Qualitative Simulation - Towards A Situation Calculus Based Unifying Semantics for Space, Time and Actions[⋆]

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1 Background and Motivation

Qualitative simulation (QS) is a well established artificial intelligence technique for modelling and predicting the behaviour of physical systems [Weld and de Kleer, 1989]. Most notable research outcomes in this area, which gathered momentum during the mid-80's and early-90's, are QSIM [Kuipers, 1986], the Qualitative Process Theory (QPT) [Forbus, 1984] and the (somewhat different in approach) qualitative simulation system QSSIM [Cui, Cohn, and Randell, 1992]. The basic functionality supported in all of these systems is usually the same – the capability to generate some form of a behaviour model (usually a tree-based structure) in the form of a temporal partial ordering of the qualitative states that a physical system can evolve into given some indexed state. Such a behaviour model, also referred to as an *envisionment* [Weld and de Kleer, 1989], is meant to trace the evolution of the system being modelled with respect to time. Depending on which aspects of change, encompassing *space, time* & *actions (or causality* in general), have been accounted for in the theory, envisionment based qualitative simulation can be used as the basis of a planning and/or prediction function. The theory per se can be regarded to be general or rich enough to model the set of rules of behavioural dynamics[3] of the objects, both autonomous or human-controlled, in the domain being modelled to an extent to which it accounts for these differing aspects that are relevant to the domain. For example, the qualitative simulation system QSSIM is based on a topological view of space – qualitative states in their system are sets of distinct dyadic

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[3] For example, involving a change of spatial location and orientation of the objects or even the manipulation of one object by another [Christou and Bülthoff, 2000].

topological relations holding between the primitive objects of the theory's spatial ontology. In this sense, QSSIM can be only regarded as a topological theory of simulation. Albeit novel and different from QSIM or qualitative process theory in its use of a spatial ontology of regions & states based on sets of simultaneously satisfiable formulae [Cohn et al., 1997], QSSIM still left a few open questions by considering merely one aspect of space, viz topology. To quote the authors: "*Further envisaged extensions to the theory would include motion as a subtheory...other useful extensions would include explicit information about causality and processes, the latter including teleological accounts of a physical systems behaviour*" [Cui et al., 1992, Sec. 5]. Such an extended theory, which is based on an integration of various aspects of space, time & causality, provides a far more richer basis for planning and procedure generation, with varied applications in intelligent analysis & control, robot planning etc.

At a much broader level, diametrically opposite to the issue of integration of theories of space, time and actions is that of sub-division of endeavours in AI [McCarthy, 1987]. McCarthy singled out spatial reasoning as an important task, mostly concentrating on the aspects necessary to resolve some specific tasks. Such separation of tasks is necessary and important from an AI research viewpoint; however, within the context of the integration of such sub-divided endeavours, and in the narrow context of a particular application such as one considered herein, an important question is: *What is more fundamental? spatial reasoning or general logic-based reasoning* [Freksa, 1992]. The issue of the integration of a theory of qualitative physics with a theory of action & change has been addressed before in the context of the QPT; Forbus [1989] proposed *action-augmented envisionments*, which incorporates both the effects of an agent's actions and what will happen in the physical world whether or not the agent does something. However, note that this integration, done totally within the context of the qualitative process theory, does not take into account the enormous amount of work done in the field of *Reasoning about Action & Change* (RAC) [Shoham, 1988, Shanahan, 1997, Reiter, 2001]. An alternative approach is the transition-based qualitative simulation system in [Gooday and Cohn, 1996], wherein the behaviour model of the system corresponds to the set of landmark *events* that occur in it. Their representation is based on transition calculus, which is a high-level formalism for reasoning about action & change. With the spatial-temporal ontology and the envisionment axioms that are used as the basis of of temporal projections still being the same, the system is basically a reformulation of QSSIM using transition calculus. Although most of the important features of transition calculus involving concurrency and default reasoning remain un-utilized in the reformulation, the general utility of their proposed approach cannot be taken for granted. There are many advantages of such an approach (in our case, the Situation Calculus [McCarthy and Hayes, 1969]) involving the use of representational tools like the transition calculus developed in the field of reasoning about action & change – Rather fundamental problems (e.g., Frame, Ramification, Qualification [Shanahan, 1997]) relevant to modelling/simulating systems that change have been thoroughly investigated in the context of the representational formalisms aforementioned, leading to non-monotonic solutions for reasoning in the presence of incomplete information. Furthermore, these formalisms provide a rigorous account of continuous & concurrent phenomena, which manifest themselves even in the most simplest of dynamic domains.

This is especially important for the qualitative spatial reasoning (QSR) domain, where the issue of concurrent spatial changes has not received due attention. Such technical benefits notwithstanding, note that from an overall QSR & RAC research viewpoint too, such an approach promotes a closer interaction between the two disciplines than has been previously undertaken in the QSR community.

2 Integrating Space, Time and Actions - Ontological Issues

2.1 An RCC Based Topological View of Space

Models of spatial knowledge can either represent abstract point objects or spatially extended objects. There has been a tendency within the QSR community to take regions of space as the primitive spatial entity [Cohn, 1997]; or formally speaking taking 3-D volumes, 2-D areas or 1-D intervals as primitive [Freksa, 1992]. Such an ontological commitment is common in the work on topology, which is usually regarded as the fundamental aspect of qualitative spatial reasoning since topological distinctions are inherently qualitative in nature. Synonymous with topology in the QSR domain is the Region Connection Calculus (RCC) [Randell, Cui, and Cohn, 1992]. The approach of RCC is that extended spatial entities, i.e the regions of space they occupy, are taken as primary rather than the dimensionless points of traditional geometry. Note however that RCC is a very general theory of topology; For e.g., it makes no distinction between rigid and non-rigid bodies, which is likely to be very important for our work. To be used as a basis for the representation of space, qualitative accounts of distance, direction and orientation need to be integrated with the RCC system. However, (atleast initially) we regard the issue of such integration to be secondary to our own work thereby restricting ourselves to a topological view of space based on regions of space and the connections between them.

2.2 The Temporal Framework

The notion of time plays a crucial role in the representational aspects of systems that are dynamic, i.e., systems that *change* their state over time. The fundamental question her being, over what do we interpret temporal assertions – *How do we interpret the truth of a temporal assertion* - over a interval or a time point? [Shoham, 1988]. Though most work in theoretical computer science and AI takes time points as primitive, there are notable exceptions like the formalism in [Allen, 1984] which takes time intervals as the basic primitive. Alternative approaches to Allen's standard linear time theory and its derivatives has been the implicit temporal framework provided by the situation calculus [McCarthy and Hayes, 1969]. The early situation calculus formalism by McCarthy and Hayes viewed time as discrete and provided only a implicit account of it. Various extensions have been provided, most notably by Pinto [1994], Ternovskaia [1994], & Pinto and Reiter [1995], so as to explicitly accommodate continuous time within situation calculus. Of particular interest to us are the ontological extensions in [Pinto and Reiter, 1995] for the representation of time and events. In their formalism, Pinto and Reiter define a time line, which is isomorphic to the non-negative reals, corresponding to a sequence of situations. This sequence basically corresponds to one directed path (an actual as opposed to a hypothetical evolution), starting at the initial situation, in the overall branching tree structure of situations. Our work appeals to the ontology of such an extended situation calculus; the justifications for which, for the time being, may be informally cited as follows: **(1)** The extensions aforementioned (See [Pinto, 1994]) easily realise the essential features of linear temporal theories such as the interval calculus [Allen, 1984] or the calculus of events [Kowalski and Sergot, 1986]. **(2)** As has been shown in [Pirri and Reiter, 2000] and [Reiter, 2001], these extensions lead to rather intuitively meaningful formalisations for concurrent and continuous phenomena. **(3)** More importantly for our work, the *action* (or *event* [McCarthy, 2002]) based ontology of the situation calculus is preserved – conventional temporal logics do not provide for actions and their effects in their ontologies.

2.3 The Primacy of Events

There are relatively few recent studies in the QSR domain aimed at integrating actions and events in the overall spatial cognition process. In [Hommel and Knuf, 2000], a theoretical account of the impact of action related factors on the organisation of spatial information in perception and memory is provided. Likewise, in [Mecklenbräuker et al., 1998], connections between spatial information and actions has been explored by way of an empirical study. At a practical level, the simulation system in [Gooday and Cohn, 1996] admits *event-types* to its ontology whereas Forbus [1989] proposes *action-augmented* envisionments – an integration of qualitative physics with the effects of actions. For us, a key ontological question that arises is: What is more general, events or actions? In the context of the situation calculus, McCarthy [2002] presents a formalism featuring events (called internal events) as primary and the usual actions (called external events) as a special case. According to McCarthy, actions are just a kind of event, and formalized *reasoning about action and change*[4] needs to treat events as the general case and those events which are actions as special. To quote McCarthy on the subject, "*Whether an event is external depends on the theory. If we can formulate when an event will occur, then we can make our theory more powerful by including an occurrence axiom for that event. If we assume a deterministic world, the limiting case is a theory in which all events are internal*". A deterministic world, interpreted in the rather restricted context of a dynamic system, implies that all events or happenings in the system are governed by known laws of physics, i.e., there is No Free Will. A similar differentiation has also been made by Pirri and Reiter [2000] in the form of *Natural* and *Free Will* actions. According to their distinction, free will actions are actions on the part of agents with the ability to perform or withhold their actions, like choosing to pick up an object, or deciding to walk to some location. In contrast, natural actions are the ones whose occurrence times are predictable in advance, in which case they must occur at those times unless something happens to prevent them. Nature has no free will; her actions must occur provided the time and circumstances for their occurrence are right [Pirri and Reiter, 2000].

[4] Later, McCarthy suggests *events and change* might be a better terminology.

3 Research Goal - An Incremental Qualitative Simulation System with Situation Calculus Semantics

The aim of our research is to develop a qualitative simulation system that uses the extended situation calculus formalism [Reiter, 2001] as a basis for integrating space, time and actions/events. Practically, the result is envisaged to be a incremental simulator that is capable of incorporating dynamically available information (relevant to spatial or non-spatial attributes) into its envisionments. The is especially important if the system is to be applied in a dynamic environment where dynamically available information relevant to various aspects of space (e.g., distance, size etc) is easily available and must be taken into account. Note however that this presumes that the relevant aspects of space have been account for in the theory per se. As a starting point (and similar to [Gooday and Cohn, 1996]), we subscribe to a topological view of space based on the RCC system and its associated Conceptual Neighbourhood Diagram (CND) that can be used as the basis of (topological) envisionments. A theory of our spatial changes in our work corresponds to the RCC system (i.e., RCC-8 with its compositional inference mechanism) and its associated CND specified using the situation calculus. The starting point of our work is the formalisation of a basic simulation system encompassing our understanding of space using the extended situation calculus formalism; This we intend on pursuing within the context of various high-level languages, e.g., *Golog* [Levesque et al., 1997], *ccGolog* [Grosskreutz and Lakemeyer, 2000], that are based on the extended situation calculus. Precise details are a matter of further study.

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References

J. F. Allen. Towards a general theory of action and time. *Artif. Intell.*, 23(2):123–154, 1984. ISSN 0004-3702. doi: http://dx.doi.org/10.1016/0004-3702(84)90008-0.

C. Christou and H. H. Bülthoff. Using realistic virtual environments in the study of spatial encoding. In *Spatial Cognition*, pages 317–332, 2000.

A. G. Cohn. Qualitative spatial representation and reasoning techniques. In *KI '97: Proceedings of the 21st Annual German Conference on Artificial Intelligence*, pages 1–30, London, UK, 1997. Springer-Verlag. ISBN 3-540-63493-2.

A. G. Cohn, N. M. Gotts, D. A. Randell, Z. Cui, B. Bennett, and J. M. Gooday. Exploiting temporal continuity in qualitative spatial calculi. In R. G. Golledge and M. J. Egenhofer, editors, *Spatial and Temporal Reasoning in Geographical Information Systems*. Elsevier, 1997.

Z. Cui, A. G. Cohn, and D. A. Randell. Qualitative simulation based on a logical formalism of space and time. In *Proceedings of AAAI-92*, pages 679–684. AAAI Press, 1992.

K. D. Forbus. Qualitative process theory. *Artif. Intell.*, 24(1-3):85–168, 1984. ISSN 0004-3702. doi: http://dx.doi.org/10.1016/0004-3702(84)90038-9.

K. D. Forbus. Introducing actions into qualitative simulation. In N. S. Sridharan, editor, *Proceedings of the Eleventh International Joint Conference on Artificial Intelligence*, pages 1273–1278, San Mateo, California, 1989. Morgan Kaufmann.

C. Freksa. Using orientation information for qualitative spatial reasoning. In *Proceedings of the International Conference GIS - From Space to Territory: Theories and Methods of Spatio-Temporal Reasoning on Theories and Methods of Spatio-Temporal Reasoning in Geographic Space*, pages 162–178, London, UK, 1992. Springer-Verlag. ISBN 3-540-55966-3.

J. Gooday and A. Cohn. Transition-based qualitative simulation. In *Proceeding of the 10th International Workshop on Qualitative Reasoning*, pages 74–82. AAAI press, 1996.

H. Grosskreutz and G. Lakemeyer. cc-golog: Towards more realistic logic-based robot controllers. In *AAAI/IAAI*, pages 476–482, 2000.

B. Hommel and L. Knuf. Action related determinants of spatial coding in perception and memory. In *Spatial Cognition*, pages 387–398, 2000.

R. Kowalski and M. Sergot. A logic-based calculus of events. *New Gen. Comput.*, 4(1):67–95, 1986. ISSN 0288-3635.

B. J. Kuipers. Qualitative simulation. *Artif. Intell.*, 29(3):289–338, 1986. ISSN 0004-3702. doi: http://dx.doi.org/10.1016/0004-3702(86)90073-1.

H. J. Levesque, R. Reiter, Y. Lespérance, F. Lin, and R. B. Scherl. Golog: A logic programming language for dynamic domains. *J. Log. Program.*, 31(1-3):59–83, 1997.

J. McCarthy. Epistemological problems of artificial intelligence. pages 46–52, 1987.

J. McCarthy. Actions and other events in situation calculus. In *KR*, pages 615–628, 2002.

J. McCarthy and P. J. Hayes. Some philosophical problems from the standpoint of artificial intelligence. In B. Meltzer and D. Michie, editors, *Machine Intelligence 4*, pages 463–502. Edinburgh University Press, 1969.

S. Mecklenbräuker, W. Wippich, M. Wagener, and J. E. Saathoff. Spatial information and actions. In *Spatial Cognition*, pages 39–62, 1998.

J. Pinto and R. Reiter. Reasoning about time in the situation calculus. *Annals of Mathematics and Artificial Intelligence*, 14(2-4):251–268, 1995.

J. A. Pinto. *Temporal reasoning in the situation calculus*. PhD thesis, 1994. Supervisor-Raymond Reiter.

F. Pirri and R. Reiter. Planning with natural actions in the situation calculus. pages 213–231, 2000.

D. A. Randell, Z. Cui, and A. Cohn. A spatial logic based on regions and connection. In B. Nebel, C. Rich, and W. Swartout, editors, *KR'92. Principles of Knowledge Representation and Reasoning: Proceedings of the Third International Conference*, pages 165–176. Morgan Kaufmann, San Mateo, California, 1992.

R. Reiter. *Knowledge in action: Logical foundations for describing and implementing dynamical systems*. MIT Press, 2001.

M. Shanahan. *Solving the frame problem: a mathematical investigation of the common sense law of inertia*. MIT Press, 1997. ISBN 0-262-19384-1.

Y. Shoham. *Reasoning about change: time and causation from the standpoint of artificial intelligence*. MIT Press, 1988. ISBN 0-262-19269-1.

E. Ternovskaia. Interval situation calculus. In *KI '94: Proceedings of the 18th Annual German Conference on Artificial Intelligence*, page 400, London, UK, 1994. Springer-Verlag. ISBN 3-540-58467-6.

D. S. Weld and J. de Kleer. *Readings in Qualitative Reasoning about Physical Systems*. Morgan Kaufmann Publishers, 1989.