# Qualitative Spatial Reasoning for Rule Compliant Agent Navigation

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## Abstract

Artificial agents participating in public traffic must respect rules that regulate traffic. Rule sets are commonly formulated in natural language using purely qualitative terms. We present a case study on how to realize rule compliant agent control in the domain of sea navigation by using qualitative spatial reasoning techniques.

## Introduction

There exist numerous regulations or recommendations on how to behave in traffic scenarios. They are designed for use by humans and usually employ *qualitative terms* only. For example, in traffic laws qualitative spatial concepts like "from the right" are used to describe situations governed by the law as well as the correct behavior of agents in these situations. To make such rules processable by artificial agents, these rules need to be formalized. We investigate a formalization that allows for implementing an autonomous vehicle that behaves in compliance with a rule set: This is particularly important in domains where artificial agents interact with humans. Furthermore, rules often govern the relations and actions of *two* agents only. To obtain *global* compliance involving more agents a sound integration of local rules must be performed.

We present a method that shows how representation formalisms and reasoning techniques known from *qualitative spatial reasoning (QSR)* (Cohn & Hazarika 2001), namely constraint solving procedures and *neighborhood-based reasoning* techniques (Freksa 1991), can be applied for deriving suitable actions for an agent in compliance with a given set of rules. As a testbed, we apply this method to the domain of right-of-way rules in sea navigation.

## Formalizing Rule Compliance

Usually a rule is defined for a specific class of *configurations* (in our case, spatial arrangements of agents) and also to specific roles of the agents in that configuration. A rule then determines a set of admissible actions with respect to a configuration.

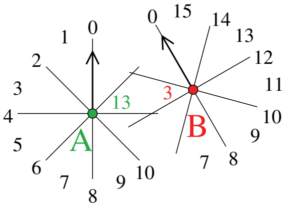

Figure 1: $\mathcal{OPRA}_4$ relation $A\ {}_4\angle^{3}_{13}\ B$

## Formalizing Spatial Knowledge with $\mathcal{OPRA}_m$

Qualitative (spatial) calculi abstract from metrical data by summarizing similar quantitative states into one qualitative characterization. They define sets of relations, each relation standing for a particular class of constellations of objects in a given domain. Here, positions and orientations of agents are the domain and the relations of two agents to one another are relevant. An appropriate binary calculus for joint representation of position and orientation is provided by the $\mathcal{OPRA}_m$ calculus (Moratz 2006) which describes relations between oriented points. Depending on the granularity parameter $m$, $4m$ angular directions are distinguished (see Fig. 1). $\mathcal{OPRA}_m$ is expressive due to a double relation: Oriented points $P$ and $Q$ are related $P$ to $Q$ and vice versa, denoted by ${}_m\angle^{Q\sim P}_{P\sim Q}$. A value of $m = 4$ has proven adequate in experimental analysis for the domain of sea navigation.

We model configurations defined as preconditions in rules as qualitative scene descriptions. For example, a configuration of "two vessels in head-on positions" is modeled as qualitative relation ${}_4\angle^{0}_{0}$.

### Neighborhood-Based Transitions Systems

Actions are performed in time and thus their formalization introduces a temporal aspect. Temporal information can be integrated into a static qualitative spatial representation by following the idea of conceptual neighborhoods (Freksa 1991), providing an integrative approach to spatio-temporal formalization. The idea of conceptual neighborhoods is to extend a qualitative calculus by specifying which continuous transformations in the domain (such as movement of an object) can cause discrete relation transitions. Two relations are conceptually neighbored if there can be a change-over due to an infinitesimal transformation of the objects. For example, as a slight movement can cause vessels originally

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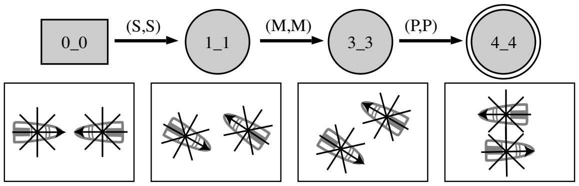

Figure 2: Idealized thread for the rule shown in Fig. 3

in head-on position to take on one of the relations $4\angle_0^{15}$, $4\angle_{15}^0$, $4\angle_1^0$, and $4\angle_0^1$, these relations are conceptually neighbored to $4\angle_0^0$ (cp. Fig. 1). When defining the conceptual neighborhood structure for the domain of sea navigation, we considered three aspects: agent kinematics (motion capabilities), concurrency and asynchronicity of actions, and lack of superposition. A conceptual neighborhood graph can be constructed interpreting the binary relation of neighborhood as adjacency in the graph (Freksa 1991). For each action covered by the rules a specific neighborhood graph is constructed that builds the basis for formalizing the dynamics.

For each rule we define a *transition system* (Dylla *et al.* 2007). We define the start configuration, end configuration (when the rule is no longer applicable), and a prototypical sequence of actions and intermediate configurations—see Fig. 2 as an example of two boats in head-on course giving way to one another ($i\_j$ stands for $4\angle_i^j$). We consider the actions "turn starboard (S)", "turn portside (P)", and "keep course/midships (M)". We refer to this prototypical run as *idealized thread*. The idealized thread itself is no suitable formalization of the rule-compliant action as any effect of an action must be interpreted in a prototypical sense: Depending on the precise position of objects in the domain, the same action may lead to different change-overs with respect to the qualitative relations. Thus, we construct a transition system by extending the idealized thread by neighborhood-based relaxation: Spatial configurations that are possible action effects are added. For each of the new configurations added, an appropriate action is derived. Analogously, we apply neighborhood relaxation to start and end configurations. The resulting complete transition system for the example is depicted in Fig. 3.

## Constraint-Based Integration

Transition systems formalize the local, rule-compliant actions for each agents. We apply constraint-based reasoning to check whether actions according to the local transition systems are compatible from a global point of view. Additionally, constraint-based reasoning allows us to select a globally admissible action when a transition systems allows for alternative actions. For this, we first generate a constraint network that encodes all spatial relations between vessel positions that may result from admissible actions. A solution of the constraint network is computed (if possible) and pins globally consistent spatial relations among the agents. On this basis we can determine the actions that will lead to these spatial relations. This process ensures that the selected actions are admissible with respect to the individual rules (by construction of the constraint network) and with respect to the global scene (by global constraint satisfaction).

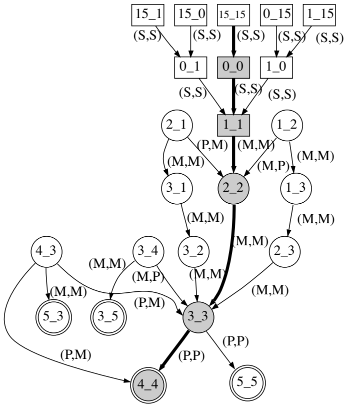

Figure 3: Transition system for the rule depicted in Fig. 2

## Experiments & Conclusion

We implemented the outlined approach and applied it to the "International Regulations for Preventing Collisions at Sea". A simulator has been implemented that moves the vessels according to a physical model and that provides simple action primitives. In the experiments we observed that all vessels moved according to the rules. Furthermore, the system detected globally inconsistent configurations, that is, situations in which an agent had no admissible action to choose.

Our investigation confirmed previous research in that qualitative representations enable mediation between real-world metric information and conceptual knowledge as used in communication or rule descriptions. It turned out that one needs to combine different reasoning techniques for applying formal reasoning techniques to a real-world scenario. By combining constraint-based and neighborhood-based reasoning we have been able to link formal representation and reasoning techniques to a real-world agent control application. In future work we will integrate our approach with a deliberative planning component that links the formalization to high-level agent control languages.

## Acknowledgments

We would like to thank Christian Freksa for fruitful impulses. Our work was carried out in the DFG SFB/TR 8 Spatial Cognition, projects R3-[Q-Shape] and R4-[LogoSpace].

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