REASONING ABOUT SPACE, ACTIONS AND CHANGE

A PARADIGM FOR APPLICATIONS OF SPATIAL REASONING

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ABSTRACT

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. This article is an attempt to position such integrated reasoning as a useful paradigm for the utilization of qualitative spatial representation and reasoning techniques in relevant application domains. From a logical perspective, I note that formalisms already exist and that effort need only be directed at specific integration tasks at a commonsense conceptual, formal representational and computational level.

Subject keywords: Knowledge Representation and Reasoning, Ontology, Spatial Cognition; Qualitative Spatial Reasoning (QSR), Reasoning about Actions and Change (RAC), Commonsense Reasoning (CR), Dynamic Spatial Systems.

Application keywords: Cognitive Robotics, Geographic Information Systems, Ambient Intelligence, Spatial and Architectural Design

Contents

1 INTRODUCTION

The field of Qualitative Spatial Reasoning (QSR) investigates abstraction mechanisms and the technical computational apparatus for representing and reasoning about space within a formal, non-metrical framework [Cohn and Renz 2007, Freksa 1991b]. Logical formalizations of space and tools for efficiently reasoning with them are now well-established [Renz and Nebel 2007]. Similarly, temporal calculi, in a minimalist sense of the interval-interval relations of Allen [1983], and other more elaborate formal methods in reasoning about change provide the general mechanisms required to handle various aspects such as continuity, concurrency, causality and the fundamental problems resulting therefrom [Davis and Morgenstern 2004, Mueller 2006, Shanahan 1997]. Developments in this latter field, generally referred to as Reasoning about Actions and Change (RAC) [Van Harmelen et al. 2007], have primarily been motivated by some of the fundamental epistemological problems that arise in reasoning about actions and their effects, e.g., the *frame* [McCarthy and Hayes 1969], *ramification* [Finger 1987] and *qualification* [McCarthy 1977] problems. Within RAC, efforts have resulted in formal calculi such as the Situation Calculus [McCarthy and Hayes 1969], Event Calculus [Kowalski and Sergot 1986] and Fluent Calculus [Thielscher 1998], and other more specialized formalisms also similarly grounded in mathematical logic [Davis and Morgenstern 2004]. In contrast to the field of RAC, QSR has acquired its present status as a sub-division within Artificial Intelligence (AI) only relatively recently [Stock 1997], and has its most direct origins in the work on Qualitative Reasoning in the late 80s and early 90s [Weld and de Kleer 1989].

With the aim of realizing practical applications of '*logic-based*' reasoning about space and spatial change, this article poses the question of the integration of formal methods in qualitative spatial representation and reasoning on the one hand, and general commonsensical approaches to represent and reason about action and change on the other. The question is posed within the context of a certain class of application scenarios, and ensuing computational requirements therefrom, which inherently require the ability to model and reason about changing spatial datasets. In a rather specific sense, this posits the question of the integration of qualitative spatial theories encompassing one or more aspects of space with calculi of action and change such as the Situation Calculus, Event Calculus and Fluent Calculus; the range of available specialized formalism for modelling commonsense reasoning, and reasoning about action and change being rather extensive [Davis and Morgenstern 2004, Van Harmelen et al. 2007].

1.1 Why is Integration Necessary?

The integration of qualitative spatial representation and reasoning techniques within general commonsense reasoning frameworks in AI is an essential next-step for their applicability in realistic (relevant) domains, e.g., in the form of spatial control and spatial planning in cognitive robotics, for spatial decision-support in intelligent systems and as explanatory models in a wide-range of systems requiring the formulation of hypothesis, e.g., diagnosis, event-based geographic information systems, robotic control scenarios. It is also imperative that the intended integration be achieved at uniform ontological, representational and computational levels, or aptly, a paradigm such as '*Reasoning about Space, Actions and Change*' (RSAC) is needed. 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, for instance to model the qualitative spatial reasoning abilities of a robot, their integration with formal calculi and tools to model change in general needs to be adequately investigated in a fundamental manner. Furthermore, it is necessary that the integration and the supported computational mechanisms therefrom be generic / applicable in a wide-range of application domains, such as the ones highlighted in this chapter.

1.2 Integration and Sub-Division in AI

The proposed integration is also closely related to the general problem pertaining to the sub-division of endeavours [McCarthy 1977], such as spatial reasoning, in artificial intelligence in general. Within the context of the formalisation of commonsense knowledge, McCarthy [1977] singled out spatial reasoning as an important task, mostly concentrating on the aspects necessary to resolve some specific problems. 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, an important question is what is more fundamental: spatial reasoning or general logic-based reasoning [Freksa 1992]. 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 development of such a unifying semantics is necessary to, for instance, realize the intrinsic representation and reasoning capabilities of an intelligent entity such as the 'well-designed child' of McCarthy [2008], or its more specialized form by way of the 'well-designed (young) mathematician' of Sloman [2008]. Among other things, it is this application-centered '*integration*' aspect and its logical '*well-designed'ness*' that are discussed in this chapter.

1.3 Organisation of Chapter

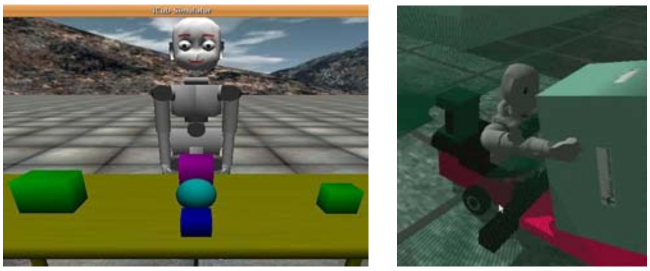
The chapter is written in the form of an opinion piece that advocates a particular line of research. The chapter does not strive to provide an in-depth literature review. I highlight the importance of the proposed integration by way of the RSAC paradigm, the problems that may be solved in this context, point out related research that addresses these questions explicitly, and present immediate agenda for furthering the proposed paradigm. The chapter is organized as follows:

- Section 2 provides diverse motivating application domains where integrated reasoning about space, actions and change is useful. Each application domain is independent in itself and does not affect the continuity of the chapter.

- Section 3 discusses the key challenges connected to the RSAC paradigm vis-à-vis the logical well-designed'ness. The section also includes a more or less chronological discussion of perspectives related to the proposed integration.

- Section 4 builds-up on Section 3 and discusses the ontological, representational, commonsensical and computational challenges involved in integrated logical reasoning about space, actions and change.

- Section 5 concludes with a brief summary of the chapter. In addition to references, key reading material is also cited at the end.



(a) Spatial reconfiguration (b) Control and decision-making

Figure 1.: Spatial Planning in Cognitive Robotics.

2 Space, Actions and Change: Application Perspectives

Actions and events are a crucial connecting-link between space and spatial change, i.e., spatial configurations typically change as a result of interaction within the environment, whatever be the ontological status of the interaction or the nature of the environment. Actions and events, both in a predictive as well as an explanatory sense, also constitute the mechanisms by which we establish and nurture commonsense knowledge about the world that we live in: our anticipations of spatial reality conform to our commonsense knowledge of the effects of actions and events in the real world. Similarly, our explanations of the perceived reality too are established on the basis of such apriori established commonsense notions. In the following subsections, I present some application domains where this interpretation of integrated reasoning about space, actions and change is applicable.

2.1 Spatial Control & Decision-Making in Cognitive Robotics

High-level spatial planning/re-configuration, or more generally spatial control and decision-making [Bhatt 2009b] in *Cognitive Robotics* [Levesque and Lakemeyer 2007] is a domain where integrated reasoning about space, actions and change is most directly applicable. High-level agent / robot control languages such as INDIGOLOG [Giacomo and Levesque 1999] and FLUX [Thielscher 2005], which pursue a vision of cognitive robotics from a logical viewpoint, share many important common features, chiefly among them being the availability of imperative programming style constructs for robot/agent-control tasks, i.e., statements in the program correspond to actions, events and properties of the world in which an agent is operating. What these languages lack, and rightly so, is a generic domain-independent spatial theory that could be used as a basis of a high-level spatial planning in arbitrary tasks. For instance, consider a robot such as in Fig. 1 with grasping, locomotion, and vision capabilities. On the table lie a few solid/rigid boxes and balls, containers that are either empty or filled with some liquid and possibly other specialized bodies. Further, presuppose that the robot is equipped with basic vision and scene grounding[1] (by qualification) capabilities at least in this limited context. From the viewpoint of the RSAC paradigm, it is *desired* that the robot's built-in spatial reasoning capabilities be general (i.e., be applicable in new situations and completely different domains) and elaboration tolerant[2] from the viewpoint of the representational and computational requirements.

For this robot, spatial changes could be denoted by relational variations (e.g., topological and orientation changes), which accrue as a result of actions, in the grounded spatial configurations of objects, or possibly incremental updates to the layout and structuring of the environment as perceived (and grounded) by less than perfect sensory devices in real-time as the robot performs *move* and *turn* actions. The range of application possibilities for integrated reasoning about space, actions and change in the domain of cognitive robotics are rather extensive, and also perhaps most natural [Bhatt 2009b].

2.2 Dynamic Object and Event-Based GIS

Modelling and analysis of dynamic geospatial phenomena within *Geographic Information Systems* (GIS) and the integration of time in GIS (Temporal GIS or T-GIS) has emerged as a major research topic within the GIS community. Although present representational and analytical apparatus to examine the dynamics of such phenomena is nascent at best, the issue is increasingly being considered as a major research priority in GIS [Yuan et al. 2004]. Integrating time with GIS is clearly necessary toward the development of GIS capable of monitoring and analysing successive states of spatial entities [Claramunt and Thériault 1995]. Such capability, necessitating the representation of instances of geographic entities and their change over time rather than change to layers or scenes is the future of GIS and has been

[1] Here, *grounding* should be interpreted in a limited sense to correspond to the derivation of qualified relational scene information from (noisy) quantitative or metrical data.

[2] Broadly, elaboration tolerant theories are those where addition of new domain-independent truths or axioms may be easily achieved to account for "*new phenomena or changed circumstances*" [McCarthy 1998].

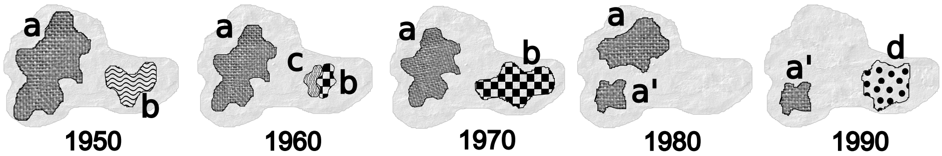


Figure 2.: Abduction in GIS

emphasized in the National Imagery and Mapping Agency's (NIMA) vision for Integrated Information Libraries [NIMA 2000]. A (temporal) GIS should, in addition to accounting for spatial changes, also consider the events behind changes and the facts which enable observation of these changes [Beller 1991]. In the words of Claramunt and Thériault [1995]:

> '*To respond adequately to scientific needs, a TGIS should explicitly preserve known links between events and their consequences. Observed relationships should be noted (e.g., entities A and B generate entity C) to help scientists develop models that reproduce the dynamics of spatio-temporal processes. Researchers will thus be able to study complex relationships, draw conclusions and verify causal links that associate entities through influence and transformation processes*'.

Clearly, such a facility necessitates a formal approach encompassing events, actions and their effects toward representing and reasoning about dynamic spatial changes. Such an approach will be advantageous in GIS applications concerned with retrospective analysis or diagnosis of observed spatial changes involving either fine-scale object level analysis or macro-level (aggregate) analysis of dynamic geospatial phenomena. For instance, within GIS, spatial changes could denote (environmental) changes in the geographic sphere at a certain temporal granularity and could bear a significant relationship to natural events and human actions, e.g., changes in land-usage, vegetation, cluster variations among aggregates of demographic features, and wild-life migration patterns. Here, event-based and object-level reasoning at the spatial level could serve as a basis of explanatory analyses, for instance by abduction, within a GIS [Couclelis 2009, Galton and Hood 2004, Worboys 2005]. For instance, a useful reasoning mechanism that applications may benefit from could be the task of causal explanation [Bhatt 2009a], which is the process of retrospective analysis by the extraction of an event-based explanatory model from available spatial data (e.g., temporally-ordered snap-shots such as in

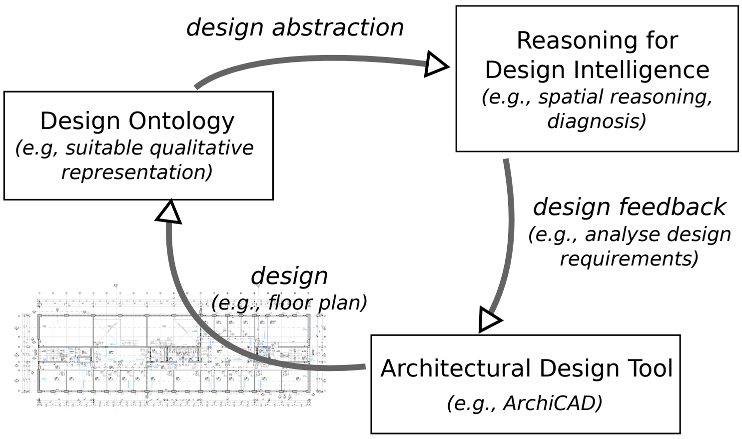


Figure 3.: Iterative Refinement by Intelligent Design Assistance

Fig. 2)[3]. Indeed, the explanation would essentially be an event-based history of the observed spatial phenomena defined in terms of both domain-independent and domain-dependent occurrences. At the domain-independent level, the explanation may encompass behaviour such as *emergence*, *growth* & *shrinkage*, *disappearance*, *spread*, *stability* etc, in addition to the sequential/parallel composition of the behavioural primitives aforementioned, e.g., *emergence* followed by *growth*, *spread / movement*, *stability* and *disappearance* during a time-interval. At a domain-dependent level, such patterns may characterize high-level processes, environmental / natural and human activities such as deforestation, urbanisation, transformations in land-use types etc. Such explanatory analysis is especially important (e.g., in the context of a query-based GIS system) where the available data needs to be analysed for various purposes such as managerial decision making, policy formation and so forth. This aspect is further discussed in Section 4.3.3.

2.3 Spatial Computing for Design

Spatial computing for design refers to the use of formal methods in qualitative spatial representation and reasoning for solving requirement modelling and consistency problems in the domain of spatial design [Bhatt and Freksa 2010]. Here, the main goal is to develop the formal representational and computational frame-

[3]This example is further discussed in the context of causal explanation in Section 4.3.3

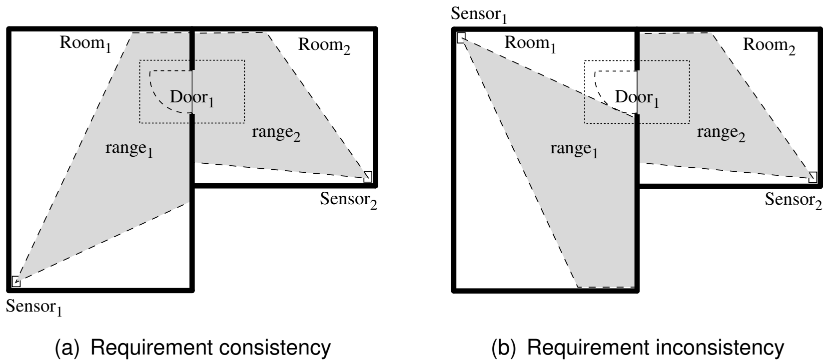


Figure 4.: A two room scenario with the requirement that the door must be supervised by sensors, i.e., the functional space of the door must be completely covered by some sensor range (not necessarily only from a single sensor). Source: Bhatt et al. [2009]

work that may be used as a basis of providing assistive design intelligence within a conventional spatial design workflow.

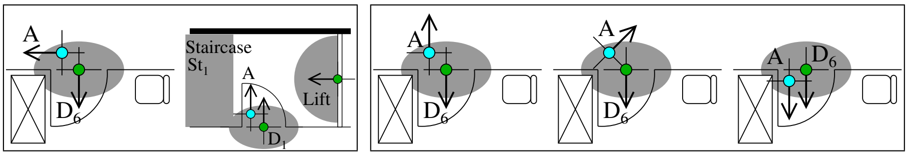
The availability of assistive intelligence capability for *spatial design* tasks, e.g., within a computer assisted architecture design (CAAD) tool, is essential to reduce design errors and failures, and also to ensure that functional requirements of a design are met when the design is actually deployed/constructed in reality [Bhatt and Freksa 2010, Bhatt et al. 2010]. An operational overview of the iterative design refinement cycle is illustrated in Fig. 3. Here, a design is modelled in an architectural design tool such as ArchiCAD [Graphisoft Inc. 2010]. Subsequently, the geometrical / quantitative data-model of a concrete design (e.g., a CAD model) is transformed to an alternate symbolic representation within the intelligent system, wherein reasoning is performed with a potentially symbolic / qualitative spatial model, and the work-in-progress design is evaluated along different dimensions. The results of the reasoning process, e.g., detected inconsistencies, are then provided as feedback to the designer in a cognitively adequate manner, and the design (re)adjustments are incorporated within the iterative refinement phase. The process is ideally repeated until certain design objectives and/or functional requirements are satisfied, e.g., until no requirement inconsistencies occur.

The crux of such a iteratively-refined, intelligence assisted design approach is that it becomes possible to automatically validate a designer's *conceptual space* against the precisely modeled *quantity space*, as constituted by a work-in-progress design. As an example, Bhatt et al. [2009] illustrate the approach for the specific case where the new generation of smart environments and building-automation systems are being designed. Consider the example in Fig. 4 [Bhatt et al. 2009], which illustrates two alternatives of a selected part of a sample floor plan. Here, a requirement constraint that stipulates the non-existence of security blind-spots (e.g., wrt. Sensor_1 and Sensor_2) whilst people utilise the door (Door_1) can be easily checked for (topological) (in)consistency at the design stage itself. For a reasoner that aims at not only detecting the inconsistencies, but also at coming up with alternate recommendations that are consistent, spatial re-configurations and transformations (e.g., translation and deformation actions) at the qualitative level that solve inconsistencies may represent a useful solution approach in this domain. In general, within an decision-support or design assistance tool, metrical changes in the structural layout or changes in the relative spatial relationships of the design elements – i.e., qualitative changes along the conceptual space of the designer – will directly or indirectly entail differing end-product realizations in terms of spatial design requirements, building construction costs, human-factors (e.g., traversability, way-finding complexity), aesthetics aspects, and energy efficiency and long-term maintenance expenses thereof.

2.4 Activity Recognition in Smart Environments

The field of *Ambient Intelligence* (AmI) is beginning to manifest itself in everyday application scenarios in public and private spheres. Key domains include security and surveillance applications and other utilitarian purposes in smart homes and office environments, ambient assisted living, and so forth [Augusto and Shapiro 2007, Streitz et al. 2007]. Notwithstanding the primarily commercial motivations in the field, there has also been active academic (co)engagement and, more importantly, an effort to utilize mainstream artificial intelligence tools and techniques as a foundational basis within the field [Augusto and Nugent 2006, Ramos et al. 2008]. For instance, the use of quantitative techniques for sensor data analysis and mining, e.g., to look for patterns in motion-data, and for activity and behavior recognition has found wide acceptability [Philipose et al. 2004, Youngblood and Cook 2007].

AmI systems that monitor and interact with an environment populated by humans and other artefacts require a formal means for representing and reasoning with spatio-temporal and event-based phenomena that are grounded to real aspects of the environment [Bhatt and Guesgen 2009]. Here, the location of a mobile entity may be required to be projected or abduced (i.e., be explainable) within a (dynamic) spatial environment being modelled (e.g., smart homes, airports, shopping-malls, traffic junctions, smart factories) for purposes of dynamic scene analysis and inter-



(a) Start/end configuration for *exit* pattern.

(b) Start and end configurations for motion patterns.

Figure 5.: Activity Recognition in Smart Environments. Source: [Bhatt and Dylla 2009]

pretation, event-recognition, alert generation, surveillance and so forth [Bhatt and Dylla 2009]. For instance, within a *behavior monitoring* and/or security system for a smart environment (e.g., home, office), *recognition of dynamic scenes* from changes in pre-designated configurations of qualified spatial configurations could be used as a basis of activity recognition and alert generation [Bhatt and Dylla 2009, Galton 2006]. Similarly, the unfolding of sequences of spatial configurations that correspond to certain activities within the application domain of interest may be required to be modelled too, e.g., in the form of causal explanation of observations on the basis of the actions and events that may have caused the observed state-of-affairs. A fundamental requirement within such application domains is the representation of dynamic knowledge pertaining to the spatial aspects of the environment within which an agent/robot or a system is functional. Furthermore, it is also desired that the perceivable variations in space be explicitly linked with the functional aspects of the environment being reasoned about – in other words, it is necessary to explicitly take into consideration the fact that perceivable changes, both spatial and non-spatial, in the surrounding space are typically the result of interaction (i.e., events, actions) within the environment. Therefore, a unified view of space, change and occurrences – events and actions – is necessitated.

3 RSAC: A Logical Perspective to Integration

To realise the predictive and explanatory reasoning capabilities for the class of application domains identified in Sections 2.3–2.1, a foundational approach and a formal (logical) basis for representing and reasoning about space, actions and change at uniform ontological and computational levels is needed; indeed, the integration is approachable from a cognitive perspective too, however, this is beyond the scope of the logical perspective of the present discussion. The key aspects to bear in mind before embarking on a particular logical approach to integration are the reasoning patterns that the respective approach / formalism lends itself to. To re-iterate, for the class of applications being considered herein, predictive (e.g., projection, planning and simulation) and explanatory (e.g., causal explanation) capabilities may be deemed essential. From a computational viewpoint, it is intended that these reasoning tasks follow directly from the semantics of the foundational approach or representational formalism that is being utilised. These aspects are further discussed in Section 4. In this section, we turn to the nature of the integration and its logical well-designed'ness, discuss key challenges therein, and present a brief review of some existing perspectives on the proposed integration.

3.1 Integration: Key Challenges and Well-designed'ness

Reasoning about dynamic phenomena in general is a difficult proposition involving several epistemological issues such as: the *frame problem*, which is the problem of modelling inertia [McCarthy and Hayes 1969], the *ramification problem*, which pertains to accounting for the indirect effects of actions and events [Finger 1987] and the *qualification problem*, which is the problem of weak/exceptional pre-conditions of actions [McCarthy 1977]. Indeed, the need to model aspects concerning the representation of continuity and concurrency in dynamic systems in general only adds to the complexity [Reiter 2001].

Along the (strictly) spatial dimension alone, the complexity first of all stems from the fact that space is characterized via various aspects – topology, orientation, size, shape and some other attributes that are not purely geometrical [Galton 2000]. Furthermore, the complexity is compounded for the specific case of dynamic spatial systems where it is known that sets of qualitative spatial relationships pertaining to more than one aspect of space (e.g., orientation, topology, direction, distance) undergo changes as a result of actions and events occurring within the system [Bhatt and Loke 2008]. Since the respective sets of qualitative spatial relationships correspond to a *qualitative calculus*,[4] it is imperative to ensure that all high-level axiomatic aspects[5] of the concerned calculi being modelled are preserved within the dynamic context. Indeed, the need to reason about space, spatial change, events and actions in a unified manner takes the complexity to a completely new level. For instance, such reasoning involves functional specifications of entities and their interaction with the environment, typically encompassing explicit accounts of the

[4]See "*What is a qualitative calculus*? by [Ligozat and Renz 2004].

[5]These, for instance, correspond to the following properties of the underlying relationship space: jointly exhaustive and pair-wise disjoint property (JEPD), the composition theorems, basic symmetric and asymmetric properties, continuity constraints. See Section 4.

causal and goal-directed aspects of the (spatial) changes that are being modeled and reasoned upon. Key problematic aspects herein that have to be accounted for in the context of qualitative spatial calculi pertaining to any arbitrary aspect of space can be classified in following fundamental categories:

F1. Epistemological

Problems that are *epistemological* in nature [Bhatt 2010], namely problems of global spatial (compositional) consistency of spatial information and the modeling of spatial persistence & ramification/indirect effects within the context of dynamic spatial system.

F2. Phenomenal

Problems pertaining to *phenomenal* aspects [Bhatt 2009a] that are intrinsic to dynamic spatial systems, and involve behaviours such as *appearance*, *disappearance*, *re-appearance*, and other transformations of properties, spatial or non-spatial, which characterize an object, and the closely connected issue of object identity [Bennett 2002, Hornsby and Egenhofer 2000].

F3. Reasoning Requirements

Specific *reasoning requirements* (e.g., abduction for causal explanation) [Bhatt 2009a] that are required in the class of application domains, such as those discussed in Sections 2.3–2.1. This can have a significant bearing on the choice of the representational formalism, since it is the semantics of the formalism that will dictate the essential nature (e.g., monotonic vs. non-monotonic) of the reasoning patterns that are possible per se.

These aspects in (F1–F3) are further discussed in the rest of the chapter in Section 4. At this stage, the significance of (F1–F3) is further discussed in light of the need to have an integration that is logically well-designed with respect to a specific notion of logical well-designed'ness [McCarthy 2008]. Basically, McCarthy 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]:[6]

[6]The robotics centered discussion suffices here since the same principles extend to arbitrary spatial domains / systems of a dynamic nature [Bhatt and Loke 2008].

"*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, the scale and complexity of the abilities of the robot or of the realities / phenomena of the world being represented are secondary. What is important is that the child's '*innate structures*', or from a logical viewpoint, the 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 in (I1–I4):[7]

I1 persistence of objects in terms of their composition and absolute position in space

I2 spatial and temporal continuity of perceptions

I3 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?*"

I4 commonsense conservation laws pertaining to spatial quantities [Piaget and Inhelder 1967]

Primarily, and in a broader sense, the issue of integration discussed in this article in fact echoes the same principle for the specific case where the *innate structures and reasoning abilities* correspond to the commonsense and qualitative conceptions pertaining to space, spatial change, and interaction within a dynamic spatial system. The *well-designed'ness* here 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. In a rather focussed or narrow sense, the issue of the integration proposed herein, and specifically of this notion of logical well-designed'ness, has been exemplified by Bhatt and Loke [2008], where the innate logical structures for representing domain-independent truths pertaining to space, spatial change and dynamic spatial phenomena are represented in the situation calculus. Some categories that have been accounted for include (C1–C5):[8]

[7] Only categories closely related to the topic of the present discussion are included.

[8] Note the correspondences between I1-C2, I2-C3, I3-C4, and I4-C5.

C1 *global consistency* of relational (spatial) information, an aspect that is closely related to the ramification problem or the problem of modelling indirect-effect yielding state constraints (Section 4.2.3)

C2 spatial property *persistence*, which is connected to the frame problem (e.g., the inference-pattern involved in making the default assumption that the spatial relationship between two objects *typically* stays the same, or that the absolute position of an object in space stays the same)

C3 *continuity* of spatial change, involving the modelling of the conceptual neighbourhood of qualitative relationships

C4 *phenomenal* aspects such as the *appearance* and *disappearance* of entities and the inference mechanisms required to account for an incompletely known domain of discourse

C5 *explanatory* capability, for instance modelled as an abductive inference pattern, that provides a logical basis to formulate hypotheses about observed spatial phenomena

Needless to say, the range of innate categories pertaining to commonsense notions of space, spatial change and dynamic spatial phenomena covered by Bhatt and Loke [2008], or those enumerated in a much broader context by McCarthy [2008] for the "logical well-designed'ness" of a robot are by no means all-encompassing. Whereas the potentialities to further refine and extend the categories of innate structures are enormous[9], we further discuss the ones that have been presented here in Section 4.

3.2 (SOME) RELATED PERSPECTIVES ON INTEGRATION

There exist several works that either explicitly addresses the issue of integration or bear a close relationship to it. For the purposes of this chapter, we broadly classify these works in two categories[10]: foundational techniques that use some form of logic of action and change, possibly involving commonsense and non-monotonic researching frameworks, and other early work grounded in the area of

[9]For instance, an important next step in this direction is to further identify phenomenal aspects that may be considered inherent in a wide-range of dynamic spatial systems.

[10]A comprehensive literature review has not been attempted in this chapter. Instead, I have only reviewed closely related works that are directly connected to the RSAC paradigm being pursued herein.

qualitative simulation of physical/spatial system. The term ‘foundational approach’ corresponds to the use of mathematical logic based formalisms, in the spirit of the logical well-designed’ness discussed in Section 3.1; it does not imply that other works are non-foundational or ad hoc.

3.2.1 Integration within Qualitative Simulation Systems

One of the earliest explicitly stated accounts of an attempt toward a unifying semantics of space, time and actions, done within the context of the Qualitative Process Theory (QPT), can be found in the work of Forbus [1989]. Forbus proposed *action-augmented envisionments*, which incorporate both the effects of an agent’s actions and what will happen in the physical world whether or not the agent does something. Most research in this area, which gathered momentum during the mid-80s and early-90s, focussed on techniques for modelling and predicting the behaviour of physical systems in general [Bobrow 1984, Weld and de Kleer 1989]. In addition to the qualitative process theory [Forbus 1984], another notable outcome during this time was Kuipers’s qualitative simulation system QSIM [Kuipers 1994; 1986]. 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 modelled 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 and causality, 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 involving several spatial attributes (e.g., changing location, orientation or the manipulation of objects) 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 in [Cohn et al. 1997c, Cui et al. 1992] is based on a topological view of space – qualitative states in their system are sets of distinct dyadic 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 and states based on sets of simultaneously satisfiable formulae, QSSIM still left a few open questions by considering merely one aspect of space, viz topology. To quote Cui et al. [1992; Sec. 5]:

> '*Further envisaged extensions to the theory would include motion as a sub-theory...other useful extensions would include explicit information about causality and processes, the latter including teleological accounts of a physical systems behaviour*'

An extended theory that includes causal and teleological accounts of a physical systems behaviour (i.e., is based on an integration of various aspects of space, time and causality) provides a far richer basis for planning and procedure generation, with varied applications in intelligent analysis & control, robot planning etc. A similar viewpoint, which is presently a general consensus within the GIS community, is also promoted in the context of event-based models of dynamic geographic phenomena in the GIS area where the use of dynamic aspects of geographic phenomena has been considered essential toward serving a useful explanatory and prediction function within GIS [Worboys 1998; 2005], [Allen et al. 1995, Beller 1991, NIMA 2000].[11]

3.2.2 (Strictly) Logical Perspectives to Integration

A foundational approach toward the broader integration of spatial and logic-based common-sense reasoning frameworks is adopted in the works of Allen and Ferguson [1994], Bennett and Galton [2004], Bhatt [2008b], Bhatt and Loke [2008], Shanahan [1995], and Davis [2008; 2009].

I. Foundational Approaches

Allen [1984] and Allen and Ferguson [1994] addressed the much broader (and still open-ended) problem of developing a general representation of actions and events that uniformly supports a wide range of reasoning tasks, including planning, explanation, prediction, natural language understanding, and commonsense reasoning in general. According to Allen and Ferguson [1994; pg. 51], the novelty of their work is the combination of techniques (relevant to temporal reasoning and reasoning about action and change) into a unified framework that supports explicit reasoning about temporal relationships, actions, events and their effects. Here, the temporal

[11] Application and resulting computational aspects are discussed in Sections 2.2 and 4.3.3 respectively.

part of Allen's theory is based on his seminal interval temporal logic [Allen 1983, Allen and Hayes 1985]. Bennett and Galton [2004] propose Versatile Event Logic (VEL), which consists of a general temporal ontology and semantics encompassing many other representations such as the situation calculus and event calculus. In essence, VEL includes a temporal ontology and an expressive mechanism for representing temporal relationships and events. The main motivation for the development of VEL is its use as a foundational representational framework for comparing and interfacing different AI languages. Bennett and Galton illustrate this in the context of the situation and event calculus. Although spatial reasoning is not addressed in this context by Bennett and Galton, the general utility of an interfacing language such as VEL is promising from the viewpoint of the proposed RSAC paradigm.

Shanahan [1995] describes a default reasoning problem, analogous to the frame problem, which arises when an attempt is made to construct a logic-based calculus for reasoning about the movement of objects in a real-valued co-ordinate system. As Shanahan [1995] elaborates:

> '*If we are to develop a formal theory of commonsense, we need a precisely defined language for talking about shape, spatial location and change. The theory will include axioms, expressed in that language, that capture domain-independent truths about shape, location and change, and will also incorporate a formal account of any non-deductive forms of commonsense inference that arise in reasoning about the spatial properties of objects and how they vary over time*.'

Indeed, what Shanahan's all-encompassing theory refers to is a unification of spatial, temporal and causal aspects at representational and computational levels. Bhatt [2008b; 2009a] extends the aforementioned default reasoning about spatial occupancy of Shanahan [1995], also within the situation calculus, by presenting scenarios where default and/or non-monotonic reasoning patterns are useful and (sometimes) necessary for the modelling of dynamic spatial domains. Here, the identified instances bear a direct relationship to the fundamental epistemological issues relevant to the frame and ramification problems and are utilized to realize essential computational tasks such as (abductive) causal explanation and spatial property projection[12] The use of commonsense reasoning about the physical properties of objects within a first-order logical framework has been investigated by

[12]These works are discussed in detail in Section 4.

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].

Gooday and Cohn [1996] propose an event-based qualitative spatial simulation system by employing the transition calculus [Gooday and Galton 1997], which is a high-level formalism for reasoning about action and change, as the basic representation tool. Using this event-based approach, the behaviour model of the system corresponds to the set of landmark *events* that occur in it. With the spatial-temporal ontology and the envisionment axioms that are used as the basis of temporal projections still being the same, the system is basically a reformulation of QSSIM [Cui et al. 1992] using the transition calculus. Although most of the important features of transition calculus involving concurrency and non-monotonic reasoning remained unutilized, the general utility of the proposed approach is in line with overall objective of a unifying semantics for space, time and events.

Bhatt and Loke [2008] and Bhatt [2008a] explicitly formalize a *Dynamic Spatial Systems* ($\mathscr{DSS}$) approach for the modelling of changing spatial domains. A dynamic spatial system here is regarded as an instantiation of the generic *dynamic systems* approach [Reiter 2001, Sandewall 1994] for the specific 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 $\mathscr{DSS}$ 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 spatial theory itself is primarily derivable from the all-pervasive generic notion of 'qualitative spatial calculi' that are representative of differing aspects of space. The key advantage of the $\mathscr{DSS}$ approach is that based on the structure and semantics of the underlying situation calculus framework, fundamental reasoning tasks such as projection and explanation directly follow. As elaborated on in Section 4, these translate to spatial planning/re-configuration and causal explanation. The work of Bhatt and Loke may be regarded as a rather specific instantiation of the general RSAC proposal, which is paradigmatic and a much broader call than what any individual piece of research may encompass.

II. Application-Oriented Approaches

Ferguson et al. [2003] describe an architecture consisting of JEPD spatial relation sets as nodes in a dependency network for dynamically handling spatial information in an incremental, non-monotonic diagrammatic reasoning system. These spatial relation sets include interval relations, relative orientation relations, and connectivity relations, but in theory could include any jointly exhaustive and pair-wise disjoint (JEPD) sets of spatial relations, e.g., such as those illustrated in Fig. 7 (Section 4). The system is designed with the aim to support higher-level reasoning, including support for creating default assumptions. Albeit indirectly related to the theme of integration, also important is the work of Cardelli and Gordon [2000; 2006] on ambient modal logics, where the truth of a modal formula is defined to be relative to its spatial and temporal location. In their work on defining mobile interactions, mobility is understood as a change of spatial configurations over time. Although the work does not explicitly refer to spatial properties in the strictly spatial sense (e.g., orientation or topological relationships), the approach is nevertheless useful toward formalising concurrent interactions within a spatio-temporal framework, given its foundations in the process calculus and its model-theoretic semantics.

More application-centric is the work by Dylla and Moratz [2004], Ferguson et al. [2003] and Cardelli and Gordon [2006]. Dylla and Moratz directly utilize the situation calculus based high-level cognitive robotics language GOLOG [Levesque et al. 1997] for modelling the conceptual neighborhoods that arise within the line-segment-based Dipole calculus [Moratz et al. 2000].[13] Dylla and Moratz define complex *turn actions* such as *go-right, turn-left* on the basis of primitive (intrinsic) orientation relations of the Dipole calculus [Moratz et al. 2000]. Their work adopts a high-level approach by directly utilising the cognitive robotics language GOLOG [Levesque et al. 1997], but leaves out finer representational problems (e.g., concerning issues such as the ramification problem) that arise whilst modelling a qualitative theory of space within a formalism to model change in general. Regardless, together with the cognitive robotics centered application perspective in Section 2.1 and the discussion of spatial property projection and planning in Sections 4.3.1 and 4.3.2 respectively, this work further reinforces the indicated robotic application scenarios that may be tackled with a foundational integrative approach as envisaged by the proposed RSAC paradigm.

[13]Continuity constraints resulting from the conceptual neighbourhood of a spatial calculus constitute one aspect of modelling a spatial theory within a logic of action and change. Additional properties that constitute a "*qualitative calculus*" [Ligozat and Renz 2004] (Section 4) also need to be accounted for.

4 RSAC: Key Challenges and Questions

From the perspective of the computational requirements of the application domains discussed in Section 2, it is expected that a 'Reasoning about space, actions and change' approach should essentially provide predictive and explanatory reasoning capabilities. From the viewpoint of the logical well-designed'ness of the overall framework discussed in Section 2, it is desired that these reasoning capabilities be available within a (preferably) first-order logical framework, in the context of existing formal methods to model and reason about space on the one hand, and general commonsense approaches to reason about change on the other. This section discusses the challenges and research questions that accrue in fulfilling these requirements.

4.1 Ontological and Representational Aspects

It should be possible to generate a qualitative scene description backed by a formal spatial ontology that is grounded in adequate spatial calculi. Depending on the richness of the spatial calculi being utilized, this will primarily consist of qualitative spatial relationships relevant to one or more spatial dimensions, e.g., with topological, orientation, directional and size information. At a basic level, the scene description ontology should provide for the following:

4.1.1 Multi-Perspective Characterizations

When one considers the potential areas where computational tasks such as spatial planning/re-configuration and explanation are applicable, it becomes clear that conventional approaches that are based on a uniform ontological handling of primitive spatial entities are not sufficient. For instance, one need only conceptualize the qualitative descriptions that would be required to represent the configuration of objects for the *table-and-blocks* world or for a *room* with everyday objects in it – some objects are best conceptualized or modeled as two-dimensional entities (the *table-top*), some as three-dimensional semi-rigid (a *container*) or rigid entities (e.g., a *ball*), some as fully deformable entities (e.g., *liquids*), some as directed line-segments with an intrinsic orientation (the *agent* itself), and some simply as points (e.g., *landmarks* and possibly some *locations* such as the corner of a *table* or of a *room*). Therefore, a mixed ontology with regions, points and line-segments is required.

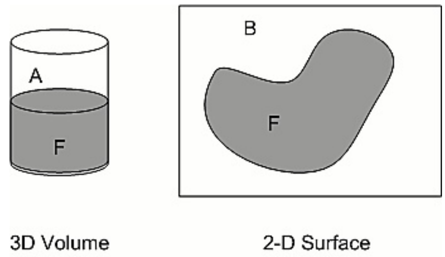


Figure 6.: Dynamic Properties - Fluids

4.1.2 MIXED-DIMENSIONS

Regularity or uniform dimensionality of the object space within one spatial theory is sometimes restrictive. Take the case of fully-flexible *fluids* that acquire the dimensionality of the containing object, i.e., they may be regarded as two-dimensional surfaces and three-dimensional volumes in different situations (Fig. 6). For instance, *water*, when contained in something, is volumetric, whereas when spilt on the *table-top*, acquires a planar form at least from a commonsense viewpoint. Therefore, there should be an inherent way to account for the multi-faceted nature of such a transformation of dimensionality within one theory. For the case where an ontology of mixed-dimensional entities is not feasible or does not exist, the suggestion by Hazarika [2005] is interesting: "One way of reasoning about regions of different dimensionality would be to impose a sort structure (one sort for each dimension) and essentially taking a copy of the theory for each dimension-sort." Whereas the respective merits and demerits of such an approach need closer examination, intrinsic (ontological) support within a spatial theory for allowing entities of mixed dimensions seems to be a more preferred approach in comparison to dimension-sorted approach [Cohn et al. 1997a, Galton 1996, Gotts 1996].

4.1.3 DYNAMIC PHYSICAL / OBJECT PROPERTIES, AND CONSTRAINTS

Objects in the domain may have varying properties relevant to their physical aspects at different times. To aid the discussion, let's appeal to a commonsense notion of rigidity where objects tend to maintain their shape; this is essentially similar to the physics-based notion where a rigid body is an idealization of a solid body of finite size in which deformation is completely neglected. In other words, the distance between any two given points of a rigid body remains constant, regardless of external forces exerted on it. Given this interpretation, an important issue that concerns the characterisation of dynamic object properties is that of classification of objects into 'strictly rigid' and 'non-rigid' types. Consider the following scenarios:

1. A 'delivery object' (o) is *disconnected* (dc)[14] '*next to*' a 'delivery vehicle' (v) in one situation (s_1) and in a later situation (s_2), is *inside* (tpp) the delivery vehicle. Topologically, this is equivalent to the following:

$$\text{situation } s_1\text{: } Holds(\phi_{top}(o,\ v),\ dc,\ s_1)$$
$$\text{situation } s_2\text{: } Holds(\phi_{top}(o,\ v),\ tpp,\ s_2)$$

2. Consider the representation of a bouncing *ball* inside a *room* using purely topological primitives. Here, the state continuously oscillates for a finite duration between tpp and $ntpp$ until eventually steadying at tpp.

3. A *container* object is completely filled with *water*. In this state, the container (or water) can still contain some other object, let's say, by way of *dropping* a small metal *ball* in the *container*. Now let's say that in a later situation, the *water* is frozen and stays that way for eternity.

When dealing with material (rigid) objects, such as the metal ball in scenario 3, the observed topological changes can be understood to be the result of motion, rather than other possibilities such as continuous deformation that are possible with non-rigid objects, such as fluids. However, a coarse distinction into strictly rigid and non-rigid objects is not sufficient. For example, consider the delivery vehicle (or the room) in the examples aforementioned. Although the object identifying the vehicle cannot *grow* or *shrink*, it can certainly contain other objects.[15] Therefore, the vehicle can neither be classified as being strictly rigid (being in a similar class as that of a metal ball), thereby not allowing interpenetration, nor is it a fully flexible non-rigid object like a water body that can *grow*, *shrink* or change *shape*. To take the case further, the solidification of the water-body in scenario 3 reveals that upon it being frozen, there is a fundamental change in the physical property of water. This change, namely water being solidified into ice, is important and must be reflected as a change of spatial (physical) property from a fully flexible to a strictly rigid object so that the container, which was previously filled with water and could still contain other objects cannot contain other objects anymore.

[14] See Fig. 7(a) for 2D interpretations of the topological relationships $\{dc, ec, po, eq, tpp, ntpp, tpp^{-1}, ntpp^{-1}\}$ in the context of the Region Connection Calculus [Randell et al. 1992].

[15] The vehicle and room can be conceived as one hollow object bounded by the sides with an opening at one end so as to allow containment relationships with other objects.

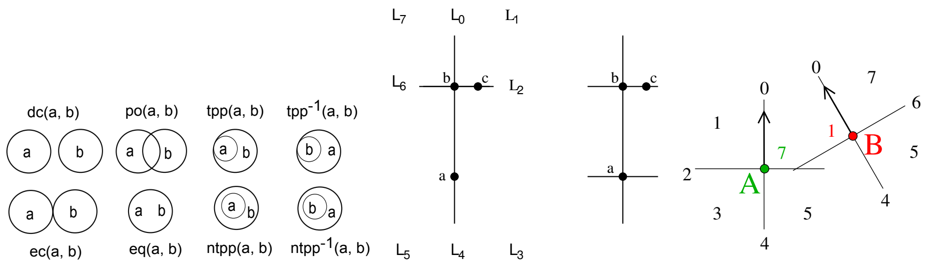
It may be stipulated that a *dynamic physical property* [Bhatt and Loke 2008] is one that:

> characteristically pertains to the physical nature of a material object and which necessarily restricts the range of spatial relationships that the respective object, or class of objects, can participate in with other objects, or class of objects. Using this notion, for instance, certain configurations of objects may be completely disregarded from the *state space* in view of the implausibility of their physical realisation.

Like physical properties, dynamic physical constraints are definable only within a specific spatial framework. For instance, containment constraints can be identified within the context of a mereotopological framework. Likewise, constraints on the potential rotation and direction of motion of objects (e.g., by *turn* and *move* actions) can be defined within a spatial framework consisting of orientation and direction information.

Commonsense Ontologies: An interesting exercise in this direction would be the identification of *taxonomies of generic spatial actions* and single and multi-object *motion patterns* that may be definable, given specific ontological assumptions and spatial calculi under consideration. It may be added that an integration of constraints relevant to more than one aspect of space is necessary in realistic applications, e.g., if distinctions such as an object *approaching* another from the *right* and from the *left* are to be made. It is essential that dynamic physical properties be modelled at the level of a domain-independent spatial theory. This way, domain-independent constraints on the potential spatial transformations, and spatial action taxonomies may be used by modellers in arbitrary spatial scenarios.

In general, the utility of elaborate commonsense characterizations for spatial entities cannot be overemphasized – these are useful in wide-ranging applications, e.g., for the qualitative abstraction of low-level motion control tasks in robotics or high-level spatial planning, for the modelling of taxonomies of spatial changes in event-based GIS and so forth. Commonsense characterizations corresponding to aspects concerning (dynamic) physical properties such as *containment*, *deformity*, *semi-rigidity*, *full-rigidity non-rigidity*, *surface information*, *stability*, *graspability* and their impact vis-à-vis the actions / affordances that may be possible / performed given the backdrop of such knowledge.



(a) $RCC-8$ Primitives (b) SCC & DCC Partitioning (c) The $OPRA_2$ relation $\vec{A}\ _2\angle_7^1\ \vec{B}$

Figure 7.: Topological and Orientation Calculi

4.2 Commonsense Spatial Dynamics

Commonsense notions of spatial change— naive physics —to reason about the (ontologically) grounded material world should also be part of a domain-independent spatial theory, e.g., for the cognitive robotics domain, these should be a part of the innate abilities of McCarthy's *child robot* (Section 3.1). This section presents some spatial calculi specific as well as foundational epistemological & phenomenal aspects that need to be given consideration whilst handling spatial change within a commonsensical framework.

4.2.1 Consistency with Axiomatic Aspects of Spatial Calculi

We presume that spatial information representation corresponds to the use of spatial calculi such as the Region Connection Calculus [Cohn et al. 1997b, Randell et al. 1992] (RCC), Single-Cross and Double-Cross Calculi (SCC, DCC) [Freksa 1992], Oriented Point Relation Algebra (OPRA) [Moratz 2006] (Fig. 7).

When spatial configurations change as a result of spatial actions and events, it is necessary that the spatial scene descriptions corresponding to the changing state of the system at each situation/time-point/interval be globally consistent with respect to the constraints and properties of the underlying (qualitative) relationship space, as encompassed by the respective spatial calculi that are being modelled.

To aid the discussion, let $\mathscr{R} = \{\mathscr{R}_1, \mathscr{R}_2, \ldots, \mathscr{R}_n\}$ be a finite set of n-ary base relationships of a qualitative spatial calculus over a domain $\mathscr{U}$ with some spatial/spatio-temporal interpretation. From a high-level axiomatic viewpoint, a spatial calculus defined on $\mathscr{R}$ has the following properties that must be preserved within a dynamic context:

P1. JEPD Property

$\mathscr{R}$ has the jointly exhaustive and pair-wise disjoint (JEPD) property, meaning that for any two entities in $\mathscr{U}$, one and only one spatial relationship from $\mathscr{R}$ holds in a given situation. Any integration of a spatial theory within a theory action and change will need to preserves this basic property.

P2. Basic Relational Structure

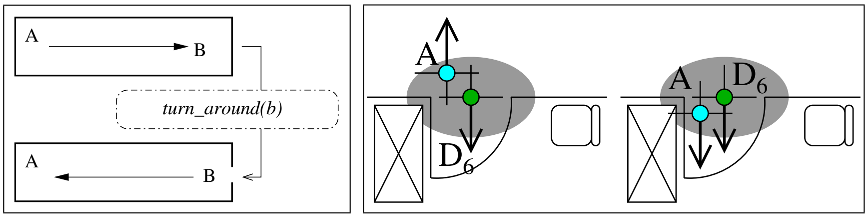
Just like the JEPD'ness of $\mathscr{R}$, the basic transitivity, symmetry and asymmetry properties of the relationship space should be explicitly modelled or preserved in the context of the changing logic of action and change.

P3. Continuity Structure

The primitive relationships in $\mathscr{R}$ have a continuity structure, referred to its conceptual neighborhood (CND) [Freksa 1991a], which determines the direct, continuous changes in the quality space (e.g., by deformation, and/or translational/rotational motion). This continuity structure for $\mathscr{R}$ also needs to be explicitly modelled so that spatial projection and abduction tasks that are performed in the context of a given logic of action and change conform to the conceptual neighbourhood of the spatial calculus that is being modelled within.

P4. Composition Theorems

For a spatial calculus with $n = |\mathscr{R}|$ JEPD relationships, $[n \times n]$ composition theorems are known apriori. These composition theorems need to be modelled comprehensively in order to achieve global compositional consistency within the dynamic context of the logic of action and change that is being utlized. Composition theorems, and the resulting notion of global compositional consistency, is a key (contributing) notion in operationalizing the principle of 'physically realizable/plausible' situations for spatial planning and (abductive) explanation tasks. For instance, in finding potential models abductively, the composition theorems are usable in eliminating models that may not be physically possible in reality [Bhatt 2010].



(a) Property persistence (b) Positional persistence

Figure 8.: Incorporating Spatial / Qualitative Inertia

P5. Axioms of Interaction

Axioms of interaction that explicitly model interactions between interdependent spatial calculi, when more than one calculi are being applied in a non-integrated manner (i.e., with independent composition theorems)

From the viewpoint of integration with a logic of action and change, one may assume that for any spatial calculus, (P1–P5) are known apriori. In order to realize a domain-independent spatial theory that is re-usable across arbitrary dynamic domains, it is necessary to preserve all the high-level axiomatic semantics in (P1–P5), and implicitly the underlying algebraic properties, that collectively constitutes a 'qualitative spatial calculus' [Ligozat and Renz 2004].

4.2.2 Spatial Inertia

Inertial aspects of a dynamic spatial system determining what remains unchanged need to be accounted. The following forms of persistence may be identified:

Spatial Property Persistence

The intuition that the spatial relationship between two (or more) objects typically remains the same, is one default reasoning pattern rooted in the *frame problem* that is identifiable within the spatial context. The frame problem, first identified by McCarthy and Hayes [1969] in the context of mathematical logic, is one of the most fundamental problems that occurs whilst reasoning about the effects of actions [Shanahan 1997]. In so far as the limited context of logic-based AI is concerned, the general problem is this: '*How do we reason about those aspects of the state that remain unchanged as a result of performing an action*?' Imagine if there were a set

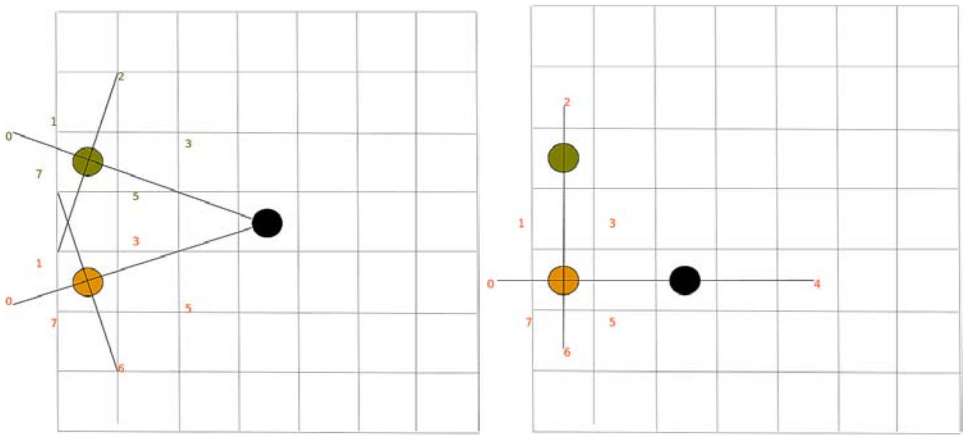


Figure 9.: Default Reasoning about 'Emptiness' in Discrete Space

of spatial actions / events involving the translation and rotation of objects, we would have quite a number of conditions to write down that certain spatial actions do not change the state in some way. Precisely, with *m* actions and *n* values (representing the state), we would have to write down $m \times n$ such conditions.

For the spatial case, the frame problem translates to spatial property / relational persistence: assuming that dynamic topological and orientation information constitutes the state descriptions, the problem is that of formalizing the intuition that the topological / directional relationship between two objects or the orientation of an object relative to another '*typically*' remains the same.

Absolute Positional Persistence

In addition to persistence at the qualitative or relational level, absolute positional persistence at the metric level is also required to formalize the intuition that the absolute spatial extension of an object, whatever that may be from a geometric viewpoint, remains the same

Emptiness

Default reasoning about empty space is another useful inference pattern that is useful within a dynamic context. Here, the intuition that needs to be formalised is that an empty region of space *typically* remains empty [Shanahan 1995]. This is a default assumption that a robot must make before moving objects from one loca-

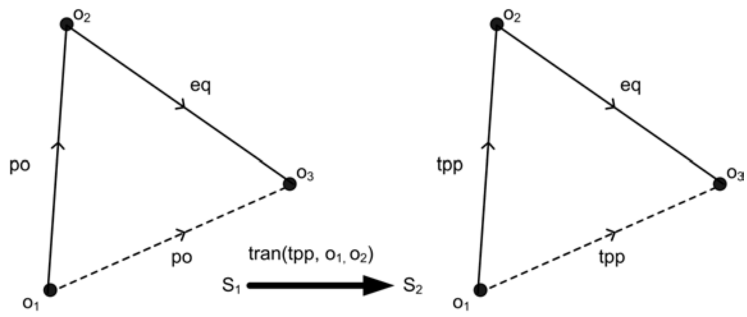


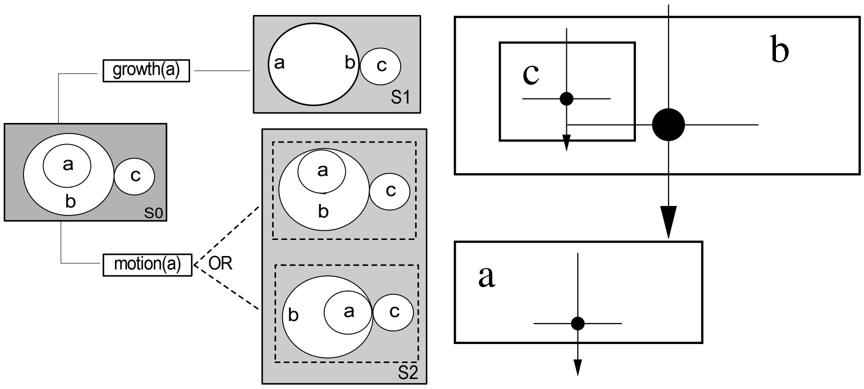
Figure 10.: Compositional Constraints and Ramifications

tion to another, or before moving itself to a new location. As an example, consider the discrete grid world of Fig. 9: the illustration consists of three point-abstracted entities, and their relative orientation relationships modelled as per the partitioning scheme of the Single-Cross Calculus (see Section 4.2.1, Fig. 7). Here, one (or more) of the three entities / agents that may want to move to a new location in the grid should be able to perform a *move* action by implicitly making a default assumption of the emptiness of the target location. Indeed, such an assumption is possible only if default reasoning about emptiness has been incorporated within the underlying commonsense reasoning approach.

4.2.3 Ramifications – Indirect Effects

The *ramification problem* [Finger 1987] is concerned with the capability to model actions whose execution causes indirect effects. These effects, not formally accounted for in the respective action specification, are consequences of general laws describing dependencies between components of the world description [Thielscher 1997]. The concept of ramification is closely related to the notion of domain constraints, causality and transitive dependencies that exist between various properties of a particular dynamic system that is being modelled [Hall 2000, Lin 1995, Papadakis and Plexousakis 2003, Thielscher 1997].

Basically, ramification yielding state constraints contain implicit side-effects in them that need to be accounted for whilst reasoning about the effects of events and actions. Since indirect effects are a recurring problem whilst modelling several aspects of qualitative spatial calculi, the ramification problem is of special significance from the viewpoint of commonsense reasoning about spatial change [Bhatt



(a) Compositional theorems (b) Axioms of interaction

Figure 11.: Ramifications / Indirect Effects

2010][16]. As an example of how this is relevant to spatial change, consider the basic case of compositional inference with three objects o_1, o_2 and o_3 in Fig. 10: when o_1 and o_2 undergo a transition to a different qualitative state (either by translational motion and/or deformation), this also has an indirect effect, although not necessarily, on the spatial relationship between o_1 and o_3 since the relationship between the latter two is constrained by at least one of the $[n \times n]$ compositional constraints (Section 4.2.1; P4) of the relational space.

For a more action and event oriented example, consider the illustration in Fig. 11(a): the scenario depicted herein consists of the topological relationships between three objects 'a', 'b' and 'c'. In the initial situation 'S_0', the spatial extension of 'a' is a *non-tangential part* of that of 'b'. Further, assume that there is a change in the relationship between 'a' and 'b', as depicted in Fig. 11(a), as a result of a direct effect of an event such as *growth* or an action involving the *motion* of 'a'. Indeed, as is clear from Fig. 11(a), for the spatial situation description in the resulting situation (either 'S_1' or 'S_2'), the compositional dependencies between 'a', 'b' and 'c' must be adhered to, i.e., the change of relationship between 'a' and 'c' must be derivable as an indirect effect from the underlying compositional constraints. The new relationship between a and c in situation S_2 can either result

[16]The computational tasks where such commonsense reasoning is relevant are discussed in Section 4.3

in: increased ambiguity, decreased ambiguity and in some cases no change at all.[17] For instance, in the case of the RCC-8 topological calculus, there exist a total of 64 composition theorems, 27 of which provide unambiguous information as to the potential relationship. All other compositions provide disjunctive information that may further be refined by the inclusion of complementary spatial calculi, e.g., in a manner such as in [Randell and Witkowski 2004]. Modelling of complementary aspects of space requires the so called "*axioms of interaction*" [Bhatt 2010], which produce ramification similar in nature to the compositional constraints. This is illustrated Fig. 11(b) for the case of three extended and (also) point-abstracted entities *a*, *b* and *c* – the interpretation of the ramification is left to the reader.

4.2.4 Dynamic Spatial Phenomena

The range of *phenomenal* aspects that may be accounted for from a commonsensical viewpoint is, in principle, open-ended. The identification of default spatial reasoning patterns, the general utility of non-monotonic reasoning about change from a specific spatial reasoning viewpoint is broadly an interesting and open research area. In the following, some instances are summarised:

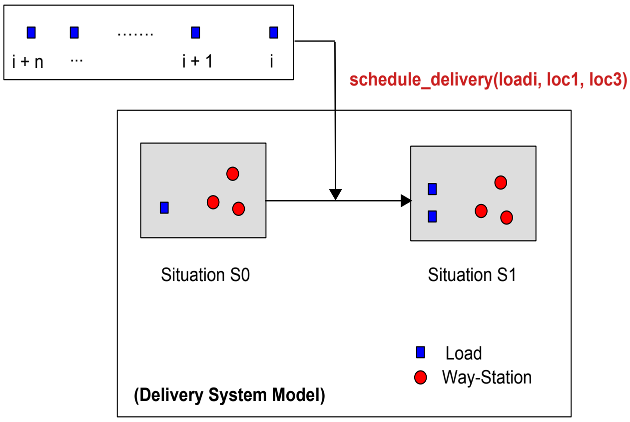
Appearance and Disappearance of Objects

Appearance of new objects and disappearance of existing ones, either abruptly or explicitly formulated in the domain theory, is characteristic of non-trivial dynamic spatial systems. In robotic applications, it is necessary to introduce new objects into the model, since it is unlikely that a complete description of the robot's environment is either specifiable or even available. Similarly, it is also typical for a mobile robot operating in a dynamic environment, with limited perceptual or sensory capability, to lose track of certain objects because of issues such as noisy sensors or a limited field-of-vision.

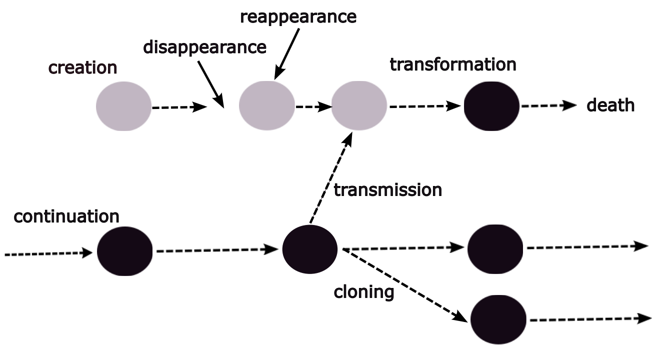
As an example, consider a '*delivery scenario*' (Fig. 12(a)) in which a vehicle/robot is assigned the task of delivering '*object*(*s*)' from one '*way-station*' to another. In the initial situation description, the domain consists of a finite number of '*way-stations*' and deliverable '*objects*'. However, the scheduling of new objects for delivery in future situations will involve introducing new 'objects' into the domain theory. For example, an external event [18] such

[17] The former two cases involve ramifications whereas the last case pertains to *spatial inertia* (Section 4.2.2).

[18] An external event is an event that may occur non-deterministically at some time-point.



(a) Appearance and disappearance - Delivery example



(b) Object change history, Source: [Worboys 2005]

Figure 12.: Phenomenal Aspects

as ‘$schedule\_delivery(new\_load, loc_1, loc_5)$’ introduces a new object, namely ‘*new_load*’, into the domain. Appearance and disappearance events involving the modification of the domain of discourse are not unique to applications in robotics. Even within event-based geographic information systems, appearance and disappearance events are regarded to be an important typological element for the modelling of dynamic geospatial processes [Claramunt and Thériault 1995, Worboys 2005]. For instance, Claramunt and Thériault [1995] identify the basic processes used to define a set of low-order spatio-temporal events which, among other things, include appearance and disappearance events as fundamental. Similarly, toward event-based models of dynamic geographic phenomena, Worboys [2005] suggests the use of the appearance and disappearance events at least in so far as single object behaviours are concerned (see Fig. 12(b)).

Within a logical framework, appearance and disappearance has ramifications from the (model-theoretic) viewpoint of modelling an incompletely known domain of discourse. The case of disappearance is not too problematic, however, for the case of appearance and re-appearance, some questions that need to be addressed include:

- What is the spatial relationship (e.g., topological, directional) of the newly appearing object with other existing objects? Clearly, within a relational spatial framework, the whole notion of the existence of an object/entity is based on its spatial relationship with at least one other existing entity

- Given the fact that a newly appearing object is, from a model-theoretic viewpoint, *unknown* in the past, how to make it 'known' and 'not exist' in the past? Clearly, here it is important that the approach to handle this problem be domain-independent

- How to make past and present situation descriptions 'compositionally consistent'?[19] Here, knowledge about the past may be completely irrelevant in the best case, but in principle, this still does not dispel the need to maintain consistent beliefs about the past

Apart from above-discussed logical difficulties of modelling incompletely known domains, from a strictly spatial reasoning perspective, such appearance, disappearance and re-appearances are also connected to the issue of object identity maintenance, e.g., from a GIS centered perspective [Bennett 2002, Hornsby and Egenhofer 2000].

4.3 Commonsense Reasoning about Spatial Dynamics

Given some 'action description logic' ($\mathscr{ADL}$) and the 'domain theory' ($\mathscr{D}$) for the application under consideration, basic reasoning capabilities encompassing *projection*, *simulation*, *planning* and *explanation* should be available in the context of $[\mathscr{ADL} \cup \mathscr{D}]$. It must be emphasized that all desirable reasoning patterns or computational tasks should directly follow from the semantics of the underlying $\mathscr{ADL}$ and the domain-specific instance as presented by way of $\mathscr{D}$. For instance, standard

[19]Recall that compositional consistency refers to the satisfaction of the global constraints formulated by composition theorems relevant to every spatial calculus that is modelled.

computational techniques such as *regression* and *abductive explanation* should remain applicable within the context of the $\mathscr{ADL}$ being utilized. Depending on the richness required with respect to *time*, *continuity*, *concurrency*, and the *action ontology*, there are many possibilities for the choice of the $\mathscr{ADL}$. Whereas Bhatt and Loke [2008] illustrate this for the case where the $\mathscr{ADL}$ corresponds to a basic situation calculus based causal theory, this may be substituted with the event calculus, fluent calculus and possibly even other specialised formalisms [Davis and Morgenstern 2004]. In principle, any *basic action theory* in a sorted first-order logic with action and event types, preconditions and effect axioms, and a general mechanism to handle the frame problem and ramification problems should be sufficient.

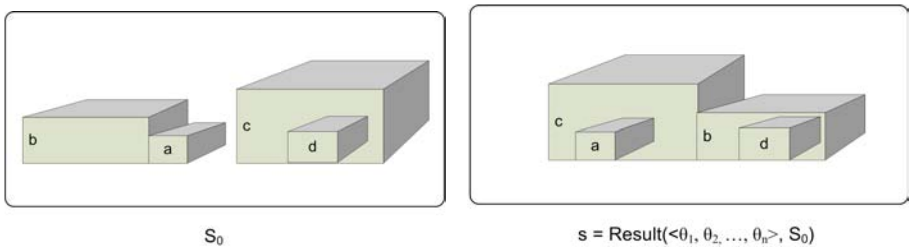
4.3.1 Spatial Property Projection and Simulation

Given a sequence consisting of events and/or actions, *projection* corresponds to the task of determining what would be true if those actions were performed or if the events occurred starting in the initial situation. It is of course a separate matter to determine whether or not the events and actions present in the sequence could in fact occur or be possible/performed sequentially in compliance with the action/event preconditions and the relational constraints of the spatial theory that is being modelled. The related task of determining such compliance is termed as *legality testing*. These tasks are fundamental from the viewpoint of planning (e.g., by goal regression) and/or theorem-proving within the framework of $\mathscr{ADL}$.

Projection and simulation are necessary to apply *'what if...'* scenarios on one or more spatial and non-spatial properties (or fluents) that reflect the state (e.g., spatial configurations) of the system. Differences in the axiomatisation of the precise $\mathscr{ADL}$ notwithstanding, the fundamental reasoning task of *projection* and its essential counterpart of *legality testing* are definable within the context of the underlying action theory (e.g., [Reiter 2001]). To reiterate, these tasks should directly follow from the semantics of the foundational axioms of the concerned $\mathscr{ADL}$.

4.3.2 Spatial Planning / Re-Configuration

The objective in *spatial planning* is to derive a sequence of spatial actions that will achieve a goal, e.g., *transfer* of *liquid* from one *container* to another, and other forms of spatial re-configuration, e.g., topological and orientational *rearrangement*, involving physical manipulation and movement of objects by translation and rotation. Given a basic mechanism for projection and legality testing with



(a) Initial configuration (denoted by situation S_0) representing the initial configuration of objects.

(b) Desired configuration s is the *Result* of sequentially performing $[\theta_1,\ \theta_2,\ \theta_n]$ in S_0.

Figure 13.: Spatial Re-configuration with $[\mathscr{ADL}]$ for the Blocks World

an $\mathscr{ADL}$, the formulation of offline planning is rather straight-forward [Brachman and Levesque 2004].

As a basic example, consider Fig. 13 where a topological and orientation re-configuration task is illustrated for the *block world*. Here, instead of a naive representation of relationships such as $on(a,\ b)$ and $on(b,\ table)$, which is common approach adopted in planning tasks, it is desired that there be an inherent way within the underlying $\mathscr{ADL}$ to maintain commonsense knowledge about space and spatial changes by way of a generic / domain-independent spatial theory. The objective in doing so is that the spatial semantics, e.g., as constituted by the formal properties of one or more spatial calculi, be explicitly integrated with the semantics of the $\mathscr{ADL}$. With this setup, the $\mathscr{ADL}$ together with the domain-specific instance $\mathscr{D}_{blocks}$ may be directly applied for planning tasks. For the re-configuration example of Fig. 13, given an *initial* and *desired* situation description in Fig. 13(a) and 13(b) respectively, a plan by way of a sequence of movement actions $[\theta_1,\ \theta_2,\ \theta_n]$ is directly obtainable in a conventional planner[20] from the spatial theory encoded within the $\mathscr{ADL}$, or precisely, from $[\mathscr{ADL} \cup \mathscr{D}_{blocks}]$.

4.3.3 Causal Explanation (by Abduction)

Diametrically opposite to projection and planning is the task of post-dictum or explanation [Pierce 1935, Poole et al. 1987], where given a set of time-stamped observations or snap-shots (e.g., observation of a mobile-robot or time-stamped GIS data), the objective is to explain which events and/or actions may have caused the resulting state-of-affairs. Explanation, in general, is regarded as a converse

[20] For instance, "*plans can be synthesized as a side-effect of theorem proving*" [Reiter 2001].

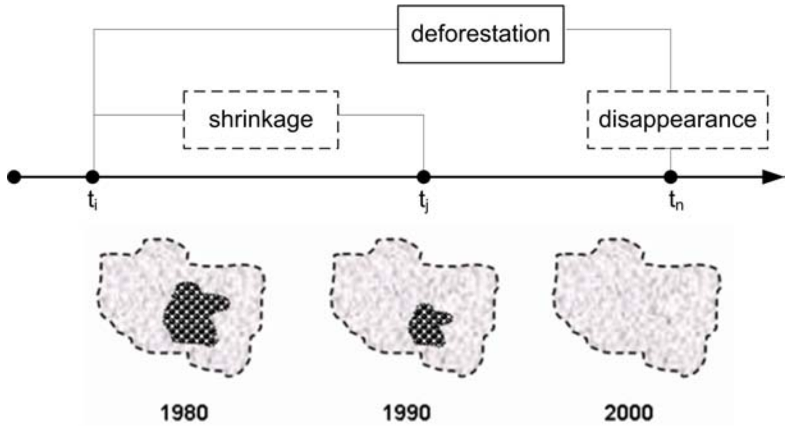


Figure 14.: Domain Independent and Specific Abduction

operation to temporal projection essentially involving reasoning from effects to causes, i.e., reasoning about the past [Shanahan 1989].

For the spatial case, causal explanation refers to the explanation of observations (e.g., observations of a robot, sensor readings in a smart home, datasets in a GIS) from temporally-ordered spatial snapshots. Here, explanation involves the interpolation of missing spatial scenes (i.e., consistent constraint networks) in adherence to the continuity and relational constraints of the relationship space (Section 4.2.1), and the derivation of high-level spatial and non-spatial actions and events that may have occurred and caused the observed state-of-affairs. Based on the (circumscriptive) abductive approach of Shanahan [1993] for explanation in the context of the situation calculus, Bhatt [2009a] formalizes and demonstrates the manner in which causal explanation may be performed within the spatial domain. The approach, as illustrated later in this section, has been further been applied in the context of the event calculus [Bhatt and Flanagan 2010]. For the purposes of this chapter, we further illustrate and exemplify the practical concepts involved in explanation within the spatial domain. Consider the examples in (E1–E2) from two very different domains. Whereas example E1 illustrates the concept of the *adequacy* of an explanation, E2 demonstrates the nature of *scenario and narrative completion*:

E1. *Abduction in GIS*.

Consider a geographic information system domain / scenario as depicted in Fig. 14. At a domain-independent level (i.e., at the level of a general spatial theory), the scene may be described using topological and qualitative size relationships. Con-

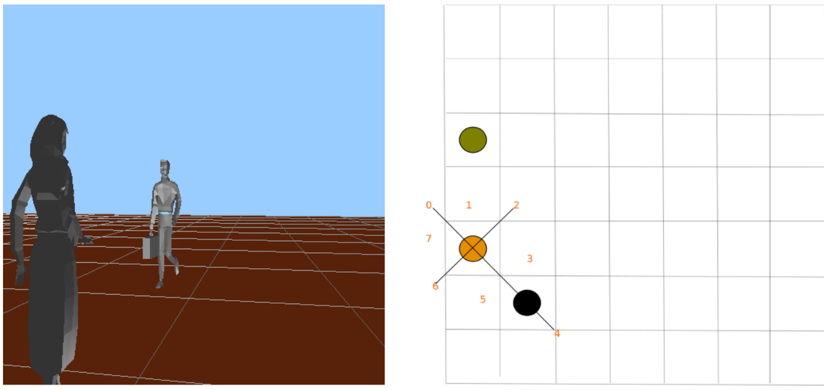


Figure 15.: Automatic Cinematography Domain: 2 Avatars and 1 Virtual Camera (black circle). Source: [Bhatt and Flanagan 2010]

sequently, the only changes that are identifiable at the level of the spatial theory are *shrinkage* and eventual *disappearance* – this is because a domain-independent spatial theory may only include a generic typology (*appearance, disappearance, growth, shrinkage, deformation, splitting, merging* etc) of spatial change. However, at a domain-specific level, these changes could characterize a specific event (or process) such as, for instance, *deforestation*. The hypotheses or explanations that are generated during a explanation process should necessarily consist of the domain-level occurrences in addition to the underlying (associated) spatial changes (as per the generic typology) that are identifiable. That is to say, that the explanations more or less take a form such as: '*Between time-points t_i and t_i, the process of deforestation is abducible as one potential hypothesis*'. Derived hypothesis / explanations that involve both domain-dependent and as well their corresponding domain-independent typological elements are referred to as being '*adequate*' from the viewpoint of causal explanation.

E2. *Scenario and Narrative Completion by Abduction*.

Consider the illustration in Fig. 15 for the domain of automatic cinematography: the world consists of three point-abstracted entities— 2 *avatars* and 1 virtual *camera*.[21] For minimality, suppose that container space is modelled a discrete grid world together with relative orientation relationships among the entities as per the partitioning scheme of the Single-Cross Calculus (see Section 4.2.1, Fig. 7). For

[21]The third entity in the simulation is a virtual camera that records the other two entities in the scene, and hence is not visible within the 3D illustration of Fig. 15.

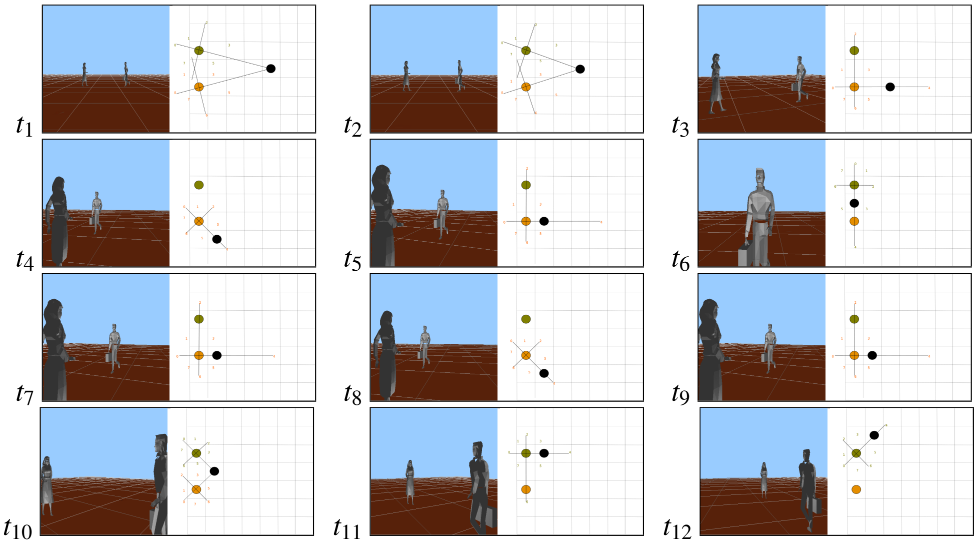


***Figure 16.*:** Scenario and Narrative Completion by Abduction. Source [Bhatt and Flanagan 2010]

this discussion, further suppose that the *camera* is the only entity that is able to move, i.e., change location from one grid-cell to another.

For a scenario such as this, causal explanation could be the basis of *scenario and narrative completion*, and for this particular example, the derivation of ideal *camera placements* as a side-effect of the abduction process. Figure 16 consists of a *narrative* (completion) from time-points t_1 to t_{12}, denoting an *abduced* evolution of the system, as represented the sequence of qualitative state descriptions for 2 stationery and 1 moving entity. For clarity, images from a 3D simulation are included together with the relational / graph-based illustrations for each of the time-points. From an initial narrative description consisting of information about only some of the time-points[22], the narrative completion has been abduced on the basis of available *camera actions – pan, zoom, move* – and pre-specified knowledge or heuristics, referred to as *film idioms*, about desired camera placements, e.g., *establishing shot*, *external shot*, *mid-shot*, *close-up* and so forth. In this example, the resulting narrative is usable by a virtual reality and/or an automatic cinematography system to generate automatic visualizations for a script.

[22]These are, for instance, (implicitly) available from linguistic descriptions about *acts* and *scenes* within a drama or film script. The progression of the script can be thought of as an imaginary evolution of the system.

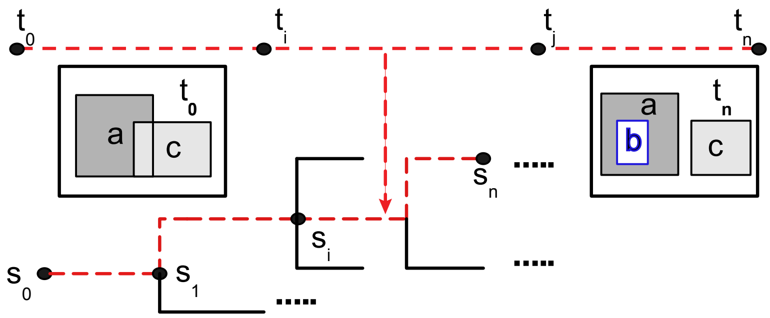


Figure 17.: Branching / Hypothetical Situation Space

Structure of Causal Explanation: Given the examples in (E1–E2), its easy to intuitively infer the general structure of causal explanation (by abduction) within spatial information. Consider the illustration in Fig. 17 for a branching / hypothetical situation space that characterizes the complete evolution of a system. In Fig. 17 – the situation-based history $< s_0,\ s_1, \ldots,\ s_n >$ represents one path, corresponding to a actual time-line $< t_0,\ t_1, \ldots,\ t_n >$, within the overall branching-tree structured situation space. Given incomplete narrative descriptions, e.g., corresponding to only some ordered time-points (such as in Fig. 16) in terms of high-level spatial (e.g., topological, orientation) and occurrence information, the objective of causal explanation is to derive one or more paths from the branching situation space, that could best-fit the available narrative information. Of course, the completions that bridge the narrative by interpolating the missing spatial and action/event information have to be consistent with domain-specific and domain-independent rules/dynamics.

Many different formalizations of causal explanation with spatial knowledge, such as within a belief revision framework [Alchourrón et al. 1985], nonmonotonic causal formalizations in the manner of [Giunchiglia et al. 2004] are possible and the subject of ongoing study. Additionally, the suitability of event calculus [Kowalski and Sergot 1986, Mueller 2009] vis-à-vis the situation calculus is also a topic that especially merits detailed treatment.

5 Summary of Chapter

The RSAC paradigm aims to address the issue of applications of qualitative spatial reasoning: by what bridges may we connect formal '*logical*' methods in reasoning about space, and reasoning about change, with applications / their computational requirements, such as those mentioned in Section 2, that are considered befitting of such methods. A secondary focus, closely related to the main issue of integration, has been on the conventional emphasis of research in the QSR domain – *qualitative spatial reasoning* [Freksa 1991b] methods have primarily remained focused on the development of new calculi for spatial information representation and on the construction of efficient algorithms for solving spatial reasoning problems [Cohn and Renz 2007, Renz and Nebel 2007]. The emphasis in QSR has primarily been on reasoning with static spatial configurations. However, for the range of application domains such as those identified in Section 2, spatial reasoning methods require a dynamic interpretation, and more importantly, support for high-level forms of inference such as prediction, planning and explanation.

In general, the areas of *commonsense reasoning*, and *reasoning about action and change* are mature and established tools, formalisms and languages [Davis and Morgenstern 2004, Van Harmelen et al. 2007] from therein are general enough to be applied to the case of *dynamic spatial systems* [Bhatt and Loke 2008], where relational spatial models undergo change as a result of interaction (i.e., actions and events) occurring within the system or environment being modeled. Consequently, the formal embedding of arbitrary spatial calculi – whilst preserving their high-level axiomatic semantics and low-level algebraic properties – has to be investigated from the viewpoint of formalisms such as the situation calculus, event calculus, fluent calculus and possibly other specialized formalisms. Broadly, this will result in the incorporation of *commonsense notions of space and spatial change*, and *dynamic spatial phenomena* of a general sort within general logic-based frameworks in artificial intelligence, and their use in application domains requiring predictive and explanatory reasoning capabilities within a dynamic context. As research in QSR moves toward practical application considerations, it is expected that the conventional focus of QSR will extend itself from reasoning about space in isolation to *logical* reasoning about space, actions and change in an integrated manner.

Literature and Community

In line with the aims of this chapter, and the book, some key reading material has been pointed-out here explicitly. Hopefully, this will be of utility to new research students and practitioners from other fields of computer science.

The textbook on *Qualitative Spatial change* [Galton 2000] is an excellent introduction and in-depth study of the advancements in the spatial reasoning area; taken together with [Stock 1997], the demystification of qualitative spatial representation and reasoning for a beginner should be easily possible. The *Handbook of Spatial Logics* [Aiello et al. 2007] is a more advanced text that presents a rather formal analysis.

The *Knowledge Representation Handbook* [Van Harmelen et al. 2007] is the definitive text for the KR community; there are several chapters within that serve as an excellent starting point for many of the topics discussed in this chapter (e.g., chapters on cognitive robotics, qualitative spatial representation and reasoning, commonsense reasoning).

The text *Knowledge in action: Logical foundations for describing and implementing Dynamical systems* by Reiter [2001] is the most comprehensive and intense study of modelling dynamic domains within the framework of the situation calculus. A good companion text for beginners would be the text *Knowledge Representation and Reasoning* by [Brachman and Levesque 2004]. The textbook on *Commonsense Reasoning* [Mueller 2006] is a comprehensive study of modelling commonsense reasoning within the framework of the Event Calculus [Mueller 2006].

Workshops and special sessions on Qualitative Spatial Representation and Reasoning (and derivatives) are regularly organised at all major AI conferences such as AAAI, ECAI, IJCAI. Furthermore, the conference series on Spatial Information Theory (COSIT) is a specialized forum devoted to theoretical and application-oriented issues surrounding QSR and related topics. These events should be a rich source of the latest advancements in the community.

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Author Biography

Mehul Bhatt is an Alexander von Humboldt Postdoctoral Fellow based at the SFB/TR 8 Spatial Cognition, University of Bremen. His academic career also includes research experiences at the Data Engineering and Knowledge Management Group, La Trobe University, Australia (PhD), at the Knowledge Representation and Reasoning Group, University of New South Wales, Australia (Research scholar) and at the Spatial Information Research Center (SIRC), University of Otago, New Zealand (Guest Researcher). His interests and publications encompass the areas of spatio-temporal reasoning, commonsense and non-monotonic reasoning as applicable to space and time, cognitive robotics, applied ontology, and parallel and distributed systems. Mehul Bhatt has been a organizer / editor of specialized workshops / publications in the area of spatial and temporal reasoning (e.g., at IJCAI, ECAI) and its application in several areas of emerging interest.

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