

A QUALITATIVE MODEL OF DYNAMIC SCENE ANALYSIS AND INTERPRETATION IN AMBIENT INTELLIGENCE SYSTEMS

Mehul Bhatt and Frank Dylla

SFB/TR 8 Spatial Cognition,* Enrique-Schmidt-Straße 5, 28359 Bremen, Germany

{bhatt, dylla}@sfbtr8.uni-bremen.de

Abstract Ambient intelligence environments necessitate representing and reasoning about dynamic spatial scenes and configurations. The ability to perform predictive and explanatory analyses of spatial scenes is crucial toward serving a useful intelligent function within such environments. We present a formal qualitative model that combines existing qualitative theories about space with a formal logic-based calculus suited to modelling dynamic environments, or reasoning about action and change in general. With this approach, it is possible to represent and reason about arbitrary dynamic spatial environments within a unified framework. We clarify and elaborate on our ideas with examples grounded in a smart environment.

Keywords Ambient Intelligence, Qualitative Spatial Reasoning, Reasoning about Action and Change

1. Introduction

A wide-range of application domains in Artificial Intelligence, from cognitive robotics to intelligent systems encompassing diverse paradigms such as ambient intelligence and ubiquitous computing environments, require the ability to represent and reason about dynamic spatial scenes or configurations. For instance, real world ambient intelligence systems that monitor and interact with an

*Funding by the German Research Foundation (DFG) is gratefully acknowledged.

Draft version.

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. Here, the location of a mobile-object (e.g., person, a vehicle, an animal or possibly other artefact) may 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) for purposes of dynamic scene analysis and interpretation, event-recognition, alert generation, surveillance and so forth. 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, e.g., a monitoring or alert generation system in a smart-home [1, 2]. 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 aspatial, 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.

In this paper, we propose to utilise a formal basis for representing and reasoning about space, change and occurrences within ambient intelligence systems or in general, within a ubiquitous computing environment. The model, on the one hand, utilises formal spatial calculi [3] for representing and reasoning about space in a qualitative manner (Sec. 2), and on the other hand, uses a general formalism for reasoning about the inherent dynamism involved within the aforementioned domains of interest (Sec. 3). Precisely, the model is based on an integration of existing qualitative theories of space, or qualitative spatial calculi, pertaining to differing spatial domains, such as topology [4] and orientation [e.g., 5] with a formal logic based approach, namely the situation calculus [6], which is a general formalism for modelling dynamic environments [7]. The key advantages of the model are two-fold:

I. Qualitative spatial characterisations: By abstracting objects in space to geometric primitives such as points, lines and regions and partitioning infinite quantity or metric spaces to finite qualitative

Draft version.

categories, qualitative spatial reasoning captures distinctions between objects and the relationships between them that make an important qualitative difference, but ignores others [3].

II. Formal modelling of dynamics: The use of the situation calculus formalism for reasoning about the spatial dynamics and importantly, the integration of spatial calculi within it, provides a uniform ontological and computational framework for the modelling of space, change and events. Given the semantics of the calculus, key reasoning tasks involving projection, planning and explanation directly follow. These tasks can be specialised in a diverse range of application scenarios, such as the ones aforementioned, in the form of spatial planning (in cognitive robotics) or causal explanation (in surveillance or smart home systems).

Sections 4 and 5 illustrate the proposed qualitative model and its realisation in the situation calculus. The reasoning facilitated by the model is illustrated for exemplary scenario in Sec. 6.

2. Qualitative Spatial Representation and Reasoning

Qualitative Reasoning (QR) is concerned with capturing everyday commonsense knowledge of the physical world with a limited set of relations and manipulating it in a non-numerical manner [3]. The sub field of Qualitative Spatial Reasoning (QSR) is only concerned with spatial aspects. The main aim of research in QSR is to develop powerful representation formalisms that account for the multi-modality of space in a cognitively acceptable way [8, 3]. A qualitative spatial description captures distinctions between objects that make an important qualitative difference but ignores others. In general, objects are abstracted to geometric primitives, e.g. points or regions in the Euclidean plane. Based on a finite set of jointly exhaustive and pairwise disjoint (JEPD) symbols, called relations, the relationships between objects are described. A set of relations together with the operations defined on them is called a *qualitative calculus*. From a reasoning perspective a *static* and *dynamic* aspect for qualitative spatial calculi can be distinguished.

On the one hand, by means of calculus' relations a spatial *constraint satisfaction problem* (CSP) can be formulated, reflecting the spatial constraints about a static configuration of objects. CSP's can be solved with specific reasoning techniques, e.g. by applying composition and intersection operations repetitively. From an axiomatic viewpoint, composition can be defined as: $(\forall a, b, c). R_1(a, b) \wedge R_2(b, c) \rightarrow R_3(a, c)$. On the other hand, two qualitative relations are

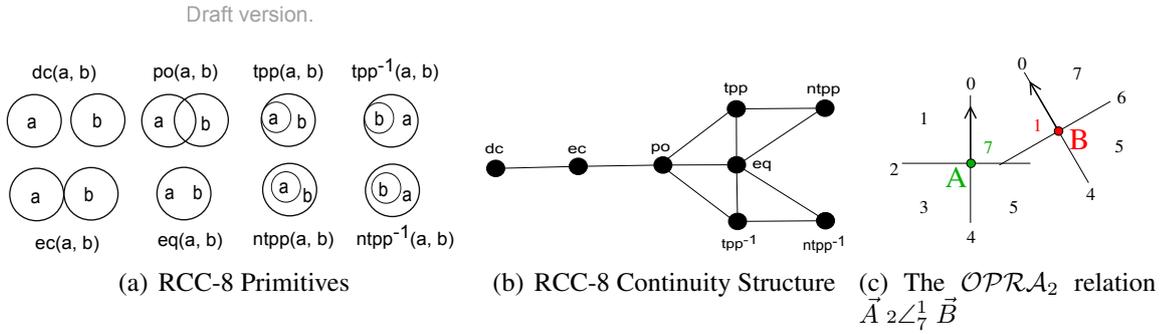


Figure 1: Topological and Orientation Primitives

conceptually neighbored, if they can be continuously transformed into each other by continuous motion and/or deformation, without resulting in a third relation in between [9]. So, qualitative representations are extended by the temporal aspect of transformation between basic entities. Different kinds of transformations, e.g. locomotion or deformation, result in different conceptual neighbourhood structures. For details we refer to [3]. In our approach we apply the topological calculus RCC-8 and the relative orientation calculus \mathcal{OPRA}_m .

Topological distinctions are inherently qualitative in nature and they also represent one of the most general and cognitively adequate ways for representing spatial information [10]. Based on the work by Clarke [11], Randell et al. [4] developed the theory of the *Region Connection Calculus*. The *RCC-8 fragment* consists of eight relations: *disconnected* (dc), *externally connected* (ec), *partial overlap* (po), *equal* (eq), *tangential proper-part* (tpp) and *non-tangential proper-part* ($ntpp$), and the inverse of the latter two tpp^{-1} and $ntpp^{-1}$ (cf. Fig. 1(a) for a 2D illustration of the relations). For example, if regions a and b are *disconnected* and c is a *tangential proper part* of b , then, by composition, it is also known that a and c are *disconnected*. The continuity structure of RCC-8 is depicted in Fig. 1(b). For example, dc is not a neighbour of po , because the state of being externally connected (ec) must occur during the transformation process.

The family of \mathcal{OPRA}_m calculi is designed for reasoning about relative orientation relations between *oriented points* (points in the plane with an additional direction parameter) and are well-suited for dealing with objects that have an intrinsic front or move in a particular direction [5]. With the granularity parameter m , the number of angular sectors can be influenced, i.e. the number of base relations is affected. Applying granularity $m = 2$ results in 4 planar and 4 linear regions (see Fig. 1(c)), numbered from 0 to 7, where region 0 coincides with the orientation of the point. An \mathcal{OPRA}_2 base relation is a pair (i, j) , where i is the number of the region, seen from \vec{A} , that contains \vec{B} and j vice versa. Relations are written as $\vec{A} \ 2\angle_i^j \ \vec{B}$. For details on composition we refer

Draft version.

to [5]. For the task at hand we can restrict the general neighbourhood structure given in [12] to:

$$\text{cn}_g(2\angle_i^j) = \{ 2\angle_{i-1}^{j-1}, 2\angle_{i-1}^j, 2\angle_{i-1}^{j+1}, 2\angle_i^{j-1}, 2\angle_i^j, 2\angle_i^{j+1}, 2\angle_{i+1}^{j-1}, 2\angle_{i+1}^j, 2\angle_{i+1}^{j+1} \}.$$

3. Dynamic Spatial Environments in the Situation Calculus

Situation calculus as a representational formalism for modelling dynamically changing domains was first formally presented by McCarthy and Hayes [6]. It is one of the most investigated mathematical logic based formalisms for modelling dynamical systems. A domain theory is axiomatised in the situation calculus with the following four classes of axioms: (A1) precondition and effect axioms for actions and events, (A2) unique names axioms for actions, events and fluents, which state that the respective ontological elements of the domain are pair-wise unequal, (A3) initial state of the world, (A4) successor state axioms, which embody a solution to the frame problem (i.e., problem of inertia) for deterministic actions [7]. Several high-level control languages, e.g., GOLOG [13], CCGOLOG [14], which are based on the situation calculus semantics have been developed and applied in the cognitive robotics domain. Each of these languages is equipped with different features including concurrent and continuous change, online/incremental execution, and sensing for applicability in real (robotic) control environments.

Spatial Reasoning in the Situation Calculus: Based on a customised situation calculus formalism, Bhatt and Loke [15] propose a dynamical systems approach for modelling a domain-independent qualitative spatial theory. The approach is primarily aimed at operationalising qualitative spatial calculi toward the representation of useful computational tasks that involve planning, explanation and simulation in arbitrary dynamic spatial scenarios – the proposed application of the analysis and interpretation of dynamic spatial scene in this paper being only one exemplar. Indeed, if the (embedded) spatial component is to be based on existing (qualitative) theories of space, it is essential that such theories (precisely, qualitative spatial calculi pertaining to differing aspects of space; see Sec. 2) be embedded within the general logic-based framework under consideration, namely the situation calculus. Most importantly, it is essential that the following high-level axiomatic semantics of the spatial calculi being embedded be preserved [15]: (C1) JEPD property of the relations, (C2) other basic properties of the relations including symmetry, asymmetry, transitivity etc. (C3) compositional inference and consistency maintenance, (C4) a primitive notion of change based on the

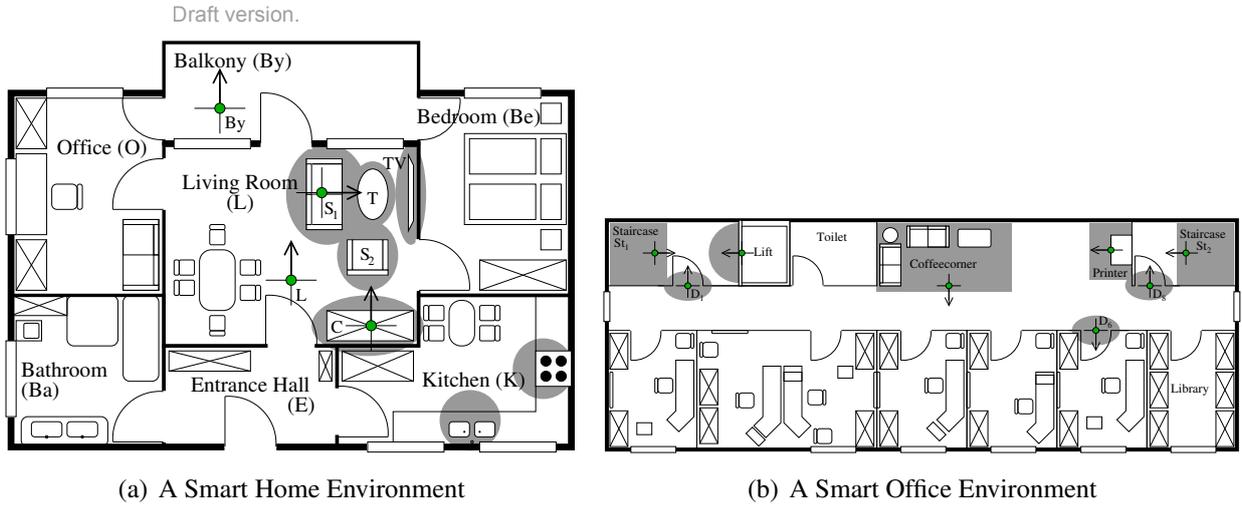


Figure 2: Layouts of application environments. The axes of o-points (cf. Sec. 2) within rooms or objects denote the intrinsic fronts of these objects, e.g., the living room (L) and the sofa (S_1). The grey areas around objects indicate the functional space (Sec. 4) of the objects.

principle of conceptual neighbourhoods (see Sec. 2), (C5) relative entailments between calculi when more than one spatial calculus is being modelled in a non-integrated manner (i.e., there exist separate composition tables). The main objective of such an embedding is that all modes of reasoning that are supported by the containing logical framework (i.e. situation calculus) can then be utilised for modelling useful reasoning tasks in the context of the spatial component. In Sec. 5, we illustrate certain key aspects of such an embedding for RCC-8 and the $OPRA_m$ calculi.

4. Qualitative Spatial Scene Description Ontology

Depending on the degree of formalisation of the spatial theory being employed, scene descriptions in ambient environments primarily consist of qualitative spatial relationships relevant to one or more spatial dimensions (e.g., topology, orientation, direction, size). Since we need to model containment (e.g., in a *room*) and also direction of motion (of an *agent*) or orientation of objects relative to one another, a mixed ontology of *regions* of space and *oriented-points* is sufficient for our scene description purposes. Using the example of a smart environment (home and office; see Fig. 2), we illustrate the manner in which some typical spatial scenes in such environments may be qualitatively modelled using a basic spatial scene description ontology that is grounded in the topological calculus RCC-8 and the relative orientation calculus $OPRA_m$. We also utilise the notion of the functional space of an object, henceforth simply ‘*functional space*’, which refers to the region of space surrounding an object within which an agent must be located to manipulate or physically interact with a given

Draft version.

Table 1: An exemplary part of the scene description matrix.

ϕ_{top}/ϕ_{ort}	By	O	L	Be	Ba	E	K	S_1	S_2	T	TV	C
By	x x	EC $2\angle_{1-3}^{5-7}$	EC $2\angle_{3-5}^{7-1}$	EC $2\angle_{5-7}^{1-3}$	DC -	DC -	DC -	DC -	DC -	DC -	DC -	DC -
O	EC $2\angle_{5-7}^{1-3}$	x x	EC $2\angle_{5-7}^{1-3}$	DC -	DC -	DC -	DC -	DC -	DC -	DC -	DC -	DC -
L	EC $2\angle_{7-1}^{3-5}$	EC $2\angle_{1-3}^{5-7}$	x x	EC $2\angle_{5-7}^{1-3}$	DC -	EC $2\angle_{3-5}^{7-1}$	DC -	PP -	PP -	PP -	PP -	PP -
Be	EC $2\angle_{1-3}^{5-7}$	DC -	EC $2\angle_{1-3}^{5-7}$	x x	DC -	DC -	DC -	DC -	DC -	DC -	DC -	DC -
Ba	DC -	DC -	DC -	DC -	x x	EC $2\angle_{5-7}^{1-3}$	DC -	DC -	DC -	DC -	DC -	DC -
E	DC -	DC -	EC $2\angle_{7-1}^{3-5}$	DC -	EC $2\angle_{1-3}^{5-7}$	x x	EC $2\angle_{5-7}^{1-3}$	DC -				
K	DC -	EC $2\angle_{1-3}^{5-7}$	x x	DC -								
S_1	DC -	DC -	PP -	DC -	DC -	DC -	DC -	x x	DC $2\angle_7^1$	DC $2\angle_0^0$	DC $2\angle_0^0$	DC $2\angle_7^1$
S_2	DC -	DC -	PP -	DC $2\angle_1^1$	x x	DC $2\angle_0^2$	DC $2\angle_7^1$	DC $2\angle_0^0$				
T	DC -	DC -	PP -	DC $2\angle_0^0$	DC $2\angle_2^0$	x x	DC $2\angle_1^0$	DC $2\angle_2^0$				
TV	DC -	DC -	PP -	DC $2\angle_0^0$	DC $2\angle_1^1$	DC $2\angle_0^4$	x x	DC $2\angle_1^1$				
C	DC -	DC -	PP -	DC $2\angle_1^1$	DC $2\angle_0^4$	DC $2\angle_0^2$	DC $2\angle_1^1$	x x				

object. We denote the functional space of an object ‘ o ’ by the function ‘ $fspace(o)$ ’ – the precise geometric interpretation of this function being determinable in domain specific ways depending on issues such as object granularity, the scale of the ambient environment being modelled etc.

4.1 Complete Spatial Scene Descriptions

A ‘*situation*’ is a unique node within the overall branching-tree structure (see Fig. 3(c)) of the space of situations starting with the initial situation S_0 . In other words, a situation includes a complete history of the evolution of the system in terms of the primitive occurrences that have occurred starting in the initial situation S_0 . Corresponding to each such situation, there exists a situation description that characterises the ‘*state*’ (henceforth ‘situation state’) of the system. Starting with the initial situation, it is necessary that the spatial component of every *situation state* be a complete specification without any missing information. Note that by ‘complete specification’, we do not imply absence of uncertainty or ambiguity. Completeness also includes those instances where the uncertainty is expressed as a set of completely specified alternatives in the form of disjunctive information. The initial situation basically includes a specification of initial fluent values. For spatial fluents, at least from the viewpoint of this paper, there exist *two* broad categories:

(I). Existential Facts: These are propositional fluents that provide an explicit existential characterisation of every spatial object that exists in the initial situation. As such, for a domain consisting of n objects in the initial situation, n existential facts to this effect are required.

(II). Spatial Relationships: These model the spatial relationships that exist between the objects that exist in the initial situation. For every type of spatial relationship being modelled, the *initial situation* description involving n domain objects requires a complete *n-clique* specification (see Fig. 3(b)) with $[n(n - 1)/2]$ spatial relationships of one type or spatial domain.

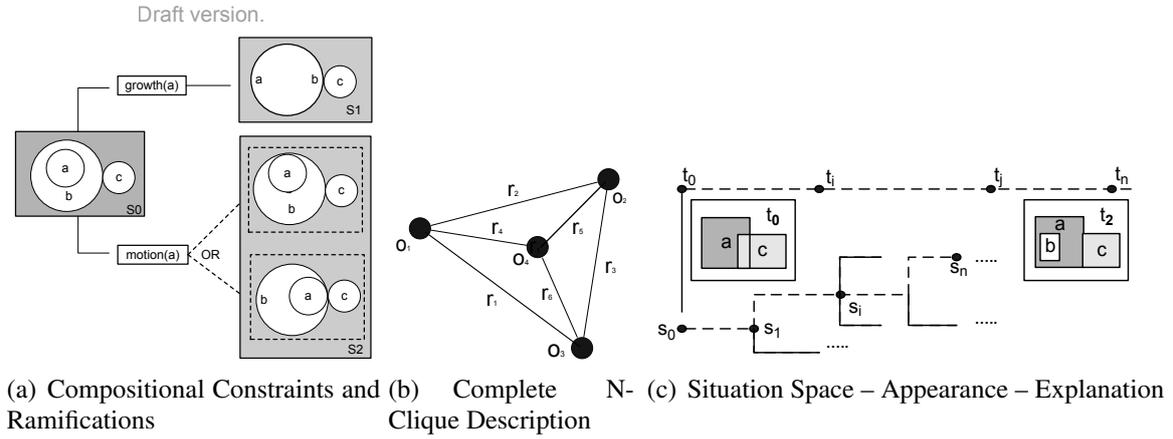


Figure 3: Spatial Scene Descriptions

Observe the ‘scene description matrix’ in Table ??, which illustrates the concept of a complete spatial description for the smart home environment depicted in Fig. 2(a). The information contained herein is grounded in the spatial vocabulary of the RCC-8 and $OPRA_m$ (cf. Sec. 2).

4.2 Global Consistency of Spatial Information (the ‘ramification problem’)

Spatial situation descriptions denoting configurations of domain objects, i.e., by way qualitative spatial relationships relevant to one or more spatial dimensions that hold between the objects of the domain, must be globally consistent in adherence to the compositional constraints of the underlying qualitative space. The notion of compositional consistency also includes those scenarios when more than one aspect of space is being modelled in a non-integrated way, i.e., relative dependencies between mutually dependent spatial dimensions should be modelled explicitly. Ensuring these two aspects of global consistency of spatial information is non-trivial because the compositional constraints contain indirect effects in them thereby necessitating a solution to the ramification problem, i.e., the problem of indirect effects¹. In the spatial representation task, i.e., the embedding of qualitative spatial calculi within the spatial theory (Sec. 3), indirect effect yielding constraints are a recurring problem – modelling composition theorems and axioms of interaction (using ordinary state constraints) leads to unexplained changes since the resulting constraints contain indirect effects in them [15]. For instance, consider the illustration in Fig. 3(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

¹The general problem of indirect-effect yielding state constraints is elaborated on in [16].

Draft version.

in the relationship between ‘ a ’ and ‘ b ’, as depicted in Fig. 3(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. 3(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. In a trivial scenario, such as the present one, consisting of few objects, it could be correctly argued that the indirect effects can be completely formulated as direct effects. However, for a more involved scene description with n objects, a complete n -clique descriptions consisting of $n(n - 1)/2$ spatial relationships for every spatial domain (e.g., topology, orientation, size) being modelled is impractical and error prone. The situation is only complicated given that fact that some of the spatial domains being modelled could be inter-dependent.

Whilst the details not being relevant here, it suffices to point out that a solution to the problem of ramifications for this particular case is obtainable from the general works of Lin and Reiter [17], Lin [16]. The solution basically involves appeal to causality and non-monotonic reasoning to minimise the effects of occurrences whilst deriving the successor state axioms or the causal laws of the domain. Note that this manner of deriving the successor state axioms is an extension to the approach proposed in [7], where only a solution to the frame problem is included under a general ‘completeness assumption’ stipulating that there are no indirect effects within the domain theory.

5. A Spatial Theory Grounded with RCC-8 and $OPRA_m$ Calculi

We describe the components of a causal theory $[\Sigma_{causal} \equiv \Sigma_{sit} \cup \Sigma_{space}]$ [15] that operationalises the proposed integration of formal spatial calculi with situation calculus. The foundational part of the theory, Σ_{sit} , is based on a customised version of the situation calculus formalism. The other component, Σ_{space} , constitutes a domain-independent spatial theory that is usable in arbitrary dynamic spatial domains. Indeed, the approach to model Σ_{space} is based on the abstract notion of a ‘qualitative spatial calculus’ (cf. Sec. 2), which constitutes a generalised view of a wide-range of spatial calculi that share common semantics. The theory also accounts for the appearance and disappearance of objects, phenomena deemed characteristic to dynamic spatial systems. Detailing the axioms of the theory Σ_{causal} is neither required nor possible in this paper; here, we outline the key aspects of Σ_{causal} so as to provide a broad view of the framework thereby facilitating an intuitive interpretation

Draft version.

of the reasoning tasks that follow from the formalisation. For elaborations, refer to [15].

5.1 The Foundational Theory Σ_{sit}

We use a first-order many-sorted language, denoted $\mathcal{L}_{sitcalc}$, with equality and the usual alphabet of logical symbols: $\{\neg, \wedge, \vee, \forall, \exists, \supset, \equiv\}$. There are sorts (and corresponding variables) for *events* and *actions* – $\Theta = \{\theta_1, \theta_2, \dots, \theta_n\}$, *situations* – $S = \{s_1, s_2, \dots, s_n\}$, *spatial objects* – $O = \{o_1, o_2, \dots, o_n\}$ and *regions* – $R = \{r_1, r_2, \dots, r_n\}$. S_0 is a constant symbol that denotes the initial situation and $\Phi = \{\phi_1, \phi_2, \dots, \phi_n\}$ is the set of propositional and functional fluents. For each functional fluent $\phi_i \in \Phi$, there exists a corresponding denotation set; let $\Gamma = \{\gamma_1, \gamma_2, \dots, \gamma_n\}$, refer to the union of all such denotation sets.

$\mathcal{L}_{sitcalc}$ consists of 5 foundational elements that are used in the formulation of the meta-theory Σ_{sit} and domain-independent spatial theory Σ_{space} . These elements include: (L1) a ternary relationship of property causation denoted by ‘*Caused*’, (L2) a ternary relationship of situation-dependent property exemplification denoted by ‘*Holds*’, (L3) action precondition axioms denoted by ‘*Poss*’, (L4) event occurrence axioms denoted by ‘*Occurs*’, and (L5) a binary function symbol ‘*Result*’ denoting the situation resulting from the happening of an occurrence. Presuming basic familiarity with situation calculus, the usage of these elements will be self-explanatory. Using the language of $\mathcal{L}_{sitcalc}$, the foundational theory Σ_{sit} comprises of: (F1) a property causation axiom determining when fluent values *hold* in situations, (F2) a generic frame axiom that incorporates the principle of inertia, i.e., what does not change when occurrences happen, (F3) unique names axioms for occurrences, fluents, fluent values and situations, and (F4) domain-closure axioms for all fluent values, including functional and propositional. Note that the formulae for F1–F4 are not included herein.

5.2 The Spatial Theory Σ_{space}

This consists of the formalisation of an underlying domain-independent qualitative physics and is founded on the meta-theory Σ_{sit} . It consists of a systematic axiomatisation of all aspects relevant to modelling RCC-8 and \mathcal{OPRA}_m in the situation calculus. Each component of $[\Sigma_{space} \equiv_{def} \Sigma_{cc} \cup \Sigma_{de} \cup \Sigma_{oc} \cup \Sigma_{rc}]$ is elaborated on in the following:

Continuity Constraints (Σ_{cc}) and Direct-Effect Axioms (Σ_{de}): At the domain-independent level,

Draft version.

the most primitive means of change is an explicit change of spatial relationship between two objects – let $tran(o_i, o_j, \gamma)$ denote such a change, read as, o_i and o_j *transition* to a state of being γ . A formalisation of the qualifications for every such spatial transition is necessary – basically, this is equivalent to incorporating the principle of conceptual neighbourhood based change (Sec. 2). Let ‘*neighbour*’ denote a binary continuity relationship between two spatial relations; given a spatial domain consisting of n distinct spatial transitions that are possible, a total of n transition per-condition axioms of the form in (1a) and (1c) are required for each spatial domain, namely topology and orientation, being modelled. Precisely, 8 axioms for RCC-8 and 72 axioms for \mathcal{OPRA}_2 are necessary.

$$Poss(tran(o_i, o_j, ec), s) \equiv [space(o_i, s) = r_i \wedge space(o_j, s) = r_j \wedge (\exists \gamma') Holds(\phi_{top}(r_i, r_j), \gamma', s) \wedge neighbour(ec, \gamma')] \quad (1a)$$

$$Poss(tran(o_1, o_2, ec), s) \vee Occurs(tran(o_1, o_2, ec), s) \supset Caused(\phi_{top}(o_1, o_2), ec, Result(tran(o_1, o_2, ec), s)) \quad (1b)$$

$$Poss(tran(\bar{o}_i, \bar{o}_j, 2\angle_7^1), s) \equiv (\exists \gamma') [Holds(\phi_{ort}(\bar{o}_i, \bar{o}_j), \gamma', s) \wedge neighbour(2\angle_7^1, \gamma')] \quad (1c)$$

$$Poss(tran(\bar{o}_1, \bar{o}_2, 2\angle_7^1), s) \vee Occurs(tran(\bar{o}_1, \bar{o}_2, 2\angle_7^1), s) \supset Caused(\phi_{ort}(\bar{o}_1, \bar{o}_2), 2\angle_7^1, Result(tran(\bar{o}_1, \bar{o}_2, 2\angle_7^1), s)) \quad (1d)$$

Similarly, for every primitive spatial transition within the spatial domain(s) being modelled, a formalisation of their respective direct effects is required, i.e., a total of n direct effects of the form in (1b) and (1d) for a domain with n base relationships.

Ordinary (Σ_{oc}) and Ramification (Σ_{rc}) Constraints: State constraints express temporally invariant laws within the theory – for the present task, these include the basic properties of the underlying spatial calculus being modelled. In general, we need a total of n (ordinary) state constraints of the form in (2a) to express the jointly-exhaustive property of a set of n base relations. Similarly, $[n(n - 1)/2]$ constraints of the form in (2b) are sufficient to express the pair-wise disjointness of n relations. Other miscellaneous properties including symmetry, asymmetry and inverse of the base relations too can be expressed using ordinary state constraints. Such constraints can also be used to model ‘*physical constraints*’ on the potential relationships that domain objects may participate in with each other. For instance, whereas (2c) represents the constraints between semi-rigid and rigid objects, (2d) covers the case of strictly rigid objects.

$$\forall s. \neg [Holds(\phi_{top}(o_1, o_2), ec, s) \vee Holds(\phi_{top}(o_1, o_2), po, s) \vee Holds(\phi_{top}(o_1, o_2), tpp, s) \vee Holds(\phi_{top}(o_1, o_2), tpp^{-1}, s) \vee Holds(\phi_{top}(o_1, o_2), eq, s) \vee Holds(\phi_{top}(o_1, o_2), ntp, s) \vee Holds(\phi_{top}(o_1, o_2), ntp^{-1}, s)] \supset Holds(\phi_{top}(o_1, o_2), dc, s) \quad (2a)$$

$$\forall s. \neg [Holds(\phi_{top}(o, o'), dc, s) \wedge Holds(\phi_{top}(o, o'), ec, s)] \quad (2b)$$

$$(\forall o_i, o_j, s). \{allows_containment(o_j, s) \wedge \neg can_deform(o_j, s) \wedge rigid(o_i, s) \supset [(\exists r_i, r_j) space(o_i, s) = r_i \wedge space(o_j, s) = r_j] \wedge Holds(\phi_{top}(r_i, r_j), \gamma, s)\} \text{ where } \gamma \in \{dc, ec, po, eq, tpp, ntp\} \quad (2c)$$

Draft version.

$$(\forall o_i, o_j, s). \text{rigid}(o_i, s) \wedge \text{rigid}(o_j, s) \supset [(\exists r_i, r_j) \text{space}(o_i, s) = r_i \wedge \text{space}(o_j, s) = r_j] \wedge \text{Holds}(\phi_{top}(r_i, r_j), \gamma, s) \quad (2d)$$

where $\gamma \in \{dc, ec\}$

$$\forall s. [\text{Holds}(\phi_{top}(o_1, o_2), tpp, s) \wedge \text{Holds}(\phi_{top}(o_2, o_3), eq, s) \supset \text{Caused}(\phi_{top}(o_1, o_3), tpp, s)] \quad (2e)$$

$$\forall s. [\text{Holds}(\phi_{ort}(\vec{o}_1, \vec{o}_2), \angle_2^6, s) \wedge \text{Holds}(\phi_{ort}(\vec{o}_2, \vec{o}_3), \angle_1^6, s) \supset \text{Caused}(\phi_{ort}(\vec{o}_1, \vec{o}_3), \angle_1^7, s)] \quad (2f)$$

A second type of state constraints constitutes the so-called ramification or indirect yielding ones – basically, these contain implicit side-effects in them that need to be accounted for whilst reasoning about the effects of events and actions [17]. Consider the example in Fig. 3(a): here, a change of topological relationship between a and b from $ntpp$ in situation S_0 to tpp in situation S_2 also has an indirect effect on the relationship between a and c in the latter situation. Referring to [15] for details, here, it suffices to mention that the theory includes one ramification constraint of the form in (2e) and (2f) for every compositional theorem. Assuming that there are no mutual entailments between the spatial calculi being modelled, we need a total of $n \times n$ ramification constraints for a calculus consisting of n spatial relationships.

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. We maintain the existential status of every object by a propositional fluent, namely $exists(o)$. Additionally, two special external events – $appearance(o)$ and $disappearance(o)$ – are definable in domain specific ways. Further, appropriate pre-condition and effect axioms (of the form in (1)) that govern the dynamics of the existential fluent are defined – e.g., “ $appearance(a)$ causes $exists(a)$ to be *true* in situation s ” – and a form of non-monotonic reasoning is applied to infer that the new object does not *exist* in the situation-based history of the system. Finally, axioms are also introduced to consistently maintain the spatial relationship of the new object with other previously existing objects in the present as well as past situations. Finally, it is also ensured that an object that has disappeared cannot participate in spatial relationships with any other object until such a future *situation* when it re-appears. The set of axioms modelling such phenomena is elaborate and therefore excluded from this paper.

Derivation of Successor State Axioms: Successor state axioms (SSA) specify the causal laws of the spatial theory, i.e., what changes as a result of various occurrences in the system. We utilise the seminal approach of Reiter [7] for the derivation of SSA’s (for solving the frame problem) and the extensions thereof by Lin and Reiter [17] for handling ramification yielding state constraints, which, in so far as the domain-independent level is concerned, are represented by Σ_{rc} .

Draft version.

$$\begin{aligned}
& Poss(\theta, s) \vee Occurs(\theta, s) \supset [Holds(\phi_{top}(o_i, o_j), tpp, Result(\theta, s)) \equiv \{\theta = tran(o_i, o_j, tpp)\} \vee \\
& \{(\forall \gamma') Holds(\phi_{top}(o_i, o_j), tpp, s) \wedge \theta \neq tran(o_i, o_j, \gamma')\} \vee \{(\exists o_k) Holds(\phi_{top}(o_i, o_k), tpp, s) \wedge Holds(\phi_{top}(o_k, o_j), eq, s)\}] \\
& \tag{3}
\end{aligned}$$

The derivation involves minimising, using circumscription [18], the extensionality of the ternary ‘*Caused*’ relation in order to derive causation axioms determining what changes, i.e., what is forced to change, given the direct effects of the known occurrences and the ramification constraints within the axiomatisation. The resulting causation axioms, not included here, are instrumental in obtaining a SSA for every fluent within the system. The SSA in (3) is presented as one example – here, it may be verified that this axiom formalises every possible way in which two objects establish a ‘*tpp*’ relationship. The conjunction of all SSA’s with the set of formulae introduced so far results in the final theory Σ_{causal} , which is then directly usable for reasoning purposes. Note that similar SSA’s, not exemplified here, would also be derived for the fluent denoting the relative orientation relationship between objects.

5.3 Explanatory Reasoning with $[\Sigma_{sit} \cup \Sigma_{space}]$

The objective in an explanation task is as follows: given a set of temporally-ordered snap-shots (e.g., qualified data from visual and other sensors in a smart home), derive a set of events and/or actions that may have caused the observations. In the following, we outline the structure of an explanation task without going into the details of the underlying axiomatisation: ‘consider the illustration in Fig. 3(c) – the situation-based history $\langle s_0, s_1, \dots, s_n \rangle$ represents one path, corresponding to an actual time-line $\langle t_0, t_1, \dots, t_n \rangle$, within the overall branching-tree structured situational space. Furthermore, assume a simple system consisting of objects ‘*a*’, ‘*b*’ and ‘*c*’ and also that the state of the system is available at time-point t_i and t_j . Note that the situational-path and the time-line represent an actual as opposed to a hypothetical evolution of the system. From the viewpoint of this discussion, two auxiliary predicates, namely $HoldsAt(\phi, t)$ and $Happens(\theta, t)$, that range over ‘*time-points*’ instead of ‘*situations*’ are needed to accommodate the temporal extensions required to map a path in the situation-space to an actual time-line; complete definitions can be found in [19]. Given an initial situation description as in Φ_1 (see (4)), where ‘*b*’ does not exist and ‘*a*’ and ‘*c*’ are partially overlapping, in order to explain an observation sentence such as Φ_2 , a formula of the form in Δ needs to be derived’.

Draft version.

The derivation of Δ primarily involves non-monotonic reasoning in the form of minimising change (‘*Caused*’ and ‘*Happens*’ predicates), in addition to making the usual default assumptions about inertia; the details are beyond the scope of this paper (cf. [15]). In Sec. 6, the use of explanatory reasoning is shown in the context of qualitative scene descriptions in a smart environment.

$$\left. \begin{array}{l} \Phi_1 \equiv \text{HoldsAt}(\phi_{top}(a, c), po, t_1) \\ \Phi_2 \equiv \text{HoldsAt}(\phi_{top}(a, c), ec, t_2) \wedge \text{HoldsAt}(\text{exists}(b), true, t_2) \wedge \text{HoldsAt}(\phi_{top}(b, a), ntp, t_2) \\ [\Sigma_{sit} \wedge \Sigma_{space} \wedge \Phi_1 \wedge \Delta] \models \Phi_2, \text{where} \\ \Delta \equiv (\exists t_i, t_j, t_k). [t_1 \leq t_i < t_2 \wedge \text{Happens}(\text{appearance}(b), t_i)] \wedge [t_i < t_j < t_2 \wedge \text{Happens}(\text{tran}(tp, b, a), t_j)] \\ \wedge [t_k < t_2 \wedge \text{Happens}(\text{tran}(po, a, c), t_k)] \wedge [t_k \neq t_i \wedge t_k \neq t_j] \end{array} \right\} (4)$$

6. Qualitative Reasoning in Ambient Intelligence Environments

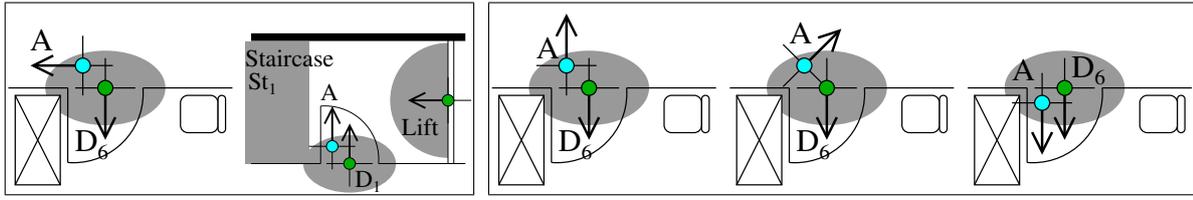
An ambient intelligence environment (e.g., smart-home or smart-office) is typically action-oriented – it is essential to represent and reason about space, actions, events and change in an integrated manner. For instance, in some environment adaptation scenarios such as energy-efficient or ambient light-control, it might be essential to project and being passively prepared to meet the requirements of the inhabitants of the environment. Similarly, for applications such as alert generation or event recognition based on the spatial content of scenes, it is necessary to generating plausible explanations on the basis of available observations pertaining to the location of objects.

6.1 Modelling the Domain Theory of a Smart Environment

A domain-theory basically consists of a description of the static and functional aspects of a particular application domain, e.g., domain-specific objects and constraints (the environment layout as in Fig. 2), a characterisation of the actions and events that occur in the environment and pre-conditions and effects of occurrences. Here, we illustrate how $[\Sigma_{sit} \cup \Sigma_{space}]$ (Sec. 5) may be applied in conjunction with a domain-description for reasoning tasks in an ambient intelligence environment.

Domain-Specific Motion Patterns Consider a scenario where the task is to determine if a person is in the process of leaving a secure office environment. Once such a behaviour is determined, the objective for a smart office system could be to perform several utilitarian functions, e.g., determine if the (exiting) persons’s office-door is locked, or, if his office lights/blinds are on/off in conformity

Draft version.

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

(b) Start and end configurations for motion patterns.

Figure 4: Several configurations for pattern definitions.

with pre-defined criteria. Similarly, when it is detected that the concerned person is exiting the office, it might be desirable to request the elevator service even before the person has actually entered the exit-way. In the following, we present an example concerning the detection of an *office exiting* pattern based on the spatial content of dynamic scenes. An explanatory approach, as exemplified in Sec. 5.3, is utilised to abduce which domain-specific pattern (potentially from a collection of several patterns) may be functional given the observations in the spatial scenes.

I. An Exemplary Motion Pattern: The spatial configurations in Fig. 4(a) represent the (typical) *start* and *end* of the motion pattern involved in exiting the office environment depicted in Fig. 2(b). One potential way in which this pattern starts is when a person is within the *fspace* of his personal office door (e.g., D_6) and is oriented away from it (left part of Fig. 4(a)). The pattern ends when a person is in the *fspace* of the main exit door (D_1) and is oriented, relative to the exit door, toward the exterior part of the office. The formulae in (5) formalise this overall motion pattern involved in exiting the office environment – (5b) and (5c) model the deterministic occurrence criteria for the start and end of the process respectively, whereas (5a) and (5d) consist of the direct effect axioms of these events on the propositional fluent ‘*is_exiting*’, which represents the functional status of the process of exiting the office. Similarly, motion patterns determining movement to and from various other locations may be defined strictly on the basis of the spatial content of the dynamic scene, e.g., going to the coffee corner, printer or someone going inside the office (see Fig. 4(b)).

$$\text{Occurs}(\text{exit_begins}(\bar{o}_1), s) \supset \text{Caused}(\text{is_exiting}(\bar{o}_1), \text{true}, \text{Result}(\text{exit_begins}(\bar{o}_1), s)) \quad (5a)$$

$$\begin{aligned} & \text{Holds}(\phi_{top}(\bar{o}_1, \text{fspace}(\bar{o}_1)), pp, s) \wedge \text{Holds}(\phi_{ort}(\bar{o}_1, \text{fspace}(D_6)), 2\mathcal{L}_3^5, s) \wedge \\ & \text{Holds}(\text{is_exiting}(\bar{o}_1), \text{false}, s) \supset \text{Occurs}(\text{exit_begins}(\bar{o}_1), s) \end{aligned} \quad (5b)$$

$$\begin{aligned} & \text{Holds}(\phi_{top}(\bar{o}_1, \text{fspace}(D_1)), pp, s) \wedge \text{Holds}(\phi_{ort}(\bar{o}_1, \text{fspace}(D_1)), 2\mathcal{L}_5^1, s) \wedge \\ & \text{Holds}(\text{is_exiting}(\bar{o}_1), \text{true}, s) \supset \text{Occurs}(\text{exit_ends}(\bar{o}_1), s) \end{aligned} \quad (5c)$$

$$\text{Occurs}(\text{exit_ends}(\bar{o}_1), s) \supset \text{Caused}(\text{is_exiting}(\bar{o}_1), \text{false}, \text{Result}(\text{exit_begins}(\bar{o}_1), s)) \quad (5d)$$

II. World Model for Abduction Task: Let Σ_{smart} denote the conjunction of the formulae in (5), and possibly other domain-specific pattern representations and constraints – the point here is that

Draft version.

Σ_{smart} (6a) constitutes as typical domain theory and the underlying process model formulation in a manner that is required for the present spatial reasoning task. Also, for exemplary purpose, let Ψ_{ini} (6b) denote an initial spatial situation description (Sec. 4.1) and Ψ_{t_1} (6c) and Ψ_{t_2} (6d) be incomplete descriptions denoting two sets of (partial) observations such that $t_1 < t_2$ (6b) holds. These observations and the initial situation description corresponds to the illustration in Fig. 4(a).

$$\Sigma_{smart} \equiv_{def} [(5a) \wedge (5b) \wedge (5c) \wedge (5d)] \quad (6a)$$

$$\Psi_{ini} \equiv [Initially(\phi_{top}(A, D_6), pp) \wedge Initially(\phi_{ort}(A, D_6), \angle_5^1) \wedge \\ Initially(exists(A), true) \wedge Initially(exists(D_6), true)] \wedge [t_1 < t_2] \quad (6b)$$

$$\Psi_{t_1} \equiv [HoldsAt(\phi_{top}(A, fspace(D_6)), ntp, t_1) \wedge HoldsAt(\phi_{ort}(A, fspace(D_6)), \angle_3^5, t_1)] \quad (6c)$$

$$\Psi_{t_2} \equiv [HoldsAt(\phi_{top}(A, fspace(D_1)), ntp, t_2) \wedge HoldsAt(\phi_{ort}(A, fspace(D_1)), \angle_5^1, t_2)] \quad (6d)$$

III. The Abduction Task – Hypothesising Potential Activity: Finally, we now have all the components in order to illustrate abductive reasoning in the manner suggested in Sec. 5.3. Given the background spatial theory $[\Sigma_{sit} \cup \Sigma_{space}]$, the domain theory in Σ_{smart} (6a), the initial situation description Ψ_{ini} and the partial observations in Ψ_1 (6c) and Ψ_2 (6d), the task here is to derive Δ (7), which would be a necessary and sufficient explanation for the given observation in terms of primitive spatial transformations, and therefore, of the domain-specific activities that may be functional.

$$\left\{ \begin{array}{l} [\Sigma_{sit} \wedge \Sigma_{space} \wedge \Sigma_{smart} \wedge \Psi_{ini} \wedge \Delta] \models [\Psi_1 \wedge \Psi_2], \text{ where } \Delta \text{ is :} \\ (\exists t_i, t_j, t_k, t_l, t_m, t_a, t_b). [t_1 < t_i \wedge t_m \leq t_2] \wedge [t_i < t_j \wedge t_j < t_k \wedge t_k < t_l \wedge t_l < t_m] \wedge \\ [Happens(tran(A, D_6, ntp), t_i) \wedge Happens(tran(A, fspace(D_6), pp), t_j) \wedge \\ Happens(exit_begins(A), t_k) \wedge Happens(tran(A, fspace(D_1), ntp), t_l) \wedge \\ Happens(exit_ends(A), t_m)] [t_1 < t_a \wedge t_b \leq t_2] \wedge [t_a < t_b] \wedge \\ [Happens(tran(A, fspace(D_6), \angle_3^5), t_a) \wedge Happens(tran(A, fspace(D_1), \angle_5^1), t_b)] \end{array} \right\} \quad (7)$$

In the explanation Δ in (7), observe that given the domain theory in Σ_{smart} , the only possible explanation is that the motion pattern denoted by the events $exit_begins(A)$ and $exit_ends(A)$ is abducible. Note that the illustration in (7) is exemplary – we have excluded details relevant to the non-monotonic abductive framework [20] that is used to derive the explanation.

7. Summary

We have shown how spatial environment and task modelling in ambient intelligence systems can be achieved by means of an integrated approach of qualitative spatial reasoning and reasoning about action and change. The relations of qualitative spatial calculi serve as the basis of a qualitative world model. In the examples of smart home and office environments, the proposed model contains topological (RCC-8) and relative orientation knowledge ($OPRA_m$) about the objects. The spatial

Draft version.

dynamics of the model, represented using the situation calculus formalism, are given by the conceptual neighbourhood structures of the applied calculi. For the integration of the two approaches, we addressed the connections between global consistency in qualitative spatial reasoning and the ramification problem in reasoning about action and change. Based on these considerations, we give a spatial theory that utilises RCC-8 and $OPRA_m$, and additional domain-dependent motion patterns that potentially characterise activities. We also give examples of how conclusions and causal explanations can be drawn from the spatial theory.

References

- [1] Björn Gottfried, Hans W. Guesgen, and Sebastian Hübner. Spatiotemporal reasoning for smart homes. In *Designing Smart Homes*, pages 16–34, 2006.
- [2] Antony Galton. Causal reasoning for alert generation in smart homes. In *Designing Smart Homes*, pages 57–70, 2006.
- [3] Anthony Cohn and Shyamanta Hazarika. Qualitative spatial representation and reasoning: An overview. *Fundam. Inf.*, 46(1-2):1–29, 2001. ISSN 0169-2968.
- [4] David A. Randell, Zhan Cui, and Anthony Cohn. A spatial logic based on regions and connection. In *KR'92*, pages 165–176. Morgan Kaufmann, California, USA, 1992.
- [5] Reinhard Moratz. Representing relative direction as a binary relation of oriented points. In *ECAI*, pages 407–411, Riva del Garda, Italy, 2006. IOS Press. ISBN 1-58603-642-4.
- [6] J. McCarthy and P. J. Hayes. Some philosophical problems from the standpoint of artificial intelligence. *Meltzer and Michie, Machine Intelligence 4*, pages 463–502, 1969.
- [7] R. Reiter. *Knowledge in Action*. MIT Press, 2001.
- [8] Christian Freksa. Qualitative spatial reasoning. In *Cognitive and linguistic aspects of geographic space*, pages 361–372. Kluwer, Dordrecht, 1991.
- [9] Christian Freksa. Conceptual neighborhood and its role in temporal and spatial reasoning. In *Proceedings of the IMACS Workshop on Decision Support Systems and Qualitative Reasoning*, pages 181–187, Amsterdam, 1991. Elsevier.
- [10] Jochen Renz, Reinhold Rauh, and Markus Knauff. Towards cognitive adequacy of topological spatial relations. In *Spatial Cognition II, Integrating Abstract Theories, Empirical Studies, Formal Methods, and Practical Applications*, pages 184–197. Springer-Verlag, 2000. ISBN 3-540-67584-1.
- [11] Bowman L. Clarke. A calculus of individuals based on ‘connection’. *Notre Dame Journal of Formal Logic*, 22(3):204–218, 1991.
- [12] Frank Dylla and Jan Oliver Wallgrün. Qualitative spatial reasoning with conceptual neighborhoods for agent control. *Journal of Intelligent and Robotic Systems*, 48(1):55–78, 2007.
- [13] Hector J. Levesque, Raymond Reiter, Yves Lespérance, Fangzhen Lin, and Richard B. Scherl. Golog: A logic programming language for dynamic domains. *J. Log. Program.*, 31(1-3):59–83, 1997.
- [14] H. Grosskreutz and G. Lakemeyer. cc-Golog: Towards More Realistic Logic-Based Robot Controllers. In *NMR-00*, 2000.
- [15] Mehul Bhatt and Seng Loke. Modelling dynamic spatial systems in the situation calculus. *Journal of Spatial Cognition and Computation*, 8(1):86–130, 2008. ISSN 1387-5868.
- [16] Fangzhen Lin. Embracing causality in specifying the indirect effects of actions. In *IJCAI*, pages 1985–1993, 1995.
- [17] Fangzhen Lin and Raymond Reiter. State constraints revisited. *Journal of Logic and Computation*, 4: 655–678, 1994.
- [18] John McCarthy. Circumscription - a form of non-monotonic reasoning. *Artif. Intell.*, 13(1-2):27–39, 1980.
- [19] Javier Andres Pinto. *Temporal reasoning in the situation calculus*. PhD thesis, University of Toronto, 1994.
- [20] Murray Shanahan. *Solving the frame problem: a mathematical investigation of the common sense law of inertia*. MIT Press, 1997. ISBN 0-262-19384-1.

Draft version.

Author's Biographies



Mehul Bhatt is an Alexander von Humboldt post-doctoral fellow based at the Transregional Collaborative Research Center SFB/TR 8 Spatial Cognition. His primary research interests encompass the areas of Qualitative Spatial Reasoning, Reasoning about Actions and Change, and Ontology. Presently, Mehul is investigating the application of tools and formalisms from these fundamental areas in domains such as experimental and cognitive robotics, smart environments and the modelling of dynamic spatial systems.



Dr. Frank Dylla received his diploma in computer science at RWTH Aachen in 2001 and his doctoral degree in the SFB/TR 8 Spatial cognition (Bremen) in 2008. Currently, he is a post-doc in the SFB/TR 8 investigating on Qualitative Spatial Reasoning and its impact on Reasoning about Action and Change. Additionally, his research interests include cognitive robotics, qualitative abstraction of moving objects, and formalization of natural language descriptions.