possible, undesired loss of knowledge source autonomy when attempting to get rid of them, there are further considerations to be taken into account when it comes to the integration of knowledge in open environments which have been largely neglected in traditional approaches to knowledge integration and sharing.

First, information about stable semantical conflicts between knowledge facets respectively their sources is not just something one should get rid of. Instead, *conflict knowledge* [7] can provide valuable information about the attitudes, world views and goals of the respective knowledge sources. More generally, a heterogeneous set of distributed knowledge sources forms a *social layer* on top of the knowledge layer, and the resulting relationships among knowledge facets in terms of, e.g., contradiction, approval, strengthening and specification are not unfavorable complications, but valuable characteristics of this social layer. They can provide the application and knowledge users with valuable meta-information about the intentions, goals and social relations among the knowledge sources, and - if made explicit and visible - they can be prerequisites for a subsequent conflict resolution.

Second, in the absence of a normative meaning governance, and due to the inherently dynamic nature of knowledge, mechanisms for knowledge integration like filtering, appliance of trust relationships and most traditional approaches to ontology merging can only provide preliminary decisions about the reasonable modeling of communicated knowledge artifacts, because within a heterogeneous group of autonomous knowledge sources and users, in the end each user can only decide for himself about the meaning, relevance and correctness of the given information, and these decision even might need to be revised in the course of time. Any decision in favor for or against the inclusion of a certain piece of information into an ontology or knowledge base requires previous knowledge which might not be given (*bootstrapping* problem), e.g. if no trust relationships among knowledge sources and users have been established, then trust or distrust can also not be used to filter out unreliable knowledge contributions.

Considering the aspects mentioned above, we believe that instead of removing or ignoring semantical inconsistencies, it is often more reasonable to *model them ex-*

plicitly while integrating using a dedicated, heterogeneity-maintaining integration layer.

3 Ontology Mapping, Matching and Merging

The decentralized nature of the development of applications using ontologies - e.g. the Semantic Web - will lead to an explosion in the number of ontologies. Whereas many of them will cover overlapping domains, many others will describe similar domains while using different terminologies.

To integrate data from multiple ontologies, there exist different possibilities called *merging*, *mapping* and *matching* [3, 6]. Whereas merging describes the process of creating a new single coherent ontology that includes the information of all merged ontologies, mapping describes the process where the original ontologies remain separately, but are made consistent and coherent with each other, either by finding pairs of related concepts or by defining rules to relate (only) relevant parts of the source ontologies. "Matching" in particular tries to cope with the problem of finding the semantic mapping between two (or more) given ontologies.

Today these processes are still largely conducted by hand, which is a very time-consuming process that also often leads to mistakes, so they have become the bottleneck in many information sharing applications. Especially the fast growing number of distributed ontologies as e.g. in the Semantic Web will therefore increase the need for semi-automated or automated tools to support these processes in order to save time and to increase performance. Today, there already exist a number of tools - such as e.g. *GLUE*, *OntoMerge*, *OntoMorph*, *Observer*, *iPROMPT* - supporting automatic or semi-automatic ontology merging/mapping. There purpose is to (interactively) guide the user through the merging/alignment process, which means that the tools identify inconsistencies or potential problems and presents suggestions for further ongoings. Regarding the type of input such tools rely on, there exists several possibilities e.g. the class hierarchy, slots, value restrictions, instances of classes, descriptions of classes or a combination of these. And whereas several research projects focus on the development of methods for determining linguistic similarities among concepts, others focus on analyzing the structure of ontologies.

4 General Knowledge and Ontology Integration Platforms

The traditional way to create ontologies and knowledge bases is using an editor. Advanced editing environments which support multiple users are e.g. *OntoEdit* [9], *Protege* [8] and the *Ontolingua*-based *Chimera* [10] (cf. also the previous section for other tools supporting the manual or semi-automatic integration of ontologies). Analogously, tools exist for the multi-user creation of ontology instances by means of the manual annotation of documents and other data with ontology-based meta-data (e.g. *Annotea* [27]). Of course, such approaches are of limited value if it comes to the integration of knowledge in large scale environments like the web. Apart from data mining approaches frameworks have been designed in order to support both the expert development of ontologies and the virtual and/or transformational integration and dissemination of heterogeneous ontologies and instance knowledge. A pioneering approach in this regard has been *OntoBroker* [28]. A more recent, ambitious example for such a framework is the RDF-based *Karlsruhe Ontology and SemanticWeb Tool Suite* (KAON) [4] which integrates available resources and provides tools for the acquisition, engineering, management, and presentation of distributed ontologies and meta-data.

If software agents are involved in integration frameworks, they are often "just" part of the technical middleware, rather than being knowledge sources. One of few exceptions in this regard is *InfoSleuth* [11], where information agents provide ontologies that are used as media for the integration of heterogeneous knowledge contributions. Beside other features, InfoSleuth allows the annotation of knowledge contributions with information about their respective sources (cf. section 7) and the long-term monitoring of knowledge domains.

Organizational Knowledge Management addresses the creation, representation, usage and distribution of knowledge within complex organizations, such as (large) companies or within the government. Most organizational knowledge management systems still aim for the creation of monolithic, centralized and homogeneous knowledge bases for the collection of corporate knowledge, according to a single ontology-based organization schema, in order to enable communication and knowledge sharing across the organization, e.g. creating *Enterprize Knowledge Portals*, i.e. interfaces which act as unique access points to the corporate knowledge base.

An example for an organizational, agent-based knowledge management framework which in contrast explicitly acknowledges the distributed and social nature of knowledge in large organizations is *FRODO* [1]. FRODO can be characterized as a large-scale meta-information system with ontology-based organizational structures and support for workflow-based knowledge *contexts* cf. section 6 for details about knowledge contexts). It makes use of social agents for the management of ontologies, workflow, and personal information assistance in order to relate individual (i.e. single agent) and organizational (i.e. social structure-dependent) concerns. Further examples for "socially enhanced" solutions to corporate ontology and knowledge bases are presented in sections 6 and 7.

5 Distributed Knowledge Emergence, Extraction and Evolution

Currently, most of the research on knowledge emergence [13] and extraction is done in the field of the automatic semantical annotation of multimedia data, as well as in text and category mining on the web. A typical example for an approach on such knowledge retrieval from the web, which combines techniques known from data mining, content search and information integration is *KnowItAll* [12]. KnowItAll is a domain-independent, autonomous system that extracts facts from the web, evaluates this information by using statistics and then associates an "objective" probability to each fact enabling to automatically trade recall for precision. Extracting information from the web, it can handle unstructured text and provides highly automated category and instance learning methods.

Whereas this and similar approaches are able to operate on dynamic knowledge domains like the web, they have no explicit concept for the modeling of knowledge dynamics and evolution *itself*. The *Simple HTML Ontology Extensions* (SHOE) [14] is a formal framework and an ontology-based knowledge representation language intended to be embedded within web pages, which does not have this restriction. Whereas the knowledge representation formalism of SHOE itself is only of historical value, and can be easily mapped to first-order predicate logic, SHOE has been an early practical approach to *Dynamic Ontologies* [14], acknowledging that knowledge on the internet is not static and ontologies do not exist in monolithic isolation. In order to tackle these issues, SHOE supports ontology revision as a change in the components of an ontology (i.e. the addition or removal of categories and their relationships), and the versioning of subsequently revised ontologies. In this regard, formal techniques like those described in section 3 are supported to relate and align different ontologies.

Whereas SHOE and similar frameworks allow the evolution of knowledge, but still demand consent at each stage of the development, other approaches support the evolution process towards agreed knowledge itself. Being one of the rare examples in this regard, *KnowCat* [15] is a web-based groupware tool, supporting the cooperatively creation of knowledge artifacts, e.g. e-books or virtual documents, which is done in a distributed and asynchronous way, with no need for an editor managing the task. The created and possibly competing knowledge artifacts will grow as a classification tree composed of nodes. What is interesting about this tool is the possibility to create heterogeneous description about a topic, which are competing with each other in order to be considered as "the best" description. The evolutionary parts are both, the hierarchical structure and the content - as to say the descriptions of the topics - which are both produced and evaluated by the KnowCat users. The evolutionary process within KnowCat is called *Knowledge Crystallization*: this means that structures/topics which are either frequently used and/or receive favorable opinions will have a high "crystallization degree" leading to the fact that they will remain a part of the knowledge artifact, whereas a low "crystallization degree" will lead to the elimination from the knowledge artifact. The strength of KnowCat lies in its support for the (yet rather informal) weighting and comparison of heterogeneous knowledge facets during the process of knowledge integration, whereas it does not provide a logical framework in this regard, and it implicitly assumes the existence of an absolute "truth" which finally can be found (cf. section 7 for an approach which does not make this assumption).

Until now, nothing has been said about the process of finding a common ontological ground among knowledge sources. *Ontology negotiation* [16] enables intelligent agents to cooperate in performing a task, even if their domain knowledge is based on different ontologies. Ontology negotiation allows agents to discover ontological conflicts and to establish a common ground for further communications though incremental mutual requests and interpretations, clarifications and explanations regarding concept meanings. For this purpose, practical approaches to ontology negotiation usually provide an *ontology negotiation protocol* and a software infrastructure in order to support the negotiation tasks. Within this protocol, certain speech acts according to the negotiation tasks can be performed by the agents, e.g., "Request clarification" (of an unknown concept name) and "Confirmation of Interpretation" (of a given concept name definition). In the course of the negotiation process, ideally, the agents come to an agreed vocabulary that can be used for further cooperation. Due to its high communicational overhead it is questionable if this approach can be applied in the large scale, but it is surely a promising, very flexible way for ontology alignment in dyadic micro-scenarios.

6 Local Knowledge Contexts and the Preservation of Inconsistencies

So far, the described approaches to knowledge integration have in common that they (at least implicitly) assume that there does exist one "objective" knowledge, however sometimes evolving and difficult to identify. The possibly most popular formal approach developed in order to overcome this assumption is *Context Logic* [17], used in practice in the field of Federated Databases since a long time. Context Logic is an extension of first-order predicate logic in which sentences are not simply true, but are true within a context (local model). The key extension is the modality operator "ist" ("is true"), which asserts that a certain statement is true in the specified logical context. Although this approach has been a big step ahead and is a valuable approach to many practical problems (especially in the context of knowledge management for multiagent systems and Peer2Peer systems), it is questionable whether it is sufficient to provide truth contexts in order to model the social layer of knowledge networks, since contexts (in the strict formal meaning of this term) still assume (i) that there is a common "world", the knowledge sources have to refer to and (ii) that knowledge contributions can be aligned, if the appropriate contexts are given. Thus, Context Logic is essentially about different, but yet compatible *viewpoints* instead of e.g. opposing *opinions* (which are often much harder to handle). We believe that therefore the context approach is often not practicable due to agent opaqueness, and that local belief contexts need to be equipped with their social semantics, e.g. providing organizational structures (cf. section 7 for a new approach).

An example for a knowledge management framework based on Context Logic is [18]. In this approach, called *Distributed Knowledge Management*, an organization of knowledge sources - so-called *Knowledge Nodes* - is viewed as a social constellation of organizational units, which are managed managed autonomously and locally.

The co-presence of syntactically and semantically heterogeneous and even conflicting knowledge within the same knowledge base is supported by the *WebKB-2* server [19]. It permits web users to add knowledge in a shared knowledge base, so that syntactical and semantical heterogeneity is advocated to permit the comparison and mutual completion of knowledge proposed by heterogeneous knowledge sources and users. This is supported by various lexical facilities, editing protocols and filtering mechanisms. The WebKB-2 has been initialized with the *WordNet* ontology and other top-level ontologies in order to provide a bootstrap content and guidance for the users.

7 Open Ontologies and Open Knowledge Bases

As we have seen, the traditional understanding of ontologies and shared knowledge leads to difficulties if the informational input the knowledge is gained from is likely to be intentionally inconsistent, and there either does not yet exist enough additional information like trust or recommendations to identify and filter out "inappropriate" or "wrong" data a priory, or there does not even exist a concept of global inappropriateness or correctness at all. *Open Ontologies* [20] and *Open Knowledge Bases* [21], henceforth denoted as OO/OKB, aim at a solution for this dilemma by embedding (possibly logically inconsistent) knowledge facets gained from a heterogeneous set of self-interested autonomous knowledge sources (e.g. information agents or humans) within contextual, partially probabilistic information about their social meaning, especially about their sources (uttering agents), their assertive weights (how "strong" is the respective opinion, and how likely can it be ascribed to a certain agent?), their social impact and dissemination, their discursive relations to other communicated knowledge (e.g., denial, approval, revision or specification), and, if possible, the likely intentions of their utterances. The derivation of, e.g., trust relationships from such social structures is then an optional, subsequent task. Both the knowledge facets and their accompanying social meanings can emerge from communication processes using formal agent communication languages (for a stochastical approach to the derivation of social structures from agent communication see [22]), but could also be derived from, e.g., structured, semi-structured or natural language documents. Doing so, information as it can be found as first-order statements in traditional ontologies and knowledge bases, is lifted to the social level, a process called *Social Reification* [21, 20], as it is based on reification facilities that can be found e.g. in the RDF [23], Notation3 [24] and much more powerful knowledge representation frameworks like *OpenCyc* [25] (*Quoting* [26] can be considered to be a very simply variant of this principle). Therefore, first-order objects within OO/OKB have a '1st-level knowledge $\longleftarrow$ 2nd-level knowledge' form, whereby 1st-level knowledge describes a domain in the same way as within usual ontologies/knowledge bases, but probably in an inconsistent way regarding other 1st-level knowledge within the same OO/OKB. In contrast, 2nd-level knowledge describes the social meaning of the respective annotated 1st-level knowledge facets. This concept is related to context logic, but in contrast, it does not aim for the provision of logical truth-contexts. Rather, 2nd-level knowledge states the sound social meaning for true as well as false 1st-level statements. OO/OKB are thus dynamic, integrated information media which receive their emergent content from the communication of multiple autonomous sources and users, and provide a dynamic representation of socially annotated, semantically heterogeneous knowledge. The practical consequences are that OO/OKB need to be acquired from and continuously adapted to ongoing, possibly controversial knowledge source communications. In addition, they require mechanisms for their leveled generalization, since otherwise their complexity would grow too large due to the sheer number of possibly contradicting individual knowledge contributions and the richness of social structures. Generalization is also a way so that certain OO/OKB appear like a homogeneous ontology or knowledge base if necessary, because at its highest level, generalization causes semantical homogenization of contradicting knowledge, e.g. single information agents can be generalized as agent roles. The task-specific knowledge associated e.g. with a certain role is assumably more general, sound and abstract than the knowledge associated with two or more concrete agents (which are able to impersonate this role temporarily). Thus, OO/OKB have the following characteristics:

- *Openness*: As few as possible assumptions are made regarding the benevolence, trustworthiness, relevance, informedness and cooperativeness of its sources.

- *Dynamical derivation from communication*: OO/OKB are emergent from and evolving during ongoing communication of autonomous knowledge sources and users which assert (deny, specify, query...) subjective information. Communication does not necessarily need to be performed explicitly using some formal communication language, but can also take place implicitly (and asynchronously) using, e.g., textual documents which refer to each other in terms of approval, denial or specification.

- *Explicitness and social annotation of heterogeneity*: OO/OKB maintain semantical inconsistencies arising from contradictions and conflicts, and contain annotations of (conceptual or instance) knowledge with 2nd-level meta-information about its social meaning within the course of communication.

- *Multiple levels of generalization*: They allow multiple levels of generalization, defining the degree of inconsistency and social meaning preciseness.

8 Conclusion

There is an obvious and rapidly growing need for knowledge-based systems capable of running in open environments with autonomous knowledge sources and users, given the increasing interoperability and interconnectivity among computing platforms. Taking the key properties of such environments like knowledge source autonomy and the emergence and dynamics of meaning from interaction seriously, the integration of heterogeneous knowledge and personal ontologies is a great challenge. Certainly, shared ontologies and knowledge is required to provide a stable ground for communication, distributed applications and subsequent knowledge modeling, but also it becomes more and more obvious that in open environments knowledge contributions tend to be semantically inconsistent without the possibility to (re-)establish a common ground, because they originate from socially competing beliefs and goals. To cope with these seemingly contradictory aspects should be a core concern for novel solutions in the field of knowledge management for open environments, both in terms of theoretical foundations and practicable software tools. To explore and to work out such a new perspective constitutes a long-term scientific and practical endeavor of considerable complexity.

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Kontakt

Tina Fröhner
Research Center Knowledge Management (RCKM)
Fachhochschule Köln
Fakultät für Wirtschaftswissenschaften
Claudiusstraße 1 50678 Köln, Germany
Phone: +49-(0)221-8275-3960
Fax: +49 221 8275 3131
Mail: Tina.Froehner@FH-Koeln.de
URL: http://www.km.fh-koeln.de

Matthias Nickles
Institut für Informatik (I7)
Technische Universität München Boltzmannstr. 3
D-85748 Garching bei München, Germany
Phone: +49-(0)89-289 17242
Fax: +49 (89) 289-17207
Mail: nickles@tiki.informatik.tu-muenchen.de
URL: http://www7.informatik.tu-muenchen.de/ nickles

Dr. Gerhard Weiß
Institut für Informatik (I7)
Technische Universität München
Boltzmannstr. 3
D-85748 Garching bei München, Germany
Phone: +49 (0)89 289 17215
Fax: +49 (0)89 289 17207
Mail: weissg@in.tum.de
URL: http://www7.informatik.tu-muenchen.de/ weissg

Prof. Dr. Dr. h.c. Wilfried Brauer
Institut für Informatik (I7)
Technische Universität München
Boltzmannstr. 3
D-85748 Garching bei München, Germany
Phone: +49 (89) 289-17204
Fax: +49 (89) 289-17207
Mail: brauer@informatik.tu-muenchen.de
URL: http://wwwbrauer.in.tum.de

Prof. Dr. Dr. h.c. Rolf Franken
Research Center Knowledge Management (RCKM)
Fachhochschule Köln
Fakultät für Wirtschaftswissenschaften
Claudiusstraße 1
50678 Köln, Germany
Phone: +49-(0)221-8275-3443
Fax: +49 221 8275 3131
Mail : Rolf.Franken@FH-Koeln.de
URL: http://www.km.fh-koeln.de

Bild

Tina Fröhner graduated with a diploma degree in 'Business Administration' at Cologne University of Applied Sciences. Currently, she is an external PhD student at Brunel University, Uxbridge, UK. Her research topic is the use and evaluation of multiagent systems and ontologies for the formal knowledge representation within the field of knowledge management.

Bild

Matthias Nickles studied Computer Sciences (minor Psychology) at the University of Munich, where he graduated with a diploma degree. Currently, he finishes his PhD thesis on agent communication at the Technical University Munich TUM. His research interests include agent communication languages, multiagent systems, formal ontologies and knowledge modeling, and declarative programming languages.

Bild

Dr. Gerhard Weiß leads the AI/Cognition Group at the chair for Theoretical Informatics and Foundations of Artificial Intelligence (headed by Prof. Dr. W. Brauer) of Technical University Munich TUM since September 1997. His main interests have been in computational intelligent and autonomous systems in general, and in the foundations and application of agent and multiagent technology in particular.

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Prof. Dr. Dr. h.c. Wilfried Brauer is a full professor of Informatics since 1971 (first at the University of Hamburg, since 1985 at Technical University Munich). His research and teaching is in the field of theoretical informatics and foundations of Artificial Intelligence. He is particularly interested in interdisciplinary research and close cooperation with industry.

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Prof. Dr. Dr. h.c. Rolf Franken is a full professor for management at the Faculty of Economics and Business Administration of Cologne University of Applied Sciences, Germany, and director of the Research Center Knowledge Management (RCKM). His research interests include multiagent systems, formal ontologies, (distributed) artificial intelligence and (distributed) knowledge management.