Report on the

Dagstuhl Seminar 10412

QSTRLib: A Benchmark Problem Repository for Qualitative Spatial and Temporal Reasoning

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QSTRLib: A Benchmark Problem Repository for Qualitative Spatial and Temporal Reasoning
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1 Introduction: Background of QSTRLib

Reasoning about spatial configurations, temporal constraints, or spatio-temporal dependencies is a major challenge in various application domains of current AI research. One of the research areas concerned with such topics is the field of Qualitative Spatial and Temporal Reasoning (QSTR). More precisely, research topics in QSTR are formalisms and algorithmic methods for processing qualitative information about continuous spatial and/or temporal aspects of physical reality. Thus QSTR forms a distinct subfield within the broader AI community working on knowledge representation and reasoning and has attracted research interest for more than 25 years now. One of the main ideas in QSTR is to describe spatial or temporal phenomena in the world in qualitative formalisms that are tailored to specific reasoning tasks. Qualitative abstraction allows for compact representations of infinite domains and hence is considered key to solve reasoning tasks on such domains efficiently. In view of this motivation of QSTR research, it seems indicated to evaluate the quality of both representation formalisms and reasoning techniques with respect to different criteria including but not limited to expressiveness, efficiency, and cognitive adequacy.

In contrast to other established AI communities, the idea of benchmarking formalisms, reasoning procedures, and implemented systems has not played a prominent role so far. For example, performance analyses of QSTR algorithms or systems are often only conducted by empiric evaluations based on random samples of problem instances which in theory are known to be hard to solve. But this gives rise to the question whether evaluations on such problem instances is adequate, since random instances typically do not reflect problem structures that also occur in concrete problem domains. Moreover, little work has been done so far towards a systematic comparison of the variety of qualitative formalisms available in the literature, which seems a crucial deficit for practitioners who want to use QSTR formalisms in applications.

The availability of a benchmarking repository is not only useful for system developers, benchmarking is also essential to evaluate new strands of research. This lesson can be learned from other communities in computer science, such as Automated Theorem Proving (ATP), Boolean Satisfiability (SAT), Constraint Satisfaction (CSP), and Automated Planning, where benchmark repositories have proven beneficial to estimate weaknesses or strengths of particular approaches and to identify reoccurring structural properties of problems or tasks.

To initiate the development of a problem repository for QSTR, a AAAI Spring Symposium on *Benchmarking of Qualitative Spatial and Temporal Reasoning Systems* was held at Stanford University in March 2009. One of the main results of this symposium was that there is a broad interest in a repository of reasoning problems, QSTRLib, against which QSTR methods can be evaluated. QSTRLib is intended to borrow from the experiences made with the development of comparable problem libraries in other communities such as CSPLib, SATLib, SMT-Lib, and TPTP. It is to be expected that the development of a problem repository will boost research and evaluation standards within QSTR and thus will help to focus the community's efforts on significant, application-driven problems.

2 Report on the Seminar: Discussions and Results

The Dagstuhl seminar "QSTRLib" was planned as a successor event of the previously mentioned AAAI Spring Symposium. The intention for organizing this seminar was to discuss requirements on a problem library in a small group of researchers with expertise in benchmarking, in formal approaches to qualitative reasoning, or in specific application areas of QSTR.

More specifically, the main objectives of the seminar were to identify (a) a set of typical spatial and temporal problems and query tasks used in real world applications, (b) significant benchmark domains and problem instances, (c) measures to compare different QSTR formalisms in terms of expressiveness and efficiency, and (d) parameters to evaluate the performance of reasoning systems. In the following we provide a brief report on the course of the meeting and summarize the results of the discussions in the working groups and plenary sessions.

The plan for the seminar was to first collect spatial problems from various application scenario, then to develop classifications of these problems according to different viewpoints, and finally to analyze for selected problem instances how these could be represented in a problem library for QSTR. The seminar started on Monday, Oct 11, with a welcome session. In a series of short talks all seminar participants introduced themselves, highlighted their research interests, and explained their expectations on the seminar. After this S. Wölfl presented more background information on the benchmarking initiative and sketched a first draft of the formal language for the problem library, which will be required to represent problem domains and problem instances. A major point in the following discussion was the expressive power of the proposed language, the underlying formal logic, and the abstraction level at which the repository language allows for expressing spatial representation and reasoning tasks. A broad agreement could be achieved in that the proposed language may serve as a starting point, but that further developments of the language should be backed up on the experience of users working with the repository.

The aim of the two afternoon sessions was to collect a wide range of spatial representation and reasoning problems from different application scenarios. To feed in material, most seminar participants contributed flash presentations each focussing on a different use case, reasoning problem, tool, or data set. The abstracts of these presentations are attached to the report in appendix A. Afterwards, tools and demos were discussed in a more informal setting with the presenters. In the following breakout session small working groups were formed to collect spatial reasoning problems in different application scenarios including spatial reasoning in GIS, human spatial reasoning and reasoning with natural language, and spatial reasoning with sensor data. A selection of reasoning tasks identified in these working groups is presented in Figure 1.

The second workshop day started with a plenary session in which the Monday afternoon working groups reported back on their results. To come up with different classification schemes of spatial reasoning problems, new working groups were formed. One group developed a catalogue of reasoning problems that are tightly connected to CSP-based representation formalisms. This catalogue is organized along the dimensions *type of reasoning task* (e.g., satisfiability checking, constraint optimization), *semantics and representation of constraints* (e.g., sorts, constraint arity, combined formalisms), and *background data* (expected difficulty, computational complexity, problem source). A second group worked on spatial reasoning problems related to exploration and concept formation from sensor data. This group classified problems according to the aspects *scale space* (figural, vista, environmental, geographical), *type of dataset* (simulated/real world, static/dynamic scenes), *type of observer* (static/dynamic, direct/indirect). A third group explored spatial problems related to interpolation, configuration, planning, and visualization, and discussed examples that potentially cover a wide range of these aspects such as design consistency in architectural layouts and spatial planning. The fourth group worked an spatial problems related to data classification, matching, and querying of spatial information. This group developed a classification schema for problems along the categories *data type* (e.g., image data, video data, sensor data, map data), *spatial type* (e.g., points/lines/regions, dimension), *task type* (classification, clustering, matching, querying), *so-*

Application	Problem	Problem description / Example
Sensors	Recognition problems	Recognize the topological structure of complex areal objects monitored by a sensor network Recognize partially occluded objects from laser scans
	Concept formation	Learn concepts from data (e.g., learn events from video data)
	Interpolation problem	Interpolate world state from data from a sensor network (e.g., air pollution monitoring and modeling)
GIS	Query and retrieval	Find instances to queries satisfying spatial constraints
	Feature extraction	Extract features from data (e.g., define mountains by spatial and semantic constraints such as elevation, water systems, forests)
	Data integration	For map-like data using different semantic classification systems, check whether both sets conform to spatial or spatio-semantic constraints
	Matching problem	Given different representations of partially overlapping scenes, identify a correspondence between the entities in the overlap
	Visualisation / realization	Generate a visualization (e.g., a graphical representation) for a geographically plausible model of given approximate/imprecise/incomplete spatial data
Human spatial reasoning	Analogical spatial reasoning	Given two sequences of shapes, one complete, the other incomplete, predict the missing shape by analogical reasoning (typical examples of such tasks are part of IQ tests)
Natural language processing	Question answering	Answer a natural language question with spatio-temporal components (e.g., ”When was Dagstuhl part of France?”)

Table 1: Examples of spatial problems in different application contexts

lution type (binary, ranked, construction, mapping), and *language* (formal/natural, vocabulary). All groups also identified sources of application data that possibly could be used for benchmarking purposes (e.g., robot rescue, robot vision, adventure games, satellite data).

The goal of the Tuesday afternoon session was to study spatial problems in selected use cases in order to identify which parts and aspects of such problems can or should be represented in a benchmarking library. For this, rather small groups were formed to work out a detailed problem structuring in the following use cases:

– Recognizing human concepts from geodata: for example, what are the specific features of a mountain? How can mountains be recognized from the data? Do the recognition results correspond to how humans understand the concept?
– Spatial planning: for example, integrate different kinds of spatial planning tasks in a dish washing scenario
– Hide and seek (treasure hunting): How to represent goals, actions, and beliefs/cognitive representations of agents in different spatial environments with increasing complexity (“wumpus worlds”, computer games, robotics)
– Spatial reasoning with sensor networks: a fundamental task is to establish a cyclic ordering of the neighbors of a sensor. Can such on ordering be derived without (or with a limited) coordinate information of the sensors? Can the problem be represented in existing QSTR formalisms?

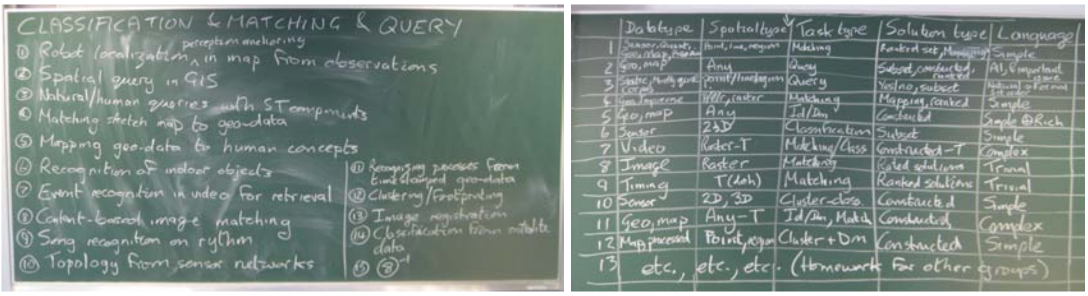

Figure 1: Classification schema of reasoning problems related to data classification, matching, and querying of spatial data

- Question answering on spatial configurations of countries, states, and cities (e.g., in an educational application context): how to mix spatial, temporal, epistemic, and ontological levels of knowledge representation?
- Sketch matching: How to match sketches to maps? How to match spatial information depicted in different, overlapping sketches?

The last day again started with a plenary session, in which the Tuesday evening working groups reported back on their results by highlighting special problems, the requirements of the problem, the kind of input, the kind of solutions, and possibly measures to evaluate the solution quality. It was discussed how selected spatial problems can be represented in the formal language presented on the first day. Moreover, G. Sutcliffe reported on the StarExec initiative, which is currently applying for funds for a cross-community infrastructure for logic solving. Finally, the meeting discussed the next steps to be accomplished to set up the benchmarking library. In particular, it was agreed that a detailed specification of the problem language is to be presented to a broader AI audience at the successor event of the seminar, namely, the IJCAI workshop *Benchmarks & Applications of Spatial Reasoning* in July 2011.

3 Summary and Outlook

Results of this seminar will be integrated into the proposed benchmarking library step-by-step. It is planned to start with a specification of a rather limited formal language that covers the symbolic formalisms and prominent reasoning tasks in QSTR research. Currently, a first draft of the language proposal is compiled and is planned to be available to the public by the end of April 2011. In the following months also the development of tools (in particular, parsers) supporting the language and the integration into existing reasoners such as SparQ and GQR will play an important role. A crucial point for the further development of the library will be to bridge the gap between potential expectations towards a problem library (i.e., the kind of problems users of the problem library would like to see included) and the level of reasoning support that users can expect from currently available reasoning engines. Nevertheless, the discussions in the seminar confirmed that interesting problem instances for the problem repository may be contributed from the following research areas:

- *Geographic Information Systems.* Qualitative reasoning methods are promising methods to check the integrity of information to be added to geographic knowledge bases and to rewrite possible queries against such knowledge bases.

- *Ontological reasoning.* Many knowledge bases (e.g., medical knowledge bases) could be enhanced by spatial relations between objects and/or temporal relations between events. Hybrid methods integrating ontological and spatial reasoning may allow for answering queries efficiently against such knowledge bases.
- *High-level agent control.* Qualitative representation formalisms provide natural representations of (spatial or temporal) situations arising in high-level agent control systems. In such systems the application of specialized qualitative spatial and temporal reasoning methods (used as external reasoning methods) can show considerable performance gains.

As a final remark, it should be mentioned that this 3-day seminar with 19 participants benefited greatly from the specific facilities at Schloss Dagstuhl, namely easy access to the relevant literature as well as the flexibility to work in small groups on specific topics and discuss the results in plenary sessions.

A Abstracts

A.1 Data and Use Cases

Alia Abdelmoty: ***Qualitative geospatial resources for building a geographic place ontology***

The recent trend of geo-referencing resources on the web has driven the need for designing and building geographical place ontologies; models of terminology and structure of geographic space and named place entities. A place ontology base extends the traditional notion of a gazetteer to encode rich spatial and non- spatial semantics, such as for example, historical and vernacular place names, events associated with a place, as well as qualitative spatial relationships between place instances. It is seen to play a key role with regard to facilitating the search for geo-referenced information and resources on the web. Resources for populating this ontology store include some ”formal” data sets in the form of maps, as well as other ”volunteered” data, collected in dedicated collaborative mapping sites and others applications on the collaborative and social web. In this work we used three resources, in particular, Wikipedia, Geonames and some data from the Ordnance Survey (OS) to build a geographic ontology of place. Geonames and the OS data were used as a source of quantitative spatial locations and Wikipedia was used as a source for qualitative spatial relationships between places. The method used for harvesting this information will be described and sample data sets will be shown. The place ontology is used as a test bed for evaluating a spatial ontology management system, that is aimed at integrating current semantic web technologies, in particular OWL2 with formalisms for QSR and existing GIS and spatial database technologies. Quantitative processing of geographic information is mixed with qualitative spatial reasoning in a hybrid architecture that allows for the deduction and spatial consistency checking over the ontology base. Some scenarios of the system in action will be demonstrated. Some interesting challenges that this case study presents of relevance to QSTR research are:

- Mining and encoding geospatial semantics from the web; including methods for dealing with fuzzy and incomplete spatial information,
- Linking multiple resources of these semantics; including issues of handling contradicting spatial information,
- Effectiveness of methods for integrating QSR with DL based technologies on the semantic web; should we strive for a homogenous approach and what implications, in terms of expressiveness, can be maintained?
- Scalability of the QSR formalisms, operating within the context of potentially very large and dynamic ontology bases,
- Strategies for integrating the quantitative reasoning (or geometric processing) within this framework.

References:

[1] Philip D. Smart, Alia I. Abdelmoty, Baher A. El-Geresy, and Christopher B. Jones. A framework for combining rules and geo-ontologies. In: *Web Reasoning and Rule Systems, First International Conference, RR 2007, Proceedings*. Ed. by Massimo Marchiori, Jeff Z. Pan, and Christian de Sainte Marie. LNCS 4524. Springer, 2007, pp. 133–147.

[2] Florian A. Twaroch, Christopher B. Jones, and Alia I. Abdelmoty. Acquisition of a vernacular gazetteer from web sources. In: *Proceedings of the First International Workshop on Location and the Web, LocWeb 2008*. Ed. by Susanne Boll, Christopher Jones, Eric Kansa, Puneet Kishor, Mor Naaman, Ross Purves, Arno Scharl, and Erik Wilde. ACM International Conference Proceeding Series 300. ACM, 2008, pp. 61–64.

[3] Alia I. Abdelmoty, Philip D. Smart, Baher A. El-Geresy, and Christopher B. Jones. Supporting frameworks for the geospatial semantic web. In: *Advances in Spatial and Temporal Databases, 11th International Symposium, SSTD 2009, Proceedings*. Ed. by Nikos Mamoulis, Thomas Seidl, Torben Bach Pedersen, Kristian Torp, and Ira Assent. LNCS 5644. Springer, 2009, pp. 355–372.

[4] Philip D. Smart, Alia I. Abdelmoty, Baher A. El-Geresy, and Christopher B. Jones. Semantic web rule languages for geospatial ontologies. In: *Handbook of Research on Emerging Rule-Based Languages and Technologies: Open Solutions and Approaches*. Ed. by A. Giurca, D. Gasevic, and K. Taveter. IGI Global, 2009, pp. 149–169.

Mehul Bhatt: *Reasoning about Space, Actions, and Change*

Qualitative spatial conceptualizations provide a relational abstraction and interface to the metrical realities of the physical world. Humans, robots and systems that act, and interact, are embedded in space. The space itself undergoes change all the time, typically as a result of volitional actions performed by an agent, and events, both deterministic and otherwise, which occur in the environment. Both categories of occurrences are a critical link to the external world, in a predictive as well as an explanatory sense: our anticipations of spatial reality conform to our commonsense knowledge of the effects of actions and events on material entities. Similarly, our explanations of the perceived reality too are established on the basis of such apriori established commonsense notions. We reason about space, actions and change in an integrated manner, either without being able to clearly demarcate the boundaries of each type of reasoning, or because such boundaries do not exist per se. Reasoning about space, actions, and change (RSAC) is a paradigm that positions such integrated reasoning as a useful paradigm for the utilization of qualitative spatial representation and reasoning techniques in application domains such as Event-based Process modelling (e.g., dynamic GIS), High-level Agent Control (e.g., Cognitive Robotics), Spatial Computing for Design (e.g., architecture), and Behaviour Interpretation and Analyses (e.g., Ambient and Smart Environments). RSAC emphasizes the role of existing logical formalisms in Space, Actions, and Change, and at specific integration tasks at a commonsense conceptual, formal representational, and computational level.

References:

[1] Mehul Bhatt and Seng Loke. Modelling dynamic spatial systems in the situation calculus. In: *Spatial Cognition and Computation* 8.1 (2008). Special Issue on Spatio-Temporal Reasoning, pp. 86–130.

[2] Mehul Bhatt. Reasoning about space, actions and change: A paradigm for applications of spatial reasoning. In: *Qualitative Spatial Representation and Reasoning: Trends and Future Directions*. Ed. by Shyamanta M. Hazarika. IGI Global, USA, 2010.

[3] Mehul Bhatt and Christian Freksa. Spatial computing for design: An artificial intelligence perspective. In: *Visual and Spatial Reasoning for Design Creativity (SDC'10)*. 2011.

[4] Mehul Bhatt, Carl Schultz, and Christian Freksa. The 'space' in spatial assistance systems: Conception, formalisation, and computation. In: *Representing space in cognition: Interrelations of behavior, language, and formal models*. Ed. by Thora Tenbrink, Jan Wiener, and Christophe Claramunt. Explorations in Language and Space. To appear. Oxford University Press, 2011.

[5] Mehul Bhatt, Hans Guesgen, Stefan Wölfl, and Shyamanta Hazarika. Qualitative spatial and temporal reasoning: Emerging applications, trends and future directions. In: *Spatial Cognition and Computation* 11.1 (2011).

Tony Cohn: *Learning about activities from video data*

In this talk I will present ongoing work at Leeds on building models of video activity. I will present techniques, both supervised and unsupervised, for learning the spatio-temporal structure of tasks and events from video or other sensor data. In both cases, the representation will exploit qualititive spatio-temporal relations. A novel method for robustly transforming video data to qualitative relations will be presented. For supervised learning I will show how the supervisory burden can be reduced using what we term ”deictic supervision”, whilst in the unsupervised case I will present a method for learning the most likely interpretation of the training data. I will also show how objects can be ”functionally categorised” according to their spatio-temporal behaviour and how the use of type information can help in the learning process, especially in the presence of noise. I will present results from several domains including a kitchen scenario and an aircraft apron.

References:

[1] Muralikrishna Sridhar, Anthony G. Cohn, and David C. Hogg. Learning functional object-categories from a relational spatio-temporal representation. In: *ECAI 2008 - 18th European Conference on Artificial Intelligence, Proceedings*. Ed. by Malik Ghallab, Constantine D. Spyropoulos, Nikos Fakotakis, and Nikolaos M. Avouris. Frontiers in Artificial Intelligence and Applications 178. IOS Press, 2008, pp. 606–610.

[2] Krishna S. R. Dubba, Anthony G. Cohn, and David C. Hogg. Event model learning from complex videos using ILP. in: *ECAI 2010 - 19th European Conference on Artificial Intelligence, Proceedings*. Ed. by Helder Coelho, Rudi Studer, and Michael Wooldridge. Frontiers in Artificial Intelligence and Applications 215. IOS Press, 2010, pp. 93–98.

[3] Muralikrishna Sridhar, Anthony G. Cohn, and David C. Hogg. Discovering an event taxonomy from video using qualitative spatio-temporal graphs. In: *ECAI 2010 - 19th European Conference on Artificial Intelligence, Proceedings*. Ed. by Helder Coelho, Rudi Studer, and Michael Wooldridge. Frontiers in Artificial Intelligence and Applications 215. IOS Press, 2010, pp. 1103–1104.

[4] Muralikrishna Sridhar, Anthony G. Cohn, and David C. Hogg. Unsupervised learning of event classes from video. In: *Proceedings of the Twenty-Fourth AAAI Conference on Artificial Intelligence, AAAI 2010*. Ed. by Maria Fox and David Poole. AAAI Press, 2010.

Matt Duckham: *Spatial reasoning in geosensor networks*

Background: Today, geosensor networks have limited spatial reasoning capabilities. Potentially, integrating spatial reasoning capabilities with geosensor networks could result in networks that are more scalable, more efficient (because they can use reasoning capabilities to reduce the amount of communication required), and with lower latencies (because events detected by the network do not need to be communicated to and collated by a centralized server).
Case study/application of spatial reasoning: We are reasoning about spatial relations and events for regions monitored by a sensor network. These regions might be “real” (like a pollution spill) or the result of thresholding a continuous field (like regions of high temperature). For example, in a fire warning system we might wish to determine the topological relations between regions of low soil moisture and high fuel load. The key challenges we face are:
(1) Reasoning capabilities need to be decentralized, in the sense that no single node ever possess global knowledge of the entire system state. Instead each node may know about its own sensed values, and may communicate with spatially proximal neighbor nodes. But no single node has global knowledge of, for example, the locations of all the other nodes at the boundary of the low soil moisture region, or the identities of all nodes that detect high fuel load. Thus, the reasoning capabilities must operate with the partial knowledge of regions available to nodes and in their spatial neighborhoods.
(2) Because of the spatial distribution of nodes and frequency of sensing, the entire system can only capture granular spatiotemporal information about the environment. Hence, spatial reasoning capabilities need to enable nodes to reason about what possible spatial relations *might* hold, given the coarse-grained spatial and temporal information they possess.

Jason Jingshi Li: ***Monitoring the air we breath – the OpenSense Project at EPFL***

Air pollution monitoring in urban areas is an important research topic as common air pollution have a direct effect on the health of many of the city's inhabitants. The next generation of air pollution monitoring systems will involve a wide variety of data sources such as meteorological data, ozone, nitric oxide, sulfur dioxide and fine particle sensors. They measure complex atmospheric chemistry and transport processes. The sensors can either be stationary or mobile, and the information can be communicated in real time via a wireless network. The OpenSense project at EPFL is about building the infrastructure of such a monitoring system, integrating data from a heterogenous mobile sensor network and perform real-time data gathering and environmental modeling.

The processes that influence the spatial and temporal distribution of air pollution are extremely complex, hence models are required to clean and interpret the data, and differentiate the various processes that contribute to the distributions. Current models used by environmental scientists typically solves a series of differential equations on a grid map. This approach becomes computational infeasible when we support sensors that cover large areas with fine-grained grids. Furthermore, much of the atmospheric phenomena such as trends of humidity for a given wind direction depend essentially on the topology of the landscape, and the data are likely to be similar. Therefore, it would be advantageous to precompute the correlations observed in numerical simulations and store them in a separate qualitative, region-based model. The qualitative model can then be used for performing tasks that are intractable for numerical models in real time. Such qualitative model should also reflect the structure of the underlying processes and allow the decision makers to interpret the states of the model in a meaningful way.

The project is still in its early phase, and mobile air-quality sensors are expected to be deployed in 2011. Once we have the data we intend to make them publicly available.

Reinhard Moratz: ***Qualitative spatial reasoning about oriented objects***

This talk will present some new work on qualitative spatial reasoning. Computers can do very precise calculations about complex spatial configurations. But these configurations have to be fully specified in metric terms (e.g. computer aided design, computer graphics). In qualitative reasoning about underdetermined spatial information humans still by far outperform automated reasoning algorithms (e.g. constructing diagrams based on linguistic abstract descriptions). A qualitative representation provides mechanisms that characterize the essential properties of objects or configurations. In contrast, a quantitative representation establishes a measure in relation to a unit of measurement. Qualitative spatial calculi are based on qualitative spatial representation, and usually deal with elementary objects (e.g., regions, points) and qualitative relations between them (e.g., 'included in,' 'adjacent,' 'to the left of"). This is the reason why qualitative descriptions are quite natural for people. The two main trends in qualitative spatial calculus research are topological reasoning about regions and positional (e.g., direction and distance) reasoning about point configurations.

Björn Pelzer: ***LogAnswer***

LogAnswer is a German language question answering (QA) system. Its goal is to provide correct and concise answers to user questions phrased in natural language (NL). For this purpose the system integrates an automated theorem prover in a framework of NL processing tools. The latter serve to construct an extensive knowledge base automatically from the German Wikipedia, while the automated theorem prover makes it possible to derive answers by deductive reasoning.

Our application aims at answering user questions in various contexts, for example in the browser of personal computers and mobile devices using an interface similar to a search engine, or as a virtual user in question answering forums. This entails a diverse range of questions, and one aspect to consider is the handling of questions regarding spatial and temporal (ST) knowledge. Several obstacles can be identified: Textual sources use no standardized way of expressing ST information, so the parsing and translation into a formal knowledge base, already hampered by the ambiguities of natural language, should nevertheless result in a consistent representation of ST data. Also, as filtering methods are used so that the prover only operates on a manageable and query relevant fragment of the knowledge base, it is difficult to ensure that this fragment contains the relevant ST data if it is scattered throughout the underlying textual sources. Finally, logical rules must allow the theorem prover to perform ST reasoning on this data in conjunction with the other logical knowledge representation.

The current ST reasoning capabilities of LogAnswer are only rudimentary, so we are interested in any methods that could help overcome these hurdles.

References:

[1] Ulrich Furbach, Ingo Glöckner, Hermann Helbig, and Björn Pelzer. LogAnswer - A deduction-based question answering system (System Description). In: *Automated Reasoning, 4th International Joint Conference, IJCAR 2008, Proceedings*. Ed. by Alessandro Armando, Peter Baumgartner, and Gilles Dowek. LNCS 5195. Springer, 2008, pp. 139–146.

[2] Ingo Glöckner and Björn Pelzer. Exploring robustness enhancements for logic-based passage filtering. In: *Knowledge-Based Intelligent Information and Engineering Systems, 12th International Conference, KES 2008, Proceedings*. Ed. by Ignac Lovrek, Robert J. Howlett, and Lakhmi C. Jain. LNCS 5177. Springer, 2008, pp. 606–614.

[3] Björn Pelzer and Ingo Glöckner. Combining theorem proving with natural language processing. In: *Proceedings of the First International Workshop on Practical Aspects of Automated Reasoning*. Ed. by Boris Konev, Renate A. Schmidt, and Stephan Schulz. CEUR Workshop Proceedings 373. CEUR-WS.org, 2008.

[4] Ulrich Furbach, Ingo Glöckner, and Björn Pelzer. An application of automated reasoning in natural language question answering. In: *AI Communications* 23.2-3 (2010). PAAR Special Issue, pp. 241–265.

[5] Ulrich Furbach, Ingo Glöckner, Hermann Helbig, and Björn Pelzer. Logic-based question answering. In: *KI - Künstliche Intelligenz* 24.1 (2010). Special Issue on Automated Deduction, pp. 51–55.

Marco Ragni, Philip Stahl: *Challenges in solving IQ-tests*

An interesting test bed for a variety of qualitative calculi offer so-called culture-fair IQ-tests. These tests consist typically of tasks containing arrangements of geometrical objects which change their relation. These transformations, which can be classified as qualitative, must be derived. Such tasks offer the possibility to introduce a difficulty measure to classify the human reasoning task with respect to a functional measure. We implemented a program which is able to solve a class of matrix tasks and to evaluate their complexity by our measure. The results of the evaluation are compared with the empirical difficulty ranking from Cattell's Culture Fair Test. At the current stage we have some difficulties with respect to certain problem classes containing topological concepts and an integration of quantitative information, which I would like to discuss.

References:

[1] Marco Ragni, Stefan Schleipen, and Felix Steffenhagen. Solving proportional analogies: A computational model. In: *Analogies: Integrating Multiple Cognitive Abilities*. Ed. by Angela Schwering, Ulf Krumnack, Kai-Uwe Kühnberger, and Helmar Gust. Publications of the Institute of Cognitive Science 5. Osnabrueck, 2007, pp. 51–56.

[2] Philip Stahl and Marco Ragni. Complexity in analogy tasks: An analysis and computational model. In: *ECAI 2010 - 19th European Conference on Artificial Intelligence, Proceedings*. Ed. by Helder Coelho, Rudi Studer, and Michael Wooldridge. Frontiers in Artificial Intelligence and Applications 215. IOS Press, 2010, pp. 1041–1042.

[3] Marco Ragni, Philip Stahl, and Thomas Fangmeier. Cognitive complexity in matrix reasoning problems. In: *European Conference on Cognitive Science (EuroCogSci 2011)*. Ed. by Annette Karmiloff-Smith, Boicho Kokinov, and Nancy Nersessian. Mahwah, NJ: Erlbaum, 2011.

Paulo E. Santos: *Knots and holes: A benchmark of problems for elaboration tolerant spatial manipulation*

The goal of this talk is two-fold: we first discuss various kinds of possible benchmarks for spatial reasoning, including industrial size data sets, data sets for efficiency checking and problem repositories; second, we propose a spatial reasoning problem set whose purpose is to instigate the development of elaboration tolerant formalisations of domains involving actions on non-trivial objects such as flexible strings and holes.

To obtain a suitable representation of spatial domains containing strings and holes we have adopted the following methodology. We begin from specific formalisations of particular scenarios, what usually implies a more abstract and simplified description level, and advance then towards more general representations to cover different domains, what necessarily implies a more fine-grained ontology. As a starting point, puzzle-like examples constitute a good test bed, as they offer a small number of objects while keeping enough complexity for a challenging problem of knowledge representation. Thus, puzzles involving physical objects are our drosophila, i.e. our base line from which we develop AI research.

References:

[1] Pedro Cabalar and Paulo E. Santos. Strings and holes: An exercise on spatial reasoning. In: *Advances in Artificial Intelligence - IBERAMIA-SBIA 2006, 2nd International Joint Conference, 10th Ibero-American Conference on AI, 18th Brazilian AI Symposium, Proceedings*. Ed. by Jaime Simão Sichman, Helder Coelho, and Solange Oliveira Rezende. LNCS 4140. Springer, 2006, pp. 419–429.

[2] P. Santos and P. Cabalar. The space within the Fisherman's Folly: Playing with a puzzle in mereotopology. In: *Spatial Cognition and Computation* 8.1 (2008), pp. 47–64.

[3] Pedro Cabalar and Paulo E. Santos. Formalising the Fisherman's Folly puzzle. In: *Artificial Intelligence* 175.1 (2011). Special Issue John McCarthy's Legacy, pp. 346–377.

Jan Oliver Wallgrün: *Learning route graphs from local observations*

Spatial reasoning plays an important role in learning spatial representations of unfamiliar environments [2, 3]. This case study addresses the application of qualitative formalism for reasoning about directions to the problem of learning graph models (so-called route graphs [1]) from local observations [4]. Multiple hypotheses about the layout of the environment are considered in parallel and consistency checking is used to discard wrong hypotheses as early as possible.

The framework developed for the investigation of the route graph learning problem allows for comparing existing qualitative spatial calculi regarding their expressivity and reasoning properties as well as different reasoning techniques or engines using a concrete application domain

[5]. It has also been used to investigate the interplay of directional reasoning with another type of spatial constraint, namely planarity. Tools for generating random problem instances (sequences of local observations and actions), either using artificial graph environments or based on sensor data from real indoor environments, have been developed. In experiments conducted with the presented framework, shortcomings of existing qualitative direction calculi (both absolute and relative ones) with respect to the addressed problem domain and challenges for future research were identified. Moreover, we expect that extensions of the described approach to other reasoning tasks in route graphs such as localization or path planning under multiple hypotheses or combinations with other kinds of spatial representation approaches should also provide for interesting benchmark problems for qualitative spatial reasoning.

References:

[1] Steffen Werner, Bernd Krieg-Brückner, and Theo Herrmann. Modelling navigational knowledge by route graphs. In: *Spatial Cognition II - Integrating Abstract Theories, Empirical Studies, Formal Methods, and Pratical Applications*. Ed. by Christian Freksa, Christopher Habel, Wilfried Brauer, and Karl F. Wender. LNCS 1849. Springer, 2000, pp. 295–316.

[2] Emilio Remolina and Benjamin Kuipers. Towards a general theory of topological maps. In: *Artificial Intelligence* 152.1 (2004), pp. 47–104.

[3] Francesco Savelli and Benjamin Kuipers. Loop-closing and planarity in topological map-building. In: *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS-04)*. 2004, pp. 1511–1517.

[4] Jan Oliver Wallgrün. *Hierarchical Voronoi graphs – Spatial Representation and Reasoning for Mobile Robots*. Springer, 2010.

[5] Jan Oliver Wallgrün. Qualitative spatial reasoning for topological map learning. In: *Spatial Cognition and Computation* 10.4 (2010), pp. 207–246.

Jan Oliver Wallgrün, Diedrich Wolter: *Qualitative matching of spatial information*

In the domain of geographic information systems (GIS) many problems of managing spatial information require the identification of the correct correspondences between objects from two or more spatial knowledge bases. Examples are the problem of merging two spatial knowledge bases and the problem of querying a spatial database, which can be seen as the task of finding configurations in the database that match the configuration described in the query. Solving such matching problems is best done on a qualitative level if the query already involves qualitative spatial relations (e.g., a query language with qualitative relations) or if the data sources can only be considered reliable on a coarse, qualitative level (e.g., when dealing with sketch maps) [1]. Qualitative matching can be formalized very generally as a largest common subgraph isomorphism problem between qualitative constraint networks and requires good heuristics supported by spatial reasoning to be applicable in the GIS domain. Additional challenges arise when relations from multiple spatial calculi are involved and only imperfect matchings exist.

In a recent case study [2], we investigated qualitative matching by looking at the problem of identifying the corresponding parts in two (or more) sketch maps of road networks drawn on a screen. The sketch maps are interpreted qualitatively using a set of spatial calculi (e.g., to capture the topology of the road network and directions). A particular matching problem is expressed as a single constraint network and an A* search is performed that searches for the optimal matching given by an evaluation function that trades off the size of the matching against the set of qualitative interpretations it satisfies. Qualitative spatial reasoning is used to prune the search space by improving the heuristic assessment. We will show the developed sketch system together with examples that illustrate the challenges of the underlying matching problem.

References:

[1] Max J. Egenhofer. Query processing in spatial-query-by-sketch. In: *Journal of Visual Languages and Computing* 8.4 (1997), pp. 403–424.

[2] Jan Oliver Wallgrün, Diedrich Wolter, and Kai-Florian Richter. Qualitative matching of spatial information. In: *18th ACM SIGSPATIAL International Symposium on Advances in Geographic Information Systems, ACM-GIS 2010, Proceedings*. Ed. by Divyakant Agrawal, Pusheng Zhang, Amr El Abbadi, and Mohamed F. Mokbel. ACM, 2010, pp. 300–309.

Matthias Westphal, Stefan Wölfl: ***Guiding manipulation plan generation by qualitative spatial reasoning***

Motion planning is a complex task for a robot that needs to grasp objects in its environment, specifically if narrow spatial conditions restrict the action space of the robot arm, which is equipped with a gripper. Usually probabilistic roadmap planners are used to generate such plans, but plans from such planners often lead to arm movements that are sub-optimal and also far from how a human might perform a comparable grasping task. In our talks we present a hybrid framework that improves the quality of generated plans in many spatial situations. The idea is to guide the probabilistic roadmap planner by a qualitative spatial plan that provides an approximation of a geometric solution on a qualitative level of description.
We state the problem on a formal level and discuss how the problem can be cast as a benchmark problem for research in the qualitative spatial reasoning domain. Moreover, we discuss two simple qualitative formalisms in which a baseline solution to the problem can be represented, and demonstrate how qualitative plans can be employed to guide the geometric planning process. Then we describe the overall architecture of our hybrid planning approach. We present the results of an evaluation of the architecture in different spatial settings and discuss how the quality of generated plans can be improved by qualitative spatial reasoning techniques.

References:

[1] Matthias Westphal, Christian Dornhege, Stefan Wölfl, Marc Gissler, and Bernhard Nebel. Guiding the generation of manipulation plans by qualitative spatial reasoning. In: *Spatial Cognition and Computation* 11.1 (2011), pp. 75–102.

A.2 Tools and Demos

Mehul Bhatt: ***DSim: An architecture design assistance tool***

The system DSim involves several different components, principle among them being conceptual modelling and design abstraction, reasoning about design requirements formulated as sets of constraints over some spatial domain, multi-perspective and multi-modal data access, and design simulation and visualization capabilities. These different components of our ongoing work are prototyped within one practical tool, which we refer to as DSim, an assistance tool being built with the philosophy of empowering a functionally-driven creative spatial design activity. (http://www.sfbtr8.spatial-cognition.de/designspace.html)

Mehul Bhatt: ***ExpCog: An experimental cognitive robotics framework***

ExpCog is a high-level cognitive robotics framework aimed at integrating logic-based and cognitively-driven agent-control approaches, qualitative models of space and the ability to apply these in the form of planning, explanation and simulation in a wide-range of robotic-control platforms and simulation environments. In addition to its primary experimental function, the framework also has a utility toward didactic purposes, e.g., as a teaching and experimental aid in courses on Artificial Intelligence, and other specialized courses, tutorials involving some form of high-level robot control. (http://cindy.informatik.uni-bremen.de/cosy/staff/bhatt/ExpCog/www/)

Matthias Westphal, Stefan Wölfl: *GQR: A generic qualitative reasoner*

GQR (Generic Qualitative Reasoner) is a constraint solver and algorithm library for binary qualitative constraint calculi as studied in the field of qualitative spatial and temporal reasoning (QSTR). The aims for the development of GQR has been twofold: first to provide a generic tool for solving reasoning tasks expressible in constraint-based QSTR formalisms and second to provide a library of reference implementations of algorithms developed in the QSTR community. It provides algorithms for syntactic verification of calculi, (path) consistency, and minimal labeling. GQR employs state-of-the-art techniques in both qualitative and constraint reasoning, such as heuristic search and usage of known tractable subclasses. The main focus in the design and implementation of GQR is to provide a generic and extensible solver that preserves efficiency and scalability.

References:

[1] Zeno Gantner, Matthias Westphal, and Stefan Wölfl. GQR - A fast reasoner for binary qualitative constraint calculi. In: *Proceedings of the AAAI'08 Workshop on Spatial and Temporal Reasoning*. 2008.

[2] Matthias Westphal and Stefan Wölfl. Qualitative CSP, finite CSP, and SAT: Comparing methods for qualitative constraint-based reasoning. In: *IJCAI 2009, Proceedings of the 21st International Joint Conference on Artificial Intelligence*. Ed. by Craig Boutilier. 2009, pp. 628–633.

Diedrich Wolter: *SparQ*

SparQ (http://www.sfbtr8.uni-bremen.de/project/r3/sparq/) is a freely available spatial reasoning toolbox that aims at providing an application- oriented collection of tools for reasoning with qualitative spatio-temporal knowledge. Thus, SparQ includes a set of atypical "reasonings" tasks such as mapping quantitative data as obtained from sensors to qualitative knowledge or sensibly resolving conflicts in inconsistent knowledge bases. Among these tools, constraint-based qualitative reasoning plays a major role.

Typically, constraint-based reasoning with qualitative representations pursues a relation-algebraic approach by exploiting converse and composition tables to decide local consistency. In some cases this approach is sufficient for deciding consistency, but what about the other cases? In our project we are aiming at a "gold standard" that, given adequate computational resources, is capable of handling any consistency problem with qualitative spatio-temporal knowledge. We believe that the field of algebraic geometry provides us with appropriate methods for developing this gold standard. Ultimately, this method would be applicable to decide whether certain specialized decision procedures are applicable for a problem at hand (e.g., whether composition-based reasoning can decide consistency for a given calculus).

References:

[1] Diedrich Wolter and Lyudmila Moshagen. Algebraic methods for analyzing qualitative spatio-temporal calculi. In: *Proceedings of the ECAI-Workshop on Spatial and Temporal Reasoning*. 2008.

[2] Diedrich Wolter and Jae Hee Lee. Qualitative reasoning with directional relations. In: *Artificial Intelligence* 174.18 (2010), pp. 1498–1507.

A.3 Logic, Reasoning, and Benchmarking

Christoph Benzmüller: *Reasoning within and about combinations of logics in simple type theory*

Various prominent logics can be elegantly embedded in simple type theory [6, 3]. Examples include (quantified) multimodal logics and intuitionistic logics, logics for security, and logics for spatial reasoning. Furthermore, simple type theory is sufficiently expressive to model combinations of embedded logics and it has a well understood semantics [1]. Off-the-shelf reasoning systems for simple type theory exist that can be uniformly employed for reasoning within and about combinations of logics [4]. One example system is our own cooperative higher-order–first-order automated theorem prover LEO-II [2] – the winner of the typed higher-order form (THF) division of the CASC-J5 competition at IJCAR 2010. We will demonstrate that LEO-II can successfully automate simple problems requiring combinations of logics, e.g., logics for epistemic and spatial reasoning (a respective example problem has been presented in [4]). We will also demonstrate recent results on reasoning about logics, for example, a verification of all logic relationships in the modal logic cube in less than 40 sec. [5].

References:

[1] Christoph Benzmüller, Chad E. Brown, and Michael Kohlhase. Higher-order semantics and extensionality. In: *J. Symb. Log.* 69.4 (2004), pp. 1027–1088.

[2] Christoph Benzmüller, Lawrence C. Paulson, Frank Theiss, and Arnaud Fietzke. LEO-II – A cooperative automatic theorem prover for classical higher-order logic (System Description). In: *Automated Reasoning, 4th International Joint Conference, IJCAR 2008, Proceedings*. Ed. by Alessandro Armando, Peter Baumgartner, and Gilles Dowek. LNCS 5195. Springer, 2008, pp. 162–170.

[3] Christoph Benzmüller and Lawrence C. Paulson. Quantified multimodal logics in simple type theory. In: *CoRR* abs/0905.2435 (2009).

[4] Christoph Benzmüller. Combining logics in simple type theory. In: *Computational Logic in Multi-Agent Systems, 11th International Workshop, CLIMA XI, Proceedings*. Ed. by Jürgen Dix, João Leite, Guido Governatori, and Wojtek Jamroga. LNCS 6245. Springer, 2010, pp. 33–48.

[5] Christoph Benzmüller. Verifying the modal logic Cube is an easy task (for higher-order automated reasoners). In: *Verification, Induction, Termination Analysis*. Ed. by Simon Siegler and Nathan Wasser. LNCS 6463. Springer, 2010, pp. 117–128.

[6] Christoph Benzmüller and Lawrence C. Paulson. Multimodal and intuitionistic logics in simple type theory. In: *Logic Journal of the IGPL* 18.6 (2010), pp. 881–892.

Manuel Bodirsky: *Complexity of qualitative calculi: A universal-algebraic approach*

The computational complexity of a constraint satisfaction problem (CSP) crucially depends on the type of constraints that are allowed in the input instances; the set of all relations allowed in the input is called the *constraint language* of the CSP. In the last decade, considerable progress has been made concerning the question for which constraint languages the corresponding CSPs can be solved in polynomial time, and for which constraint languages the CSPs are NP-hard. The most powerful approach in this context, in particular when the domain of the CSP is finite, is the so-called *universal-algebraic* approach, linking complexity questions for CSPs with deep questions of independent interest in universal algebra.

In my research, I work on extensions of the universal-algebra approach to CSPs with infinite domains. It turns out that such an extension is possible when the constraint language is ω-categorical, a well-studied concept from model theory. Most of the calculi that have been investigated in qualitative reasoning can be formulated with ω-categorical constraint languages.

This observation has many applications when we want to systematically understand the computational complexity of qualitative reasoning problems in time and space [3, 1, 2].
In this workshop, I want to learn about new qualitative calculi and their applications, and about industrial problems that can be modeled with such calculi, and I want to share the recent techniques obtained with the universal algebraic approach to analyze computational complexity and devising new efficient solvers.

References:

[1] Manuel Bodirsky and Jan Kára. The complexity of temporal constraint satisfaction problems. In: *Journal of the ACM* 57.2 (2009). An extended abstract appeared in the proceedings of STOC'08.

[2] Manuel Bodirsky and Michael Pinsker. Schaefer's theorem for graphs. In: Accepted for publication in STOC'11. 2011.

[3] Manuel Bodirsky, Michael Pinsker, and Todor Tsankov. Decidability of definability. In: Accepted for publication in LICS'11. 2011.

Geoff Sutcliffe: *The TPTP World - Infrastructure for automated reasoning*

The TPTP World is a well known and established infrastructure that supports research, development, and deployment of Automated Theorem Proving (ATP) systems for classical logics. The data, standards, and services provided by the TPTP World have made it increasingly easy to build, test, and apply ATP technology. The TPTP World includes the TPTP problem library, the TSTP solution library, standards for writing ATP problems and reporting ATP solutions, tools for processing ATP problems and solutions, and harnesses for controlling the execution of ATP systems and tools. The TPTP World infrastructure has been deployed in a range of applications, in both academia and industry.

References:

[1] Geoff Sutcliffe. The TPTP problem library and associated infrastructure. The FOF and CNF parts, v3.5.0. In: *Journal of Automated Reasoning* 43.4 (2009), pp. 337–362.

[2] Geoff Sutcliffe. The TPTP world - Infrastructure for automated reasoning. In: *Logic for Programming, Artificial Intelligence, and Reasoning - 16th International Conference, LPAR-16, Revised Selected Papers*. Ed. by Edmund M. Clarke and Andrei Voronkov. LNCS 6355. Springer, 2010, pp. 1–12.

Geoff Sutcliffe: *StarExec: Cross-community infrastructure for logic solving*

Ongoing breakthroughs in important research areas depend on continuing advances in high-performance automated theorem proving tools. Important examples include program verification and analysis, combinatorial design, hardware certification, computer security, planning and artificial intelligence, and the proposed semantic web. The typical use of these tools is as backends: application problems are translated by an application tool into (often very large or complex) logic formulas, which are then handed off to a logic solver. Over the years, distinct solver communities have grown up around different logics. While these communities have achieved impressive results, specialization has resulted in some barriers between communities, including mutual access to artifacts like solvers and benchmarks. Many communities have independently built their own research and development infrastructures, including standard formats for logic formulas, libraries of benchmark formulas, and regular solver competitions or solver-execution services, to spur solver advances and compare solvers. This duplication of equipment and human effort across logic-solving communities is wasteful, poses a significant barrier to entry for newly developing subfields, and limits the exchange of ideas between communities. A shared computing infrastructure for logic solving will eliminate these effects. The StarExec project will develop a single piece of shared computing infrastructure that can be used by many different logic solver communities. StarExec will (i) allow each solver community to manage its benchmark library, community membership, and run its solver competition, on a single shared cluster of compute nodes; (ii) provide solver execution and comparison services for registered users and the public; and (iii) provide services that will help connect different logic-solving communities. The latter will include translators between (compatible) logics, and a proof checking service. StarExec will utilize community-input mechanisms to ensure the service meets the needs of its target communities and individual users.

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