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Movement Choremes: Bridging Cognitive Understanding and Formal Characterizations of Movement Patterns[1]

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Abstract. This article discusses an approach to characterizing movement patterns (paths/trajectories) of individual agents that allows for relating aspects of cognitive conceptualization of movement patterns with formal spatial characterizations. To this end, we adopt a perspective of characterizing movement patterns on the basis of perceptual and conceptual invariants that we term *movement choremes* (MC). MCs are formally grounded by behaviorally validating qualitative spatio-temporal calculi. Relating perceptual and cognitive aspects of space and formal theories of spatial information has shown promise to foster understanding of the semantics of movement patterns. Specifically, we discuss our approach in relation to existing qualitative formalisms such as the region connection calculus (RCC) and the Egenhofer's intersection formalisms. We show that the movement choreme approach is compatible with these approaches but offers additional opportunities to improve the cognitive adequacy of these formalisms. We summarize this paper using a movement taxonomy that also provides guidance for future research.

1. Introduction

We live in a dynamic world. To cope with this fact, the embodied human mind has developed such that spatio-temporal information can be processed efficiently. One such aspect of spatio-temporal information is that of movement patterns of individual agents (paths/trajectories of pedestrians, cars, animals, tanks, or hurricanes). The centrality of movement patterns to the scientific community is documented in interdisciplinary research on: identifying meaningful segments of movement patterns (also referred to as *events*) and factors that influence the identification of event boundaries (Zacks & Swallow, 2007; Zacks, Tversky, & Iyer, 2001); revealing causal relationships that explain how events are understood (Michotte, 1946/1963; Talmy, 1988; Wolff, 2008); establishing a relationship between path characteristics (trajectories) and verbal descriptions (Pustejovsky, Moszkowicz, & Verhagen, 2010; Talmy, 2000); and developing models that meaningfully interpret and assign linguistic labels to movement patterns (Regier, 1996). We additionally find approaches that formally characterize movement patterns, often with the goal of meaningfully interpreting movement patterns or improving interface design for information systems (Gottfried & Aghajan, 2009; Kurata & Egenhofer, 2009; Schlieder, 2005).

Although many formal approaches are inspired by general results from cognitive studies, it is still an open question as to whether they adequately model a cognitive understanding of movement patterns. While we will not close this gap completely with this article, we do hope to make it a little less wide. To this end, by focusing on perceptual and cognitive invariants, we extend previous work (Klippel, Tappe, Kulik, & Lee, 2005) on the characterization of movement patterns on the basis of conceptual primitives. The technical term we use is *movement choreme* (abbreviated as *MC*). The notion of movement choremes is inspired by the French geographer Brunet (1980; 1987), who proposed a limited set of abstract models of geographic phenomena, which he termed *choremes*. *Choreme* is a made-up word taken from the root of the Greek expression for space, *chor-*, and the suffix *–eme* (indicating a small linguistic unit such as lexeme or morhpeme). With this combination, Brunet indicated his goal: the creation of a conceptual spatial language.

Movement choremes are defined as a limited set of mental conceptualizations of aspects of movement patterns that are (in some way) perceptually and cognitively invariant to a cognitive system. Just like Brunet, we consider movement choremes as building blocks that realize their full potential through their combination into more complex constructs. Brunet does not explicitly ground his work in formal approaches offered by spatial information science. In contrast, we ground the theory of movement choremes in formalisms of knowledge representation—specifically, qualitative spatial representation and reasoning (Cohn & Renz, 2008). Our goal is to contribute to work on modeling the cognitive conceptualization of movement patterns. To this end, we combine qualitative calculi with a formal grammar that operates on the conceptual level, rather than on the level of natural language expression. We will discuss requirements for using topological calculi in this conceptual grammar approach.

Figure 1. Five different movement patterns that share the same characteristics: A single entity is moving (hurricane, tornado, boat, cannonball, and circle), the entity can be conceptualized as being spatially extended, the movement results in a change in the relation with the reference entity (peninsula, city, shallow water, city, triangle), and these changing relations can be captured topologically resulting in identical characterizations.

As a motivational example, Figure 1 depicts (statically) the trajectories of five moving entities: a hurricane, a tornado, a boat, a cannonball, and a geometric figure (a circle). What is important about the movement of these entities is (in the context of the present article) that it occurs in relation to a reference entity (a peninsula, a city, an area of shallow water, a city, and a geometric figure, respectively). Within each of these scenarios the relation between the moving entity and the reference entity changes. The changing relations can be characterized qualitatively. Approaches which capture qualitative change have been influential in theories that address, as a basis for cognitively conceptualizing spatial information, the identification of invariant aspects both in our environments and in our interaction with environments. Some examples of these theories are image schemata (Johnson, 1987; Lakoff, 1987), topology based movement characterizations (Egenhofer & Al-Taha, 1992; Galton, 2000; Muller, 2002), and also influential temporal calculi in artificial intelligence (Allen, 1983).

There are many other aspects (other than the path of a moving entity in relation to a reference entity) that contribute to the cognitive understanding of dynamic aspects of spatial environments. Examples are the shape of the path (Shipley & Maguire, 2008), speed and acceleration, temporal aspect, or relations to other moving entities (Galton, 2000; Laube, Imfeld, & Weibel, 2005). This topic could also be addressed from the perspectives of conceptual learning, language generation, database design, or ontological characterizations. While we make connections to some of these aspects and they are clearly of great importance, they are mostly beyond the scope of this article.

In the following sections, we continue by briefly discussing the role of perceptual and cognitive invariants; we then focus on characterizing the changing relation between a moving and a reference entity from a topological perspective as a way to formally ground movement choremes. We also discuss how topological formalisms can enhance their cognitive adequacy by adopting a movement choreme perspective. We conclude by discussing a taxonomy that allows for identifying further research questions.

2. Perceptual and cognitive invariants

Perceptual and cognitive invariants, which we also find to be associated with conceptual primitives (Aziz-Zadeh, Casasanto, Feldman, Saxe, & Talmy, 2008; Mandler, 1992; Wierzbicka, 1992), have long been of interest to the cognitive science community. We approach this topic from the perspective of grounding conceptual primitives in invariants of the perception and cognition of objects and events (Gentner, 1983; Gibson, 1979; Lakoff & Johnson, 1980; Shaw, McIntyre, & Mace, 1974). Invariants have attracted researchers in the field of perception as well as in higher cognition. In the perception literature we find work by Klix (1992) who states that the human mind, in adapting to its environment, identified invariant characteristics of information that build the basis for cognitive processes; Shaw (1974) uses the term *transformational invariants* to denote properties of objects and events that do not change from a group (set) theoretical perspective; last but not least, the classic work by Gibson (1979) refers to temporally constant characteristics of environments as *structural invariants*. Already Klix pointed to topology as one of the best candidates for identifying invariants. Topology is important in that it potentially serves as a bridge between low-level perceptual characteristics and higher level cognitive processes.

Not surprisingly, topology is discussed by several disciplines, for example, the theory of image schemata that originated from work by Lakoff and Johnson (Johnson, 1987; Lakoff, 1987; Mandler, 1992). Image schemata are defined as recurring patterns in our sensory experience; as such, they “operate at a level of mental organization that falls between abstract propositional structures, on the one side, and particular concrete images, on the other” (Johnson, 1987, p. 29). In examining the spatial information that image schemata are built on, Kuhn writes: “Image schemas are often spatial, typically topological […]” (Kuhn, 2007, p. 155). The following image schemata explicitly capture topological aspects: *link*, *path*, *container*, *contact*, *part-whole*. These image schemata constitute a large part of spatial image schemata stressing the importance of topology as a means to formally characterize fundamental (spatial) cognitive processes.

A critical observation is that topology potentially identifies invariants for both static and dynamic spatial information relevant to a cognitive system. Piaget (1955) indicated that topology is at the core of the information that infants extract from their environments. This assessment is supported by Mandler (1996) who writes: "Because of the attention that babies give to moving objects, the first image-schemas they form are apt to be those involving movement. The simplest meaning that can be taken from such movement is the image-schema path." (p. 373).

Paths are defined as consisting of three distinct parts: a source (starting point), a goal (endpoint), and locations in-between. This construct is also referred to as source-path-goal schema. The importance of this tri-partitioning of any kind of actual physical as well as metaphorical or fictional movement is also reflected in recent developments in formally characterized trajectories of movement patterns (Kurata, 2008; Kurata & Egenhofer, 2009) and the re-awakening of time geography (Miller & Bridwell, 2009). However, as we will demonstrate in later sections, other image schema (e.g. containment, in-out) may also be important for the characterization of movement patterns.

To further understand what we mean by invariant characteristics of movement patterns—or, from an image schematic perspective, recurring patterns within movement patterns—in the different domains we discussed in the introduction (see Figure 1), we now turn to a more detailed discussion of topology.

3. Topological movement characterizations

For the identification of perceptual and cognitive invariants that originate from the changing spatial relations of a moving entity with respect to a reference entity, it is important to be able to define potential candidates that allow for discretizing change into concepts (one might say, conceptual primitives). In other words, it is important to differentiate aspects of recurring movement patterns and / or movement patterns that occur across different semantic domains that are invariant from a perceptual and / or cognitive perspective. One such distinction (and the one that we will explore in greater depth here) is attributed to the importance of *topology* in identifying the invariants used to establish a finite set of spatial relations that are meaningful to humans for understanding their static and dynamic spatial environments (see previous section).

Topology has been discussed—from a cognitive perspective—since Piaget (1955) published his theory of developmental stages. Additionally, topology is central to artificial intelligence, particularly to the area of qualitative spatial representation and reasoning that aims to develop formalisms which capture the cognitive understanding and processing of spatial information (Cohn & Renz, 2008). Hence, it is important to distinguish between movement patterns that involve a change in the topological relationship between the moving agent/entity and other entities, and patterns where the movement of an agent occurs within the same topological equivalence class. The latter may include changes of other spatial information, such as metric or ordering information.

In considering topologically changing relations during movement, one distinction necessary is the spatial dimensionality of both the moving object and the reference object. While, theoretically, three classic spatial distinctions would be possible for both (point, line, spatially extended entity), we restrict our discussion here in the following way: for the moving entity we consider moving point conceptualizations that result in (linear) trajectories as well as moving spatially extended entities (regions). This distinction reflects theoretical approaches by Muller (2002) based on both entities being regions using the region connection calculus (RCC) (Randell, Cui, & Cohn, 1992; Vieu, 1997) as a theoretical framework, and work by Kurata and Egenhofer (2009) on trajectory (directed line or DLine) - region characterizations.

The question of dimensionality in itself is, of course, an interesting question from a cognitive conceptual perspective, and potentially dependent on the granularity (Freksa & Barkowsky, 1996; Hobbs, 1985) applied to characterize and interpret a movement pattern. It is important to note that no physical entity is a point in the formal sense. However, to characterize a movement pattern as a trajectory, we do have to assume that the moving entity is indeed point-like. For the case of the reference object, we restrict the discussion here to spatially extended entities[2]. Below, we will discuss the two scenarios where the moving entity is either conceptualized as a point or as a spatially extended entity and the referent is a spatially extended entity.

One more prerequisite to characterize movement patterns on the basis of topologically changing relations are conceptual neighborhood graphs (Egenhofer & Al-Taha, 1992; Freksa, 1992a; see Figure 2). It is important to note, though, that the role that conceptual neighborhood graphs play in movement pattern characterizations differs according to the dimensionality of the moving entity. Conceptual neighborhood graphs are graph structures based on qualitative spatial and temporal formalisms. They were first proposed for Allen's (1983) temporal intervals by Freksa (1992a) and were quickly adapted to corresponding qualitative spatial calculi (Egenhofer & Al-Taha, 1992). In the temporal domain, conceptual neighbors are defined as two relations (e.g., before and meet) that can be directly transformed into another by continuous topological transformations such as shortening, lengthening, or moving (translation) of temporal intervals (Freksa, 1992a). Likewise, for the spatial domain, potential transformations include translation, rotation, and scaling (Egenhofer & Al-Taha, 1992), which result in changes in the topological relations between two spatial entities (e.g., from being disconnected to being externally connected, see Figure 2). Consequently, a conceptual neighborhood is formed if its elements (relations) are all path-connected through conceptual neighbors. Figure 2 shows a conceptual neighborhood graph based on the eight topological relations defined in both Egenhofer's intersection models and RCC-8. The focus of the present article is on translation movement patterns.

[2]For discussions including linear reference objects, please refer to Xu, 2007. The general principles developed in this paper will be applicable to the scenario of line-line objects, too, but are omitted due to space constraints.

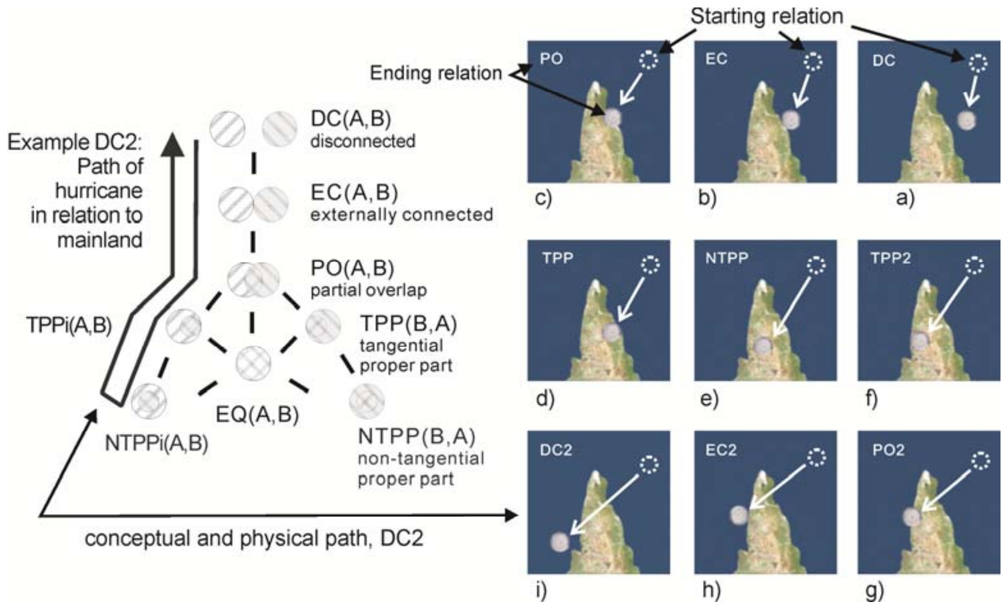

Figure 2. Left: Conceptual neighborhood graph organizing eight topological relations (Egenhofer & Al-Taha, 1992; Freksa, 1992a). Right: Different paths of hurricanes distinguished by ending relations. All hurricanes start in the upper right corner of each icon, disconnected from the peninsula (modified from Klippel & Li, 2009). Physical paths of the hurricanes correspond to path through the conceptual neighborhood graph (e.g., DC2).

3.1. *Both entities are spatially extended*

We first examine a case in which both entities are conceptualized as spatially extended (see also Muller, 2002). In this case, we can use a conceptual neighborhood graph that is established, for example, on the basis of topological relations distinguished by RCC (Randell et al., 1992), or by Egenhofer's intersection models (Egenhofer & Franzosa, 1991). For the purpose of this article we adopt the distinction of eight topological relations[3].

[3] For a detailed discussion of changing the levels of granularity of conceptual neighborhood graphs (i.e., five or eight topological relations) see Dube and Egenhofer 2009.

To model movement patterns of spatially extended entities, we use topological equivalence classes to constitute perceptual and cognitive invariants (the basic set of movement choremes, MCs). The conceptual neighborhood graph in Figure 2 shows this distinction. These eight relations are referred to in RCC terminology as: DC–disconnected; EC–externally connected; PO–partial overlap; TPP–tangential proper part; NTPP–non-tangential proper part; and two inverse relations for TPP and NTPP—TPPi and NTPPi, respectively. In the following, we will provide examples and discuss the formal characterizations of different movement patterns (see Figure 2 and also Egenhofer & Al-Taha, 1992).

Consider, for example, a case in which the moving entity is a hurricane and our reference entity is a peninsula (for the moment we ignore the fact that the hurricane is ‘in’ the ocean while it is approaching the peninsula, see Stewart Hornsby & Cole, 2007, and that the hurricane has vague boundaries, see Erwig & Schneider, 1997, and, potentially, an eye, see Vasardani & Egenhofer, 2008). Critical stages from a cognitive perspective of the hurricane’s movement pattern are potentially associated with changes in the topological relation between the hurricane and the peninsula:

- A hurricane that never makes landfall has a very short conceptual path, consisting only of the relation DC (see Figure 2a). In movement choreme notation we write: MC_{DC}
- For a hurricane that does make landfall and ebbs over land, the path through the conceptual neighborhood graph extends. Assuming that the hurricane starts disconnected from the peninsula (MC_{DC}), it passes through different topological relations as identified by the conceptual neighborhood graph (see, for example, Figure 2e). The ending relation of this movement pattern is MC_{NTPP}. Given that we assume a conceptual neighborhood graph based on eight topological relations (left side

Figure 2), the intermediary topological relations that the hurricane is passing through are EC, PO, TPP. This path characterized by movement choremes can be specified as follows:

$$MC_{DC}MC_{EC}MC_{PO}MC_{TPP}MC_{NTPP}$$

- For hurricanes that completely cross the peninsula (assuming the hurricane is smaller than the peninsula, see Figure 2i), the path through the conceptual neighborhood graph, characterized on the basis of movement choremes, looks like this:

$$MC_{DC}MC_{EC}MC_{PO}MC_{TPP}MC_{NTPP}MC_{TPP}MC_{PO}MC_{EC}MC_{DC}$$

It is important to keep in mind that the eight movement choremes (*MCs*) can be used as a basic characterization—like letters in an alphabet—and that combinations of these primitives (terminals) can be used to characterize more complex movement patterns. An example of this would be hurricane Ivan in 2004. Ivan crossed the southeastern United States, went back out into the Atlantic, turned around, and then crossed the southern tip of Florida. Conceptually, this movement pattern can be characterized using the conceptual neighborhood graph in Figure 2; simply double the example path (DC2) on the left side. The complete conceptual path of hurricane Ivan in choreme notation is given by:

$$MC_{DC}MC_{EC}MC_{PO}MC_{TPP}MC_{NTPP}MC_{TPP}MC_{PO}MC_{EC}MC_{DC}MC_{EC}MC_{PO}MC_{TPP}MC_{NTPP}MC_{TPP}MC_{PO}MC_{EC}MC_{DC}$$

This example shows that *MCs* allow for relating conceptualizations and externalizations in, for example, linguistic or graphic form. To illustrate this point, modeling the semantics of the verb *cross* or the preposition *across* (as in *the hurricane crossed / moved across the peninsula*), the following steps are necessary: First, we specify conceptual primitives used to characterize the movement pattern (here: eight topological relations). Second, valid expressions (combinations) of conceptual primitives are identified and formalized by adopting a grammatical approach. In this formal grammar, the eight topological equivalence classes are the terminals that can be combined to create more complex expressions. Complex expressions result from meaningfully combining movement choremes (referred to as *CMP*, Complex Movement Patterns). Third, the actual processing of a string of conceptual primitives can be achieved using term-rewriting rules (Dershowitz, 1993) for which the formal grammar (here: MCG–movement choreme grammar) provides the input (Klippel et al., 2005; Kulik & Egenhofer, 2003).

To illustrate, starting with the string of movement choremes for hurricane Ivan, we can identify meaningful sub-strings (e.g., the sub-string where the hurricane makes landfall or where its trajectory/path crosses the mainland for the first time). For example, a valid expression for the concept of *across* would look like this:

$$CMP_{across} \equiv MC_{DC}MC_{EC}MC_{PO}MC_{TPP}MC_{NTPP}MC_{PO}MC_{EC}MC_{DC}$$

This valid expression in the MCG can be used as a basis for defining term-rewriting rules to process strings of movement choremes into meaningful parts (Klippel et al., 2005, see also Dershowitz, 1993; Galton, 1993).

One critical question that we need to answer is: what constitutes a valid expression in this formal language? This is not trivial, as many combinations are possible from a formal perspective. The first constraint comes from the organization of the topological relations as conceptual neighbors in the conceptual neighborhood graph; only certain topological relations are conceptual neighbors. They are constrained through the movement patterns of the agent/entity in relation to a referent. Consider the example of the hurricane crossing the peninsula: assuming an idealized hurricane with crisp boundaries and no eye, its movement can be conceptualized as translation, which results in the path given above (e.g., CMP_{across}). These constraints ensure the validity of the sequence of topological relations. The hurricane cannot jump from MC_{DC} to MC_{NTPP} without going through $MC_{EC}MC_{PO}MC_{TPP}$. While there may be other scenarios where jumping is possible (e.g., a tornado), for the moment we will limit ourselves to this more constrained domain (see Worboys & Duckham, 2006 for a discussion of alternative graph structures).

An additional important observation is that humans have a tendency to pay particular attention to the ending relations of movement patterns (or events). This phenomenon is referred to as the *endpoint hypothesis (Regier, 1996; Regier & Zheng, 2007)*. To be able to identify valid expressions—that is, sequences of *MC*—on cognitive grounds we have to answer the question of which topological relations are good candidates for defining cognitively salient ending relations, and which ones are not. In other words, while the conceptual neighborhood graph defines the set of movement choremes and constrains their order, the endings (or beginnings, see below) could be arbitrary. All *MCs* are equally salient from a formal perspective, and the expression $MC_{DC}MC_{EC}MC_{PO}$ could be as valid as the expression $MC_{DC}MC_{EC}MC_{PO}MC_{TPP}$.

Our own research (Klippel & Li, 2009), results by Shariff et al. (1998), behavioral assessments of Allen's temporal calculus (Lu, Harter, & Graesser, 2009), and various formal approaches (e.g., Camara & Jungert, 2007) show that topological (and corresponding qualitative temporal) relations are cognitively salient to different degrees. For example, while it would be possible to allow for the following combination of movement choremes: $MC_{DC}MC_{EC}MC_{PO}MC_{TPP}$, it is questionable as to whether this should constitute a salient term in the MCG.

Figure 3 shows the result of an experiment (using cluster analysis) on the saliency of topologically-defined ending relations (Klippel, accepted). We used different movement pattern scenarios (see Figure 1) of which Figure 3 shows only the hurricane. To briefly summarize, participants sorted animated icons in a free classification task (Medin, Wattenmaker, & Hampson, 1987; Pothos, 2005) into groups. The icons were distinguished by the topological relation the movement of a hurricane would end in (see Figure 2).

The results show that certain topological relations form conceptual groups and are more similar to each other than to members of other groups. One striking result is that concepts that have some kind of proper part relation (TPP, NTPP) are separated from those that do not overlap (DC, EC)[4].

Identifying meaningful combinations of movement choremes based on topological equivalence classes is an important question if we want to automatically break down a characterization of a movement pattern into meaningful subparts on the basis of cognitively valid expressions. While research has been conducted on these questions, we still need more behavioral validation to guide how we assign saliency to the movement choremes within the MCG, and to decide what role they might play in defining meaningful sub-events. In the hurricane example (and within the limits of our experimental setup), we find that a distinction is made between hurricanes that do not make landfall, those hitting the coast, hurricanes that ebb over land, and those that cross the peninsula.

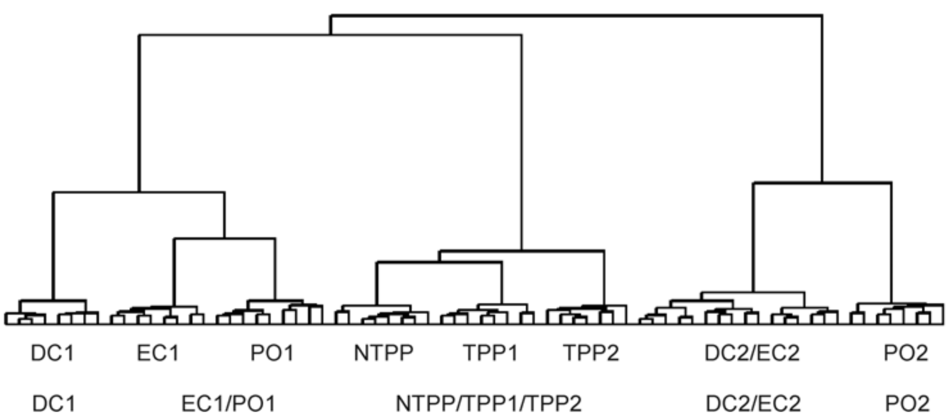

Figure 3. The dendrogram shows the result of cluster analyses (Ward's method) of the hurricane scenario. The results show that certain topological relations form conceptual groups (see also Klippel, accepted).

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[4] Note: We also found differences between different semantic domains. These results cannot be discussed here due to space constraints.

3.2. *Trajectory–region conceptualizations*

So far we have discussed only the case in which both the moving agent/entity and the reference entity are conceptualized as being spatially extended. Now we turn to the case in which the moving entity is conceptualized as a point while the reference entity is spatially extended. In this case, we can build on the well-established framework of the 9-intersection model (Egenhofer & Mark, 1995), which allows for specifying the relationship between a line—in this case a trajectory—and a spatially extended entity. This framework has been extended by Kurata and Egenhofer (2007) to allow for directed lines (DLines) that have a starting and an ending point; this model is referred to as 9^+-intersection. The 9^+-intersection model details 26 possible relations between a (directed) line and a spatially extended entity (compared to 19 relations that are formally distinguished between undirected lines and spatially extended entities). These 26 possible relations are the result of analyzing—from the perspective of point-set topology—the relationship between the following elements of the Dline and an extended spatial entity: the interior, the boundary, and the exterior. The boundary of a line is constituted by its endpoints; in the case of a Dline, a distinction is made between whether the endpoint is the start or the end of the line.

Determining, from the perspective of set theory, whether the union of these combinations is empty or not allows for specifying 26 topologically equivalent relations that are possible in two dimensions. Thereby we can formalize the relationship between a trajectory and an extended spatial entity. Figure 4 displays these 26 relations. The 9^+-intersection approach is intended to model human concepts of movement (Kurata & Egenhofer, 2009), and is currently the most elaborate topological approach to characterizing single agent movement patterns (for a trajectory / region combination) (Stewart Hornsby & Li, 2009).

We explore here how this approach could be realized within the framework of *MCs* and the MCG (see also Kurata & Egenhofer, 2009; Wang, Luo, & Xu, 2004). We start by characterizing only three basic relations between the moving agent/entity and the spatially extended entity. Slightly different to the previous discussion in Section 3.2, where both entities were spatially extended, we focus on the basic distinctions used to define the 9-intersection model rather than the full set of relations that potentially can be defined by this model. Hence, from a chorematic perspective the movement of the agent/entity can occur either in the exterior (*EX*), on the boundary (*BO*), or in the interior (*IN*)[5]. This distinction, except for the boundary, corresponds to the image schema: *in-out*. Additionally, we need to distinguish whether the movement "on" the boundary occurs only in one point, such as the start or end point, or whether it is an extended movement along the boundary. In the case where the movement on the boundary is taking place only in a single point we write *bo* instead of *BO*. Please note that this distinction is also useful for characterizing different forms of crossing from the interior to the exterior. While this information is not part of a purely topological characterization, it has received some attention in modeling relationships between two lines (Xu, 2007). For the purpose of this article, we will only make the binary distinction whether the trajectory and the boundary of the spatially extended entity have more than one point in common, or just one point. We have applied the approach of characterizing movement patterns based on movement choremes to the examples of the 26 Dline relations detailed in Kurata and Egenhofer's work. A movement pattern, for example, corresponding to an agent crossing the spatially extended entity, would correspond to the following sequence:

$$MC_{EX}MC_{bo}MC_{IN}MC_{bo}MC_{EX}$$

[5] We exclude here the *closure* which is defined as the union of interior and boundary (Open Geospatial Consortium, 2002).

To further demonstrate the feasibility of this approach based on only four movement choremes (in case of conceptualizing the moving agent/entity as a point), we show in Figure 4 how all 26 Dline relations could be characterized on the basis of four *MCs*. This approach cognitively grounds ideas briefly discussed by Kurata and Egenhofer (2009) and Wang and collaborators (Wang et al., 2004) about basing movement characterization on image schematic motivated invariants of movement patterns.

The advantage of applying the movement choreme approach is that it combines a formal grammar and string processing technique called term rewriting (Dershowitz, 1993). Once the grammatical foundations are laid, movement patterns characterized as strings of *MCs* can be processed to derive a) meaningful substrings and b) hierarchically ordered meaningful sub-patterns. For example, the combination $MC_{EX}MC_{bo}MC_{IN}$ can be defined as a valid expression in the MCG, which means that it can be simplified to a concept that could be referred to as *enter* (see also Kurata & Egenhofer, 2009; Mark & Egenhofer, 1994):

$$CMP_{enter} \equiv MC_{EX}MC_{bo}MC_{IN}$$

Likewise, the concept *exit* could be defined as:

$$CMP_{exit} \equiv MC_{IN}MC_{bo}MC_{EX}$$

These are just examples of how a characterization of movement patterns on the basis of movement choremes (that is, conceptual movement primitives) could be established. We will provide an outlook of ongoing work in the next section. One critical question remains, which is beyond the scope of the current article. While the 26 relations defined by the 9^+-intersection model are considered primitive from a formal perspective, they are most likely not primitive from a cognitive-conceptual perspective. In other words, while all 26 relations in Figure 4 can be modeled in both the 9^+-intersection model and with the four *MCs* defined above, we do not know (and doubt) whether they all constitute valid expressions for the

MCG. Experiments using a grouping paradigm (see Figure 3) could be used to elicit which formal primitives are conceptually closer than others.

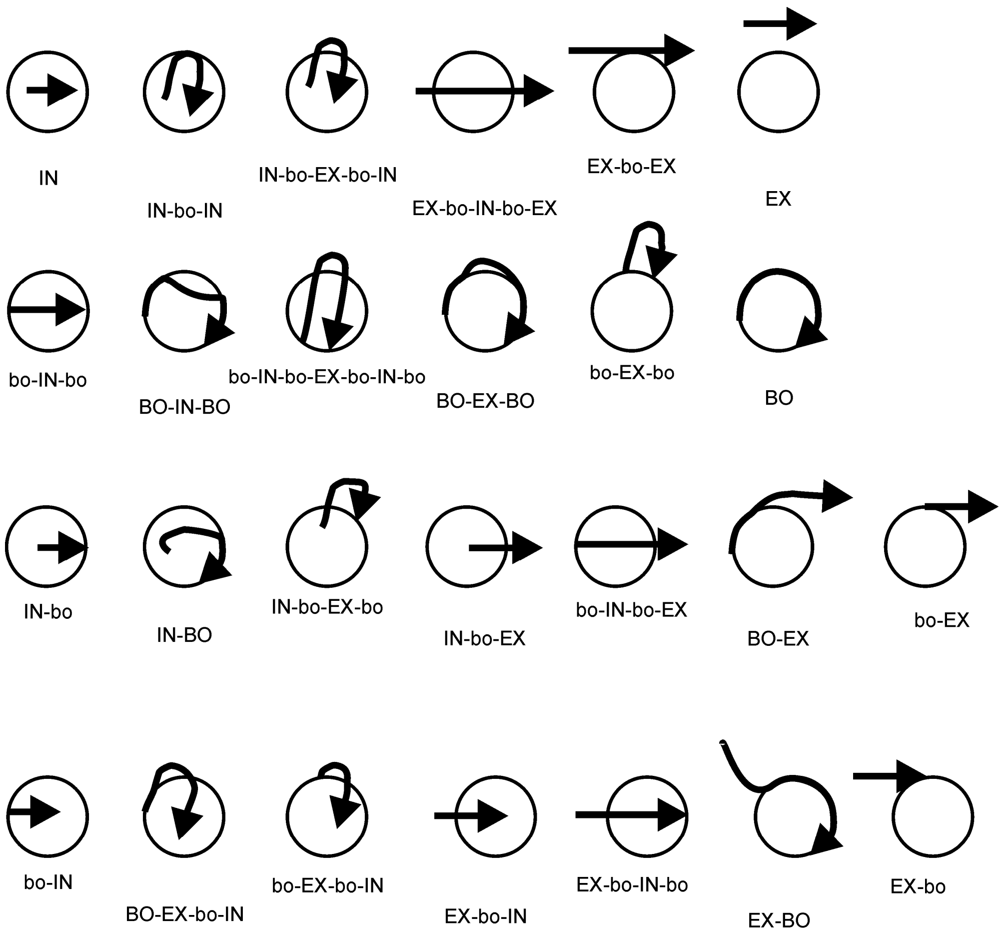

Figure 4. Shown are icons depicting the 26 Dline-region relations. Below each icon, the MC notation is provided (EX for a movement pattern outside an extended spatial entity, IN for a movement patterns inside a spatially extended entity). Please note that we modeled the relations based on the original icons by Kurata and Egenhofer (2009). To this end, we distinguished between movement patterns on the boundary that occur only in one point (start, end, and crossing) and movement patterns that are taking place along (but still on) the boundary (bo and BO, respectively). Please also note that we left out the MC and simply used the subscript to save space. The power of this approach lies in its potential to identify

meaningful substrings. For example, in case of IN-bo-EX we can summarize the movement patterns to INEX and associate a semantic (linguistic) concept with it.

4. Conclusions and outlook

To conclude this article and to provide a road map for further research, we use a taxonomy (see Figure 5) to detail various aspects of movement patterns of single agents/entities from a chorematic perspective. This taxonomy complements existing taxonomies on movement patterns (Dodge, Weibel, & Lautenschütz, 2008) and directly extends work by Freksa and Röhrig (1993). It is organized according to what we consider to be potentially critical cognitive concepts of movement patterns. The focus of the taxonomy lies in qualitative formal distinctions (Cohn & Renz, 2008) that are considered starting points for identifying cognitively relevant distinctions (see Section 3)[6]. As we have discussed using qualitative formalism for cognitive investigations, but have also shown that such formalisms require adjustments to allow for modeling spatial cognitive processes, the taxonomy allows for both a conceptual perspective on the current paper as well as identifying future research.

The first distinction is made based on whether the trajectory as such or the changing relations between a moving entity and other features / entities is of interest. Trajectory characteristics such as shape (Shipley & Maguire, 2008), speed, and manner of motion have been shown to be important. Likewise, qualitative shape and direction information has been widely discussed (Freeman, 1975; Kulik & Egenhofer, 2003). We will show briefly (see

[6]Several taxonomies have recently been proposed from different perspective such as geography, levels of granularity, data mining, and visual analysis of movement patterns (e.g., Dodge, Weibel, and Lautenschütz (2008); Hornsby & Egenhofer (2002); Yattaw (1999)). Our taxonomy specifically addresses cognitive conceptualizations of movement patterns with the goal of bridging the gap between formal and cognitive conceptualizations.

below) how this information can be integrated into the movement choreme approach. A behavioral validation of formal approaches is, however, largely missing so far.

In case the spatial relations between the moving entity and other features/entities changes, the main distinction made is whether this change is topological or not. Non-topological changes could be captured, for example, by ordering information (Schlieder, 1995). While topology has received attention from the perspective of its relevance to model cognitive processes, ordering information is still largely unexplored.

Specifically, the two aspects discussed in the present article are movement patterns that result in changing topological relations in which the moving entity is characterized either as an extended spatial entity or as a point (resulting in a linear trajectory). We do not claim that this taxonomy is complete, but it makes clear which aspect of movement patterns have been addressed in the present work, how this work integrates with other research efforts, and which aspects await behavioral validation.

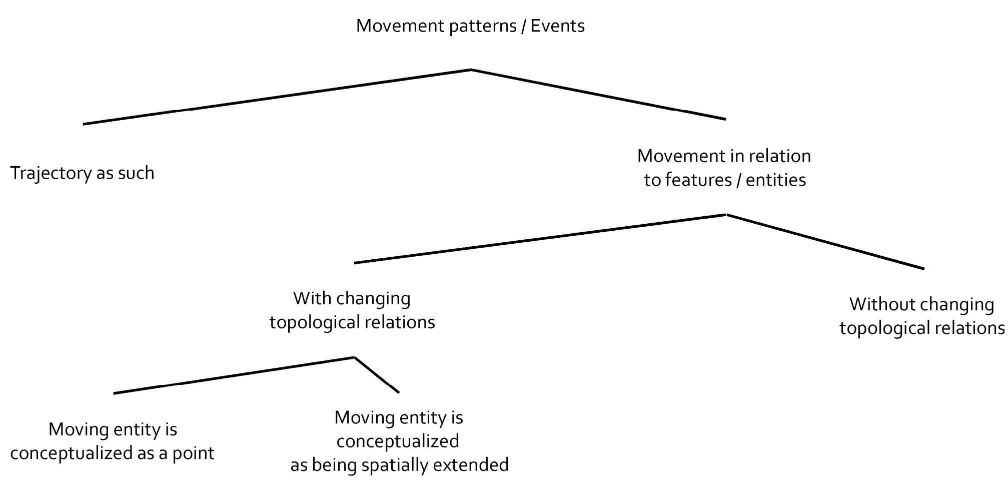

Figure 5. Movement taxonomy.

To summarize, this paper presented the basics of a developing theory for the characterization of movement patterns. The core notion of this theory is the *movement choreme*, or *MC*. A movement choreme is a conceptual primitive in the sense that it is foundational for the cognitive understanding of movement patterns. It is grounded in what we discussed as perceptual and cognitive invariants. Here, we restricted ourselves to the characterization of movement patterns of individual entities that discretely change their topological relation to a reference entity. While *MCs* are conceptual primitives, their full potential is realized through grammatical rules that combine *MCs* into chunks (letters combined to words to use a linguistic metaphor). These chunks, which we call complex movement patterns, or *CMPs*, are the basis for a) a conceptual grammar of movement patterns, and b) term-rewriting rules that can be used to meaningfully segment strings of *MCs* that characterize continuous movement patterns.

While we have not developed all of the aspects discussed above, we did show that using CMPs can add improvements to existing formal characterizations. In a future step, we plan to fully specify this framework, that is, establish a formal, conceptual language for movement patterns. Combining different aspects of movement patterns into a single notation has been discussed by Stewart Hornsby and Cole (2007). This work complements this approach by incorporating findings from behavioral experiments. For example, using either Freeman chaining (Freeman, 1975) or wayfinding choremes (Klippel et al., 2005), we could model direction changes of a hurricane—even if topological relations do not change. We would need to specify a direction model (a reference frame) such as cardinal directions for movements at the geographic scale (Hernández, 1994; Ligozat, 1998). Additionally, we need a spatio-temporal measure that would allow us to specify individual movement concepts. A hurricane going west for a while and then turning north toward the main land could be specified as:

$$MC_{DC}^{W}MC_{DC}^{W}MC_{DC}^{W}MC_{DC}^{W}MC_{DC}^{N}$$

The subscript, DC, indicates the topological relation with respect to a reference entity (here: the hurricane is disconnected from the peninsula), while the superscript provides the direction information of the movement pattern (first West, then North). As detailed in sections 3.2 and 3.3, we could specify a valid expression in the MCG that would allow us to chunk a sequence of MC_{DC}^{W}. This valid expression (and others) could be used to process movement patterns specified as strings of *MCs*.

The other aspect we left out of the specification is the area of changing spatial relations between a moving agent/entity and entities in the environment that do not involve changing topological relations. These changes could be specified by using, for example, ordering information (Schlieder, 1995) or other qualitative specification of spatial relations such as the double-cross calculus (Freksa, 1992b). The number of existing calculi is large and it may be necessary to use different calculi for different spatial environments and purposes. Our own research has demonstrated how ordering information of branches at intersections can be used to ground the semantics of concepts such as *before*, *after*, and *at* (Richter & Klippel, 2007).

One main aspect in further specifying the MCG is the behavioral validation and grounding of formal characterization in a cognitive assessment. For this purpose, we have set up an experimental framework that will extensively assess, first and foremost, the role of topology across different domains and across different topological transformations. We consider this approach an essential step in tailoring existing formal specifications toward cognitive adequacy. Second, we will address the question of different granularities, and the scale dependency of conceptualizing moving entities either as points or as extended spatial entities. While the hope is that topology could be equally important across different domains for the conceptualization of movement patterns, it may be necessary to tailor grammatical rules by taking into account the semantics of the domains.

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