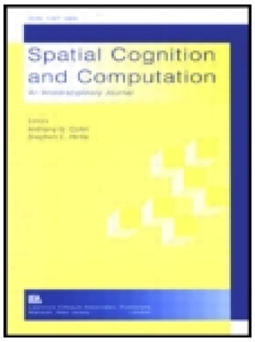

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Qualitative Spatial and Temporal Reasoning: Emerging Applications, Trends, and Directions

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1. A BRIEF 'SPATIOTEMPORAL' CONTEXT

The field of Qualitative Spatial and Temporal Representation and Reasoning (QSTR) has evolved as a specialised discipline within Artificial Intelligence (Allen, 1983; Freksa, 1991; van Beek, 1992; Ladkin & Maddux, 1994; Cohn & Renz, 2007; Renz & Nebel, 2007). Recent years have witnessed remarkable advances in some of the long-standing problems of the field, primarily pertaining to spatial calculi and model construction issues emanating from the founding premises and early work in the community (Ligozat, 1990; Guesgen & Hertzberg, 1993, 1988). Subsequently, major developments have accrued with new results about tractability of spatial calculi and characterisation of important subclasses of relations (e.g., Nebel & Bürckert, 1994; Bessière et al., 1996; Renz, 1999, 2007; Li et al., 2009) and explicit construction of models of one or more aspects of space (e.g., Freksa, 1992; Randell et al., 1992; Cohn et al., 1997; Bennett, 2001; de Weghe et al., 2005; Moratz, 2006). Similar to these works, which are situated within an Artificial Intelligence/Knowledge Representation (KR) context, many crucial advances have accrued from other communities concerned with the development of formalisms and algorithms for modelling and reasoning about spatial information, a prime example here being the domain of spatial information theory for Geography (and Geographic Information Systems (GIS)) (Egenhofer & Franzosa, 1991; Egenhofer & Mark, 1995).

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More recently, developments in QSTR strike a direct resonating chord with some of the early foundational work in the area of commonsense reasoning and naive physics (McCarthy & Hayes, 1969; Hayes, 1979, 1985a, 1985b). These include the development of new areas such as the emergence of integrated spatiotemporal calculi, spatiotemporal dynamics, commonsense reasoning about space, and the use of non-monotonic reasoning techniques for reasoning about spatial change (Galton, 2000; Hazarika, 2005; Bhatt & Loke, 2008; Bhatt, 2010a).[1]

There has also been an identifiable shift in recent years from an emphasis on developing new and more powerful qualitative spatial and temporal reasoning mechanisms to applying these in real-world applications. This is reflected not only in the literature at large, and the papers presented in this issue, but also by the focus and thematic distribution of initiatives and focus groups within the spatial and temporal reasoning community. Indeed, this special issue was conceived out of the experiences and successes of events such as the long-standing QSTR workshops at IJCAI, ECAI and AAAI, the workshop on Spatio-Temporal Dynamics (STeDy), the QSTRLib Benchmarking initiative, and the application-driven Space, Time and Ambient Intelligence (STAMI) events. In fact, three of the four research articles included in this special issue are extended and revised contributions from the QSTR Workshop at IJCAI 2009, the AAAI Spring Symposium 2009, and STAMI 2009, respectively.

From an application perspective, initiatives like STAMI show that spatial and temporal reasoning is reaching out to other areas. Especially areas like *ambient intelligence* and *cognitive robotics* benefit from this outreach. This is not just for applying spatial and temporal reasoning in these areas, but for interweaving them with the formalisms and methods used in these areas. For example, *behaviour recognition* in smart homes often employ graphical models like hidden Markov chains. By combining them with contextual information about space and time, the performance of these models can be boosted (e.g., see [Chua et al., 2009]). Such cross-fertilizations are clearly identifiable in the recent work in *cognitive vision* (Dubba et al., 2010; Sridhar et al., 2010), where the demonstrated interactions and integrations of techniques from machine learning, inductive logic programming, and spatiotemporal modelling may serve as a blue-print for the construction of hybrid intelligent systems dealing with real-world spatial information. The set of spatial relations used in the 9-Intersection Model (Egenhofer & Franzosa, 1991) has become part of the OpenGIS Implementation Specifications (ISO 19107) and are currently also supported by some commercial GIS products. In the domain of *spatial computing for design* (Bhatt & Freksa, 2011), e.g., for architecture design assistance, the integration of spatial reasoning with other forms of reasoning such as conceptual/ontological and (spatio-)terminological inference and Con-

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[1] For thorough reviews and historical perspectives on the developments in QSTR, interested readers may consult (Cohn & Hazarika, 2001; Cohn & Renz, 2007; Renz & Nebel, 2007).

straint Logic Programming (CLP) (Jaffar & Maher, 1994) has led to encouraging results, interesting fundamental questions, and possibilities for the application of QSTR in an area (i.e., CAAD) with a potential industrial impact.

Cognitive approaches characterise spatial information processing in qualitative spatial reasoning, and its applicability in spatial systems. This is expected to further drive and solidify the initial interest of interdisciplinary AI researchers in qualitative representation and reasoning, spatiotemporal interactions, the formal modelling of dynamic spatial systems, and commonsense reasoning about space. Within QSTR, qualitative conceptualisations of space and algorithmic techniques for efficiently reasoning with them are well-established, but recognized to be sufficient only for specific qualitative spatial formalisms/reasoning tasks. These techniques also manifest themselves in several ways as practical tools aimed at providing general consistency and constraint satisfaction tasks, prime examples here being *SparQ* (Wallgrün et al., 2007), *GQR* (Westphal et al., 2009), and the generic toolkit *QAT* for n-ary calculi (Condotta et al., 2006).

There is now a clearly felt need within the QSTR community to utilise the abstraction mechanisms, formalisms and algorithmic apparatus that has been constructed in recent years within novel application scenarios, and to even focus on evaluation standards and benchmarking problems for fundamental reasoning tasks as construed within the context of qualitative spatial and temporal formalisms. More generally, the key challenge is to broaden the initial interpretation of '*spatial reasoning*' to include classical and non-classical inference patterns, as they accrue within a spatial, spatiotemporal, action and change, ontological, and commonsense reasoning context. We discuss these aspects in the remaining part of the paper.

2. SPATIOTEMPORAL DYNAMICS: A PERSPECTIVE

From a more fundamental point of view, spatial and temporal reasoning have gone down slightly different paths in recent years. In the early days of spatial reasoning, dating back to the late eighties and early nineties, spatial reasoning was often closely related to temporal reasoning. This primarily includes early work on constraint-based approaches on spatiotemporal reasoning and tractability issues thereof (Guesgen & Hertzberg, 1993, 1988; Ligozat, 1990; Nebel & Bürckert, 1994; Bessière et al., 1996). In recent years not so much the commonalities but the intrinsic properties of either spatial or temporal reasoning have been exploited. Even though many QSTR formalisms have been shown to be NP-hard, maximal tractable subsets of well known calculi have been identified, and comparision methods and automatic methods for finding tractable subsets have been developed (Renz, 1999; Westphal & Woelfl, 2009; Li et al., 2009).

The principal emphasis of research in the qualitative spatial domain, however, has centred on the development of new calculi for spatial information representation, construction of efficient algorithms for solving spatial consistency problems and the study of their tractability properties. Furthermore, the emphasis in spatial representation and reasoning has been on reasoning with static spatial configurations, with the underlying paradigm being '*consistency and constraints*'. However, for a range of application domains (discussed below) involving interactions between space, action and spatial change, spatial reasoning methods require support for other forms of high-level inference such as *prediction, planning, and explanation* (e.g., by abduction). In effect, what is needed is the integration of the fundamental results achieved within the '*consistency and constraints*' paradigm with other representation and reasoning approaches in the purview of Knowledge Representation (KR) (Van Harmelen et al., 2007), or more broadly, Artificial Intelligence.

Space and time are inextricably linked, i.e., spatial configurations change over time. Humans, robots and systems that act, and interact, are embedded in space, and this change is often the result of actions and events. Actions and events 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 in the real world. Similarly, explanations of the perceived reality (e.g., by humans, robots, systems) also are established on the basis of such apriori commonsense notions. Bhatt (2010a) develops such integrated reasoning as a useful paradigm for the utilization of qualitative spatial representation and reasoning techniques in a wide-range of relevant application domains such as *dynamic GIS, smart environments, cognitive robotics*, and *spatial design*. Recent work (Bhatt, 2010b) supporting this paradigm has also explicitly addressed the formal modelling of dynamic spatial systems and ensuing interactions between the spatial reasoning domain and the field of *reasoning about actions and change*, and *commonsense reasoning*, which are themselves major areas of investigation within AI (Van Harmelen et al., 2007; Davis & Morgenstern, 2004). Spatial change may also be perceived as being spatiotemporal and relatively recent work has been devoted to providing well-grounded mereo-topological models to be used as high-level qualitative descriptions of spatiotemporal change (Hazarika, 2005; Hazarika & Cohn, 2001). The basic results in QSTR have also attracted interest from information-theoretic quarters, by the application of software engineering and application development methodology approaches for studying the design of systems dealing with spatial and temporal information (Schultz et al., 2010). These inroads clearly indicate the influence and visibility of QSTR techniques in areas distinct from Artificial Intelligence.

3. COMMONSENSE, SPACE AND CHANGE: INTEGRATION

The integration of qualitative spatial representation and reasoning techniques within general commonsense reasoning frameworks in AI is an essential nextstep for their applicability, e.g., in the form of spatial control and spatial planning in cognitive robotics, for spatial decision-support in intelligent systems, e.g., design assistance, wayfinding and navigation assistance, and as explanatory models in a wide-range of systems requiring the formulation of hypotheses, e.g., spatiotemporal diagnosis and abnormality detection, event recognition and behaviour interpretation, geospatial dynamics and event-based geographic information systems.

Indeed, if 'spatial reasoning', both qualitative and otherwise, and commonsense notions of space and spatial change are to be embedded or utilized within practical or larger application scenarios in AI, their integration with formal AI languages, calculi, and tools to model change and high-level inference patterns need to be thoroughly investigated, i.e., from ontological, representational and computational viewpoints. Furthermore, it is necessary that the integration and the supported computational mechanisms be generic/applicable in a wide-range of application domains, very much like generic knowledge representation languages and frameworks themselves. To better contextualitze the discussion pertaining to the proposed *integration*, consider the proposition of McCarthy (2008) that exemplifies the notion using the idea of a '*well-designed child*', and more specifically, that of a well-designed logical robot child that is innately equipped with abilities to interact with the world that it lives in. To quote McCarthy (2008; section 7):

> *Consider designing a logical robot child, although using logic is not the only approach that might work. In a logical child, the innate information takes the form of axioms in some language of mathematical logic.*

For McCarthy, what is important is that the robot child's '*innate structures*', or from a logical viewpoint, the robot child's innate logical structures, be well-designed. McCarthy's *well-designed'ness* in this logical context explicitly corresponds to the inclusion of following categories of innate structures corresponding to: (a) *persistence* of objects in terms of their composition and absolute position in space, (b) spatial and temporal *continuity* of perceptions, (c) relations of *appearance and reality*—"how do we describe the appearance of an object to a blind person who has not felt it with his hands?", and (d) *commonsense* conservation laws pertaining to spatial quantities (Piaget & Inhelder, 1967). The *well-designed'ness* here essentially corresponds to the use of formal conceptualizations—both for space as well as change—within a logical framework for modelling aspects concerning the different categories of innate structures that are identified by McCarthy.

Within the context of the integration of such sub-divided endeavours, an important question is what is more fundamental: spatial reasoning or general logic-based reasoning. To quote Freksa (1992) on the issue:

> *From a formal position, these two viewpoints may appear equivalent; however, from a cognitive and computational position they are not; the logic-based*

> *view assumes that spatial reasoning involves special assumptions regarding the properties of space which must be taken into account while the space-based view assumes that abstract (non-spatial) reasoning involves abstraction from spatial constraints which must be treated explicitly.*

Our viewpoint here is that the issue of *integration* in the aforementioned context, which is at least as important as the issue of *sub-division*, has been accorded a secondary status by researchers in the qualitative spatial reasoning domain in favour of the development of fundamental modes of spatial information representation and reasoning. Indeed, specialised problems need to be approached individually, but it is also necessary that the resulting solutions can be integrated seamlessly and/or be embedded within a larger unified theory, with the intended integration happening at conceptual, representational, and computational levels.

The use of commonsense reasoning about the *physical properties of objects* within a first-order logical framework has been investigated by Davis (2008, 2009). The key highlight of this work is that it combines commonsense qualitative reasoning about "continuous time, Euclidean space, commonsense dynamics of solid objects, and semantics of partially specified plans" (Davis, 2009). Cabalar and Santos (2010) investigate the formalization of the commonsense representation that is necessary to solve *spatial puzzles* involving non-trivial objects such as *holes* and *strings*. Here, the underlying logical machinery that is used to model and reason about the world also involves action and change formalisms. Bhatt and Loke (2008) explicitly formalize a *Dynamic Spatial Systems* approach for the modelling of changing spatial domains using the Situation Calculus (McCarthy & Hayes, 1969). A dynamic spatial system here is regarded as a specialization of the generic *dynamic systems* approach (Sandewall, 1994; Reiter, 2001) for the case where sets of qualitative spatial relationships (grounded in formal spatial calculi) pertaining to one or more aspect of space undergo change as a result of actions and events in the system. The formalization adheres to the semantics of the Situation Calculus and includes a systematic account of key aspects that are necessary to embed a domain-independent qualitative spatial theory within the Situation Calculus. The key advantage of this approach is that based on the structure and semantics of the underlying calculus (essentially a first-order sorted language with some second-order features), fundamental reasoning tasks such as *projection, planning, and explanation* directly follow. These translate to useful reasoning patterns (going beyond conventional consistency reasoning in QSTR) within practical application systems.

Indeed, many other formalizations of spatial change are possible, such as within a Belief Revision framework (Alchourrón et al., 1985), Non-Monotonic Causal formalizations in the manner of (Giunchiglia et al., 2004), stable model semantics, and declarative programming frameworks with non-monotonic capabilities such as Answer-Set Programming (Lifschitz, 2008), commonsense inference within the framework of the Event Calculus (Kowalski &

Sergot, 1986; Mueller, 2009). The comparision and evaluation of modelling spatial change in the respective formalizations is another interesting topic that merits detailed treatment, e.g., from the viewpoint of elaboration tolerance, computational complexity, support for diverse inference patterns, and so forth.

The works discussed here are by no means exhaustive:[2] this article is an opinion-piece, as opposed to a review document. We have presented focussed instances of recent works that illustrate the envisaged fundamental roadmap for the broader call pertaining to *Spatio-Temporal Dynamics*, and the integration of *Commonsense, Space and Change*, which are paradigmatic and a much broader call that may be interpreted in a multitude of interdisciplinary ways. Finally, it must be acknowledged that 'logic-based modelling & reasoning' is not the only alternative: we envisage that the future evolution of spatial and temporal reasoning, and its impact from an applied viewpoint, will be hugely dependent on its ability to outreach and cross-fertilise with applied and basic research activities both within and beyond Artificial Intelligence disciplines.

4. ARTICLES IN THIS ISSUE

In response to the call for this issue, we received 12 articles from *8* countries. After 2 rounds of manuscript revisions under the review of at least *3* reviewers for each contribution, *4* select publications now comprise this issue. The papers are quite naturally linked, and range from linguistic and ontological formalizations to the representational and computational aspects of *space, time, and events* within decision-making systems: *3* papers directly deal with spatiotemporal dynamics, from spatio-linguistic, planning, and event monitoring perspectives respectively, whereas *one* paper involves ontological modelling of scenes for the cognitive robotics domain, which also inherently involves space, action, and change.

The common thread that ties all the papers with respect to the methodology remains the same, namely, logic-based approaches encompassing formalizations such as dynamic interval temporal logic, description logic, and relational axiomatisations of qualitative spatial calculi within a hybrid system involving multiple representation and reasoning modules. We elaborate on this thread in the following:

The Qualitative Spatial Dynamics of Motion in Language

J. Pustejovsky and J. Moszkowicz

The conceptualisation and spatio-linguistic description of spatial information is often the first interfacing mechanism between humans and spatial informa-

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[2] A review of spatial change from the perspective of space and spatial movement can be found in the collective works of Galton (2000). A 'commonsense reasoning' and 'action and change' centred review may be consulted in (Bhatt, 2010a).

tion systems (e.g., spatial assistance systems) that aim to serve as decision-support aids; instances such as the communication of spatial *design knowledge*, descriptions of *spatiotemporal narratives* of temporally ordered scene information, and aerial *imagery* within GIS decision-support tools serve a case in point. In their paper, *Pustejovsky and Moszkowicz* present a representational and computational framework for modelling and reasoning about spatial information within these categories of systems. In particular, the authors are concerned with motion as it is expressed in language; here, the authors focus on specific characterizations involving *path predicates* and *manner-of-motion-predicates*. The proposed framework is grounded to the formal semantics of the Dynamic Interval Temporal Logic (DITL) and qualitative spatial formalisms as conceived within the QSTR community. According to the authors:

> *DITL serves a dual purpose as it provides a new way to analyze motion as expressed in language, while also motivating how spatially relevant information in text should be annotated, in order to capture objects in motion. . . . The combination of a motion annotation with DITL as its semantics affords us an important tool in our understanding of the qualitative spatial dynamics of motion.*

The presented work strives to provide a foundational basis for certain aspects of an emerging standardisation initiative, namely ISO-Space, within the auspices of the International Standards Organisation (ISO). We envisage that this manner of formally grounded spatial markup language development will be instrumental in serving as a solid interface between humans and spatial information systems confronted with the task of internalising the spatial knowledge about the world and performing different types of analytical and decision-making abilities in that context. Although several instances for the application of a standard such as this may be presented, it serves the present discussion to consider the relational grounding of spatial scenes (the topic of the next paper), which could be achieved by an *ontologized* version of the formal markup language(s) as developed within the proposed ISO-Space initiative.

Describing Images Using Qualitative Models and Description Logics

Z. Falomir, E. Jiménez-Ruiz, M. T. Escrig, and L. Museros

Falomir et al. are concerned with qualitative descriptions of spatial scenes using a range of spatial and visual characteristics: shape, color, topology, and orientation. According to the authors:

> *Our approach obtains a visual and a spatial description of all the characteristic regions/objects contained in an image. In order to obtain this description,*

> *qualitative models of shape, colour, topology, and fixed and relative orientation are applied.*

The proposed scene description model is formally modelled using the Web Ontology Language (OWL), which is an ontology modelling language grounded to the formal semantics of a Description Logic (DL). OWL based modelling has been performed to exploit the reasoning (here, *classification*) capabilities via one of the many available DL reasoning systems capable of handling OWL-based ontologies. This form of integration of a formal spatial description model via its semantic characterisation using a terminological modelling and reasoning system opens up many possibilities. For instance, it can lead to interesting conceptual/ontological inference capabilities that may provide a solid semantic foundation to other forms of reasoning concerned not only with spatial semantics, but also with spatiotemporal dynamics, e.g., in the manner of the *spatial planning* and *event-based reasoning* (for monitoring) application domains, which are investigated in the remaining two papers of the issue.

Guiding the Generation of Manipulation Plans by Qualitative Spatial Reasoning

M. Westphal, C. Dornhege, S. Wölfl, M. Gissler, and B. Nebel

Westphal et al. demonstrate the manner in which qualitative abstraction and reasoning mechanisms may be combined with high-level geometric planning toward the development of a hybrid planning system. According to the authors:

> *We have presented a hybrid planning approach to robot motion planning problems, combining work on qualitative reasoning and probabilistic roadmap planning. This approach, which is based on previous work on qualitative simulations, generates qualitative plans that can be used to guide the sampling strategy of a probabilistic roadmap planner.*

The main focus of this work is the integration of qualitative approaches with *probabilistic roadmap planners*, and a demonstration of the manner in which the performance of the latter may be improved via the use of qualitative spatial reasoning. The interesting point here is that the performance of standard quantitative methods applied in robotics may be improved via the use of qualitative spatial abstractions. From the QSTR perspective, this article also identifies deficiencies in current QSTR research such as missing methods for integration of quantitative spatial constraints and the lack of formalisms that deal with space in a 3D setting. More broadly, this work can also be perceived as providing a model for the import of QSTR techniques by the robotics community.

Spatiotemporal Aspects of the Monitoring of Complex Events for Public Security Purposes

G. Ligozat, Z. Vetulani, and J. Osiński

Ligozat et al. present a decision-support system concerned with monitoring *event* occurrences in a structured spatial environment, namely, a soccer stadium. The presented system combines techniques in spatial and temporal information representation, and natural language processing. The authors state:

> *The central idea is to process the information conveyed by messages in terms of events. Those events are located at various locations, and they occur at definite moments of the general event. Hence representing the spatial and temporal aspects of the information to be processed is one of the central functionalities of the monitoring system.*

The paper presents the design and implementation of a visualization facility, the *active map*, which involves the use of the XRCDC formalism, a temporal eXtension of the Region Cardinal Direction Calculus (RCDC). This work not only addresses an application, namely event monitoring for large scale public events, that is interesting in its own right, but also demonstrates how a spatial formalism may be customised and applied in a practical context. The synergistic connections of this paper with the work on the spatiotemporal dynamics of motion by *J. Pustejovsky, and J. Moszkowicz*, and the ontological modelling work by *Falomir et al.* are rather direct, and obvious. Spatial planning, e.g., as worked-out in the paper by *Westphal et al.*, and event-based reasoning (e.g., by explanation), as presented in this paper by *Ligozat et al.*, constitute two very important reasoning patterns that may be found in a range of spatial information systems. Together with the work on spatial planning, this work is a demonstration of the manner in which qualitative spatial representation and reasoning may be embedded within a larger application context toward serving a useful analytical/decision-making purpose.

We hope that readers will find the works described herein as interesting as we did, and that in hindsight, the combined efforts and the scientific agenda of this issue shall come across clearly as a natural occurrence within the evolutionary continuum of the field of Qualitative Spatial & Temporal Representation and Reasoning.

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