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Using Orientation Information for Qualitative Spatial Reasoning

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Abstract. A new approach to representing qualitative spatial knowledge and to spatial reasoning is presented. This approach is motivated by cognitive considerations and is based on relative orientation information about spatial environments. The approach aims at exploiting properties of physical space which surface when the spatial knowledge is structured according to *conceptual neighborhood* of spatial relations. The paper introduces the notion of conceptual neighborhood and its relevance for qualitative temporal reasoning. The extension of the benefits to spatial reasoning is suggested. Several approaches to qualitative spatial reasoning are briefly reviewed. Differences between the temporal and the spatial domain are outlined. A way of transferring a qualitative temporal reasoning method to the spatial domain is proposed. The resulting neighborhood-oriented representation and reasoning approach is presented and illustrated. An example for an application of the approach is discussed.

1 Introduction

Spatial orientation information, specifically: directional information about the environment, is directly available to animals and human beings through perception and is crucial for establishing their spatial location and for wayfinding. Such information typically is imprecise, partial, and subjective. In order to deal with this kind of spatial information we need methods for adequately representing and processing the knowledge involved. This paper presents an approach to representing and processing qualitative orientation information which is motivated by cognitive considerations about the knowledge acquisition process.

1.1 Background

In a study investigating cognitive aspects of temporal reasoning, a new approach to qualitative temporal reasoning was developed [Freksa 1992]. The main feature of this approach was the exploitation of *conceptual neighborhood* between related qualitative relations. The use of this neighborhood information results in several advantages compared with previous approaches, for example: (1) processing incomplete knowledge simplifies (rather than complicates) the computational procedure; (2) uncertainty is easily controlled in the case of fuzzy base knowledge; (3) for an important class of operations, a computationally intractable process becomes tractable.

The obvious question was raised whether the approach originally developed for the one-dimensional directed domain *time* could be advantageously transferred to a more-dimensional and/or undirected domain like 2-D or 3-D *space*. Within the spatial domain, the application of the approach both to subject-centered knowledge, i.e. knowledge available from within the domain, and to external knowledge appeared desirable due to cognitive considerations. The current state of our considerations will be presented in this paper for the 2-dimensional case.

1.2 Qualitative Reasoning

After an initial enthusiasm regarding the potential of high-precision quantitative computation, qualitative reasoning has become increasingly popular in artificial intelligence and its application areas. This is due to a variety of reasons. First of all, it has been recognized that computational quantitative approaches do not always have the nice properties of their analytical counterparts; second, the goal of a reasoning process usually is a qualitative rather than a quantitative result: a decision; third, the input for a reasoning process frequently is qualitative: the result of a comparison rather than a description in quantitative terms; fourth, qualitative knowledge is 'cheaper' than quantitative knowledge since it is less informative, in a certain sense; fifth, qualitative representations tend to be more transparent than their quantitative counterparts; and sixth, humans seem to do qualitative reasoning more easily (and sometimes better) than quantitative reasoning. Thus, we must develop methods for dealing with judgements which are non-quantitative in nature and a quantitative representation of these judgements may not be the best solution.

What do we precisely mean by *qualitative* knowledge? In the context of the present discussion, it may suffice to say that qualitative knowledge is obtained by *comparing* features within the object domain rather than by *measuring* them in terms of some artificial external scale. Thus, qualitative knowledge is relative knowledge where the reference entity is a single value rather than a whole set of categories. For example, if we compare two objects along a one-dimensional criterion, say length, we can come up with three possible qualitative judgements: the first object can be *shorter (<), equal (=),* or *longer (>)* in comparison with the second object.

From a representation-theoretical point of view, a major difference between the two approaches is that measuring requires an intermediate domain in which the scale is defined while comparisons may be performed directly in the object domain. Dealing with an intermediate domain requires mapping functions between the object domain and the scale domain which may be critical for the reasoning process. Thus, qualitative representations aim at avoiding distortions of knowledge due to intermediate mappings. In addition, reasoning based on qualitative information aims at restricting knowledge processing to that part of the information which is likely to be relevant in the decision process: the information which already makes a difference in the object domain.

1.3 Spatial Reasoning

Physical space and its properties play essential roles in all sorts of actions and decisions. Consequently, the ability to reason in and about space is crucial for systems involved in these actions and decisions. In fact, we can raise the question if formal logic or physical space is more fundamental for reasoning processes: should we view spatial reasoning as a special case of ‘general’ logic-based reasoning or should we rather view logic-based reasoning as an abstraction (and generalization) of spatial reasoning? From a formal position, these two viewpoints may appear equivalent; however, from a cognitive and computational position, they are not: the logic-based view assumes that spatial reasoning involves special assumptions regarding the properties of space which must be taken into account while the space-based view assumes that abstract (non-spatial) reasoning involves abstraction from spatial constraints which must be treated explicitly.

From a biological point of view, the issue raised above corresponds to the question which ability is more ‘primitive’ and has evolved first, abstract reasoning or spatial reasoning. If we replace the term ‘reasoning’ by the less presumptuous term ‘dealing’, it appears evident that nature has chosen to equip plants and animals first with abilities of dealing with space before abilities of dealing with abstract worlds were developed. Some interesting questions arise in this context: does the ability of dealing with abstract worlds require the ability of dealing with the concrete world or are they two completely independent abilities? Do we have representational, computational, or other advantages when using either abstract or concrete approaches to spatial reasoning – independent of the way nature may have chosen? If there are advantages for the space-based approach, how can the approach materialize?

1.4 Existing Approaches to Qualitative Spatial Reasoning

A variety of approaches to qualitative spatial reasoning has been proposed. Güsgen [1989] adapted Allen’s [1983] qualitative temporal reasoning approach to the spatial domain by aggregating multiple dimensions into a Cartesian framework. Güsgen’s approach is straightforward but it fails to adequately capture the spatial interrelationships between the individual coordinates. The approach has a severe limitation: only rectangular objects aligned with their Cartesian reference frame can be represented in this scheme.

Chang & Jungert [1986] present a knowledge structure for representing relations between arbitrarily shaped 2-dimensional objects on the basis of string representations. Lee & Hsu [1991] also use string representations and develop a ‘picture algebra’ for rectangles (or projections of convex shapes] in a 2-dimensional Cartesian framework.

Randell [1991] attacks the problem of representing qualitative relationships of concave objects. He introduces a ‘cling film’ function for generating convex hulls of concave objects; he then lists all qualitatively different relations between an object containing at most one concavity and a convex object. Egenhofer & Franzosa [1991] develop a formal approach to describing spatial relations between point sets in terms of the intersections of their boundaries and interiors.

Schlieder [1990] develops an approach which is not based on the relation between extended objects or connected point sets. Schlieder investigates the properties of projections from 2-D to 1-D and specifies the requirements for qualitatively reconstructing the 2-dimensional scene from a set of projections yielding partial arrangement information.

Hernández [1990] considers 2-dimensional projections of 3-dimensional spatial scenes. He attempts to overcome some deficiencies of Güsgen's approach by introducing 'projection' and 'orientation' relations. Freksa [1991] suggests a perception-based approach to qualitative spatial reasoning; a major goal of this approach is to find a natural and efficient way for dealing with incomplete and fuzzy knowledge.

Frank [1991] discusses the use of orientation grids ('cardinal directions') for spatial reasoning. The investigated approaches yield approximate results, but the degree of precision is not easily controlled. Mukerjee & Joe [1990] present a truly qualitative approach to higher-dimensional spatial reasoning about oriented objects. Orientation and extension of the objects are used to define their reference frames.

2 Qualitative Orientation

As we have seen, there is a number of different approaches and reference systems for representing spatial knowledge. In order to select an appropriate reference system for a given purpose, the availability of the required information must be taken into account. For example, if we want to represent spatial knowledge as acquired by a person through perception, it does not make sense to use Cartesian coordinates for representing object location since this information is not made available by the perception process.

On the other hand, information about relative spatial orientation in 2-D is available through perception. This information is also available to an external observer of a 2-dimensional spatial scene. Thus, relative orientation information is a good candidate for processing subject-centered or external qualitative spatial knowledge. Therefore we develop a representation scheme in which this kind of information can be directly represented.

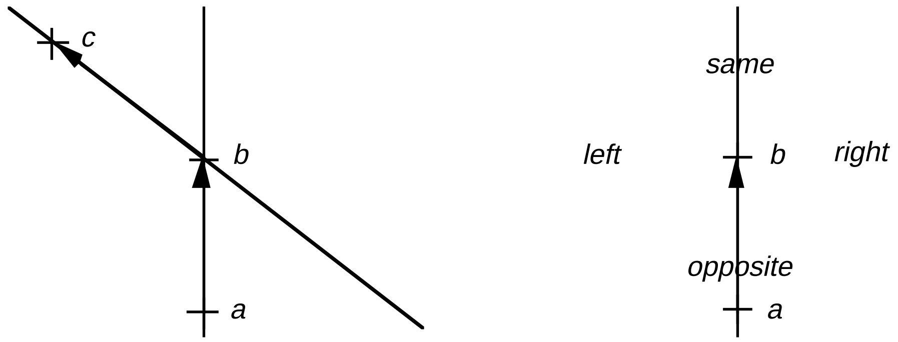
2.1 Dimensionality of Space and Domain-Inherent Constraints

In qualitative reasoning, we can relate entities of different dimensionality within a domain of a certain dimensionality. We obtain a relation space whose size depends on the dimensions involved and on constraints inherent in the modelled domain. Consider for example the one-dimensional domain 'length' which is spanned by two 0-dimensional entities (points). Within this 1-dimensional domain we can relate two 0-dimensional entities. The relation space consists of three disjoint classes: 'less', 'equal', and 'greater'.

In the one-dimensional domain we also can relate a 0-dimensional entity to a 1-dimensional entity, e.g. a point x to an interval [a, b]. If we permit $b<a$ and $b=a$, the relation space consists of nine disjoint classes: $x<a$, $x<b$; $x=a$, $x<b$; $x>a$, $x<b$; $x>a$, $x=b$; $x>a$, $x>b$; $x=a$, $x>b$; $x<a$, $x>b$; $x<a$, $x=b$; $x=a=b$. Domain-inherent properties may not permit $b<a$ (if the domain is uni-directional) or $b=a$ (if we only model extended intervals); both restrictions apply to models of temporal events, for example. In this case, the relation space reduces to five relations. Depending on the

specific requirements of the modeled domain, we can construct appropriate qualitative relation spaces, in this way.

Directional orientation in 2-dimensional space is a 1-dimensional feature which is determined by an oriented line; an oriented line, in turn, is specified by an ordered set of two points. We will denote an orientation by an (oriented) line *ab* through two points *a* and *b; ba* denotes the opposite orientation. Relative orientation in 2-D is given by two oriented lines or two ordered sets of two points. The feature *orientation* is independent of location and vice versa; therefore, the two ordered sets of points can share one point, without loss of generality. Thus, we can describe the orientation of line *bc* relative to the orientation of line *ab.* This corresponds to describing the point location *c* with respect to reference location *b* and reference orientation *ab* (Figure 1a). Note, that if locations *c* and *b* are identical, orientation *bc* is not defined; nevertheless, we can specify the location of *c* wrt. *a* and *b.*



a) **b)**

Fig. 1 a) Orientation *bc* relative to orientation *ab,* or: location *c* wrt. location *b* and orientation *ab;* **b)** Orientation relations wrt. location *b* and orientation *ab.*

2.2 Orientation Values and Properties of Qualitative Orientation

The specification of orientation as described in the previous section allows for the distinction of four qualitatively different orientation relations which we have labeled *same, opposite, left, right* (Figure 1b). These relations correspond to point *c* being positioned on line *ab* on the other side of *b* than *a,* on line *ab* on the same side of *b* as *a,* on the left semi-plane of the oriented line *ab,* and on the right semi-plane of the oriented line *ab,* respectively.

Like the qualitative relations *less, equal, greater*, the orientation relation *same* is transitive. The relation *opposite* is periodic in the sense that its repetitive application results in a periodic pattern of resulting orientations, e.g. *opposite* ∞ *left* yields *right, opposite* ∞ *opposite* ∞ *left* yields *left, opposite* ∞ *opposite* ∞ *opposite* ∞ *left* yields *right,* etc. The qualitative relations *left* and *right* are not periodic, in general; they subsume a wide spectrum of possible quantitative orientations.

Unlike in the case of linear dimensions, incrementing quantitative orientation leads back to previous orientations. In this sense, orientation is a circular dimension.

Existing approaches do not deal with periodicity of orientation explicitly. Periodicity is either eliminated by not admitting certain orientations as in [Schätz 1990] or it is ignored by treating different orientations as independent entities as in Frank [1991].

2.3 Augmenting Qualitative Orientation Relations

We can augment the number of orientation relations by introducing additional decision criteria. From a geometrical point of view, the segmentation of 2-dimensional space into two semi-planes perpendicular to the reference orientation *ab* comes to mind immediately. A front/back segmentation already became visible in the *same / opposite* distinction of orientations.

Although people and most animals do not have a perception system for explicit front/back or forward/backward discrimination as they do for left/right discrimination, the segmentation of the plane into a front and a back semi-plane also is meaningful from a cognitive point of view: we conceptualize people, animals, robots, houses, etc. as having an ‘intrinsic front side’ (compare Pribbenow [1990], Mukerjee & Joe [1990]); this results in an implicit dichotomy between a front region and a back region and a forward and backward orientation.

Introducing the front/back dichotomy results in a substantial gain of information: in combination with the left/right dichotomy we obtain eight meaningful disjoint orientation relations, namely *straight-front (0), right-front (1), right-neutral (2), right-back (3), straight-back (4), left-back (5), left-neutral (6),* and *left-front (7).*

From the viewpoint of a tradition predominantly employing quantitative descriptions it may appear confusing that categories with rather unequal scope are used on the same level of description: the relations *right-front, right-back, left-back,* and *left-front* correspond to an infinite number of angles while *straight-front, neutral-right, straight-back,* and *neutral-left* correspond to a single angle. For qualitative reasoning, however, only distinguishable features count – and most angles cannot be distinguished, in our setting. Note that the orientation relations represent comparative, i.e qualitative values; they do not require a fixed reference system or cardinal directions.

At this point it may be interesting to note the correspondence between orientation and movement. If we view points *a, b,* and *c* as a chain of positions traversed in sequence, then the orientations correspond to the directions of movement while 'undefined orientation' *(c=b)* corresponds to ‘no movement’. The correspondence between orientation and movement is particularly visible in natural language words like *forward* and *backward.*

The arrangement depicted in Figure 1a suggests four ways in which the *front/back* dichotomy can be applied: (1) perpendicular to *ab* in *a,* (2) perpendicular to *ab* in *b,* (3) perpendicular to *bc* in *b,* (4) perpendicular to *bc* in *c*. Eventually we will use all four dichotomies in order to increase the ‘qualitative resolution’ in spatial reasoning. But we will proceed in stages, in order to make the approach more transparent.

Consider orientation *ab* with a front/back dichotomy introduced in *b* (Figure 2a). We can distinguish eight regions, each corresponding to one qualitative orientation (labeled 0 - 7) and the location *b* corresponding to no orientation. We can do the same for orientation *ba* with a front/back dichotomy introduced in *a*. The result is depicted in Figure 2b.

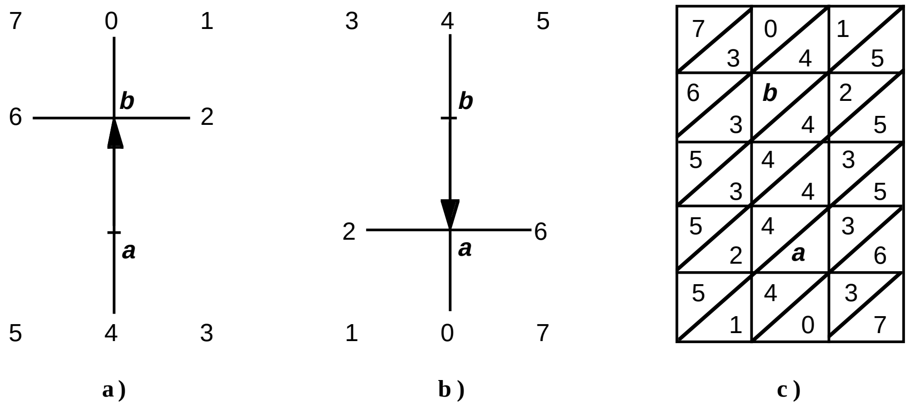


Fig. 2 Combination of left/right and front/back dichotomies into a system of orientations; **a)** front/back dichotomy wrt. *ab* in *b*; **b)** front/back dichotomy wrt. *ba* in *a;* **c)** matrix of combined orientation labels for the 15 qualitative locations.

Figure 2c merges the labels of Figures 2a and 2b into a matrix which distinguishes 15 regions. Each of the regions corresponds to an orientation wrt. *b* (designated in the upper left of the corresponding matrix field) and/or wrt. *a* (designated in the lower right of the corresponding matrix field). The matrix in Figure 2c permits the qualitative description of any location *c* wrt. location *b* and orientation *ab* and wrt. location *a* and orientation *ba.*

The orientation-based qualitative location relation is slightly more general than the qualitative orientation relation since it includes the orientation-less case *c=b* resp. *c=a*. Therefore we will use it in the following. We will use the same relation labels for denoting qualitative locations as for the corresponding locations; we will denote the orientation-less location by the reference point it corresponds to or by the symbol *i* (identical location).

3 Conceptual Neighborhood and Spatial Knowledge

Freksa [1992] shows for the one-dimensional case of temporal knowledge that there are considerable cognitive and computational advantages to arranging knowledge according to an appropriate *conceptual neighborhood* relation. The conceptual neighborhood principle can be applied to spatial knowledge equally well.

3.1 Conceptual Neighborhood of Spatial Relations

Two relations in a representation are conceptual neighbors, when an operation *in the represented domain* can result in a direct transition from one relation to the other. In physical space, operations can be movements in space or spatial deformations. For example, the relations *left-front (7)* and *left-neutral (6)* and *identical location (i)* are conceptual neighbors by pairs (Figure 3). In contrast, the relations *left-neutral* and *straight-front* are not conceptual neighbors, since any physical operation from one spatial relation to the other would result in at least one intermediate relation – for example the relation *left-front* or *identical location.*

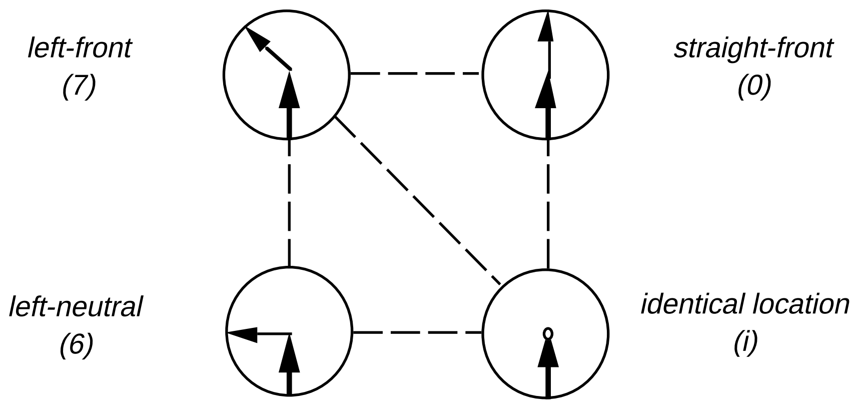


Fig. 3. Relations *7* and *0, 0* and *i, i* and *6, 6* and *7, 7* and *i* are conceptual neighbors; relations *6 and 0* are not.

What happens to conceptual neighborhood when we introduce additional differentiations as in Figure 2c? By introducing the second front/back dichotomy through point *a*, we effectively split up the relations *3*, *4*, and *5* into three finer relations each, namely *(3/5, 3/6, 3/7), (4/4, 4/a, 4/0),* and *(5/3, 5/2, 5/1).* The coarser original relation becomes a neighborhood of finer relations. Some of the finer relations within a neighborhood are neighbors, some are not. For example, *3/5* and *3/6, 3/6* and *3/7* are conceptual neighbors, but *3/5* and *3/7* are not.

Note that the finer relations do not resolve the orientation information more finely, although they are defined purely in terms of qualitative orientations. Rather, they distinguish between different qualitative distances. This is shown in Figure 4.

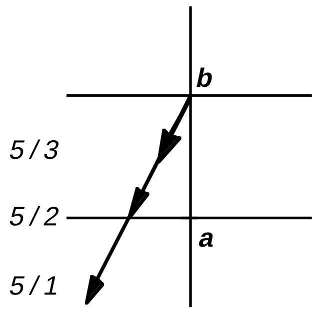


Fig. 4. The combination of orientations wrt. different reference points yields qualitative distance information.

There are also conceptual neighbor relations between fine relations from different neighborhoods, provided that these neighborhoods themselves are neighbors. For example, *3/5* and *4/4* are conceptual neighbors, but *3/5* and *5/3* are not. Figure 5 depicts the conceptual neighbor relations for all 15 location relations. The 15 qualitative relations form 105 (unordered) pairs. 30 of these pairs have the conceptual neighborhood property.

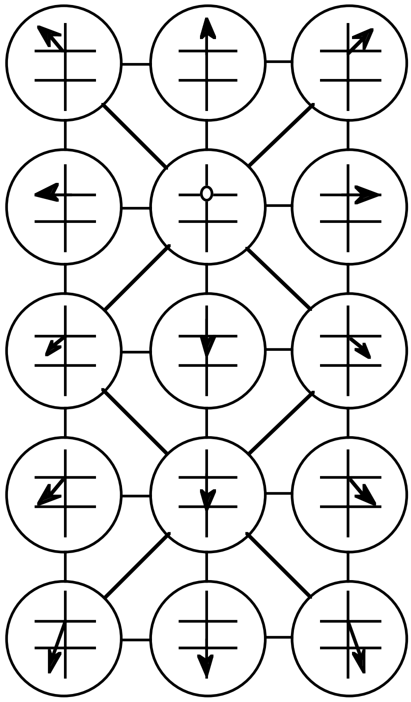


Fig. 5. The 15 qualitative orientation and location relations arranged by conceptual neighborhood. The symbol ‡ depicts iconically line *ab* with the intersections at *a* and at *b*. The arrow depicts the orientation of *bc.*

Conceptual neighborhood structures are important since they intrinsically reflect the structure of the represented world with their operations. Such representations of properties of the represented domain [Furbach et al. 1985] allow us to implement reasoning strategies which are strongly biased towards the operations in the represented domain. They can be viewed as procedural models of this domain. In the case of representing the spatial domain, conceptual neighborhoods contribute to the implementation of imagery processes. From a computational point of view they have the advantage of restricting the problem space in such a way that only operations will be considered which are feasible in the specific domain.

3.2 What are Appropriate Entities to be Spatially Related?

Models of spatial knowledge can either represent abstract point objects or spatially extended objects. Most approaches to representing qualitative spatial knowledge consider the relation between spatially extended objects, or formally speaking between (3-D) volumes, (2-D) areas, or (1-D) intervals. While this approach appears natural, at first glance, considerable drawbacks become apparent upon closer consideration. The main problem is that there is a multitude of possible classes of shapes which cannot be handled equally well. As a consequence, some approaches are restricted to convex or to rectangular shapes [Güsgen 1989, Hernández 1990].

Our representation uses point locations as basic entities. There are several motivations for this approach. First, the properties of points and their spatial relations hold for the entire spatial domain. Second, shapes can be described in terms of points at various levels of abstraction and with arbitrary precision – or can be ignored. Third, it appears desirable to be flexible wrt. the spatial entities and their resolution: in some contexts, we view objects as 0-dimensional spatial points (e.g. position of stars under the sky, position of cities on a wide-area map, position of land marks in a town); in other contexts we may be interested in their 1-dimensional extension (e.g. width of a river, length of a road); in other contexts, a 2-dimensional projection may be of interest (e.g. area of a lake); and sometimes the full 3-dimensional shape of an object or a 3-D constellation of objects is of interest. Our goal has been the development of a fundamental approach which can be used in a large variety of situations.

4 Qualitative Spatial Reasoning

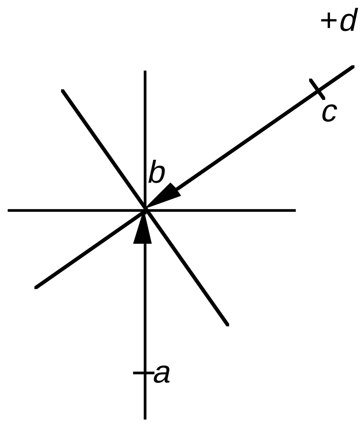
After presenting an orientation-based representation framework we now illustrate how to use this framework for qualitative spatial reasoning. Initially, the conceptual neighborhood structure of the orientation relations mainly serves to help visualize the structure, the operations, and the regularity of the domain and to clarify the approach.

4.1 Orientation-Based Inferences

The representation developed in the foregoing sections enables us to describe one spatial vector with reference to another spatial vector. In analogy to the inference scheme for relating one temporal interval to another temporal interval described by Allen [1983], we develop here an inference scheme for orientation-based spatial inferences.

We will denote the segment between *a* and *b* of the oriented line *ab* as vector ***ab***. Suppose, we know the qualitative spatial relation of vector ***bc*** to vector ***ab*** and the relation of vector ***cd*** to vector ***bc***. We would like to infer the relation of vector ***bd*** to the original reference vector ***ab***.

We will first illustrate the simple case of a single front/back dichotomy, i.e., we consider eight orientation relations for ***bc*** and for ***cd***. The result of the inference is to be expressed in terms of the same eight relations. The front/back dichotomy divides both *ab* and *bc* in point *b*. For reasons of uniformity, we will relate *d* to *cb* instead of *bc;* the front/back dichotomy then is always at the front of the vector (compare Figure 6a). We use the notation (labels *0* through *7*) to denote orientations as introduced in Figure 2.



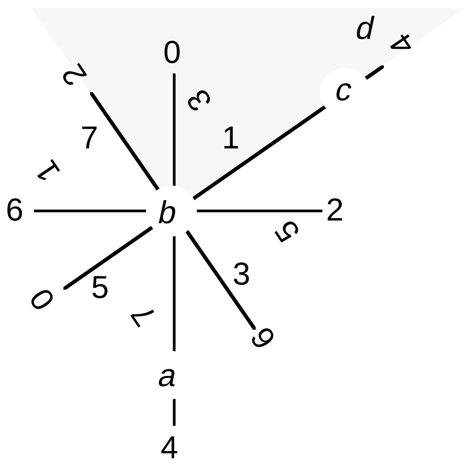


Fig. 6 a) *a, b,* and *c* define two left/right and front/back dichotomies in *b* for describing *d;* **b)** Each pair of dichotomies defines eight orientations; *d* is located in the shaded area.

Take a simple example: Let *c right-front (1)* ***ab*** and *d left-front (7)* ***bc*** (Figure 6a). We do not have a front/back dichotomy of *bc* in point *c;* thus, we cannot represent "*d left-front (7)* ***bc***". We use "*d right-back (3)* ***cb***", instead. This relation describes a more general case, since it also includes part of the region *left-back* ***bc*** (Figure 6b). Informally speaking, we can infer that ***bd*** is ahead of ***ab***; we cannot infer whether *d* is located in the left, straight, or right front region of ***ab***. More formally, we infer: ***bd*** *left-front (7)* ***ab*** or ***bd*** *straight (0)* ***ab*** or ***bd*** *right-front (1)* ***ab***.

Figure 7 depicts the composition table for the 8*8 orientation relations. Each table entry corresponds to an orientation and/or location relation as suggested by Figure 5. The location of *a* and *b* in the icons of the column of initial conditions and in the table is indicated in the top icon of the column of initial conditions; the location of *b* and *c* in the icons of the row of initial conditions is indicated in its leftmost icon. In the column of initial conditions, black squares mark the possible location of *c;* in the row of initial conditions and in the table, black squares mark the possible locations of *d*. The bottom row and the rightmost column display location inferences for the orientation-less cases (*c=b* and *d=b,* respectively).

The composition table forms the basis for qualitative orientation-based reasoning. The table is arranged in such a way that neighboring rows and columns always correspond to conceptually neighboring initial conditions for the inference. Of course, not all conceptually neighboring relations can be depicted by neighboring rows and columns in a 2-dimensional table. Note that with this arrangement, spatially neighboring table entries (corresponding to the inferences) also are conceptual neighbors.

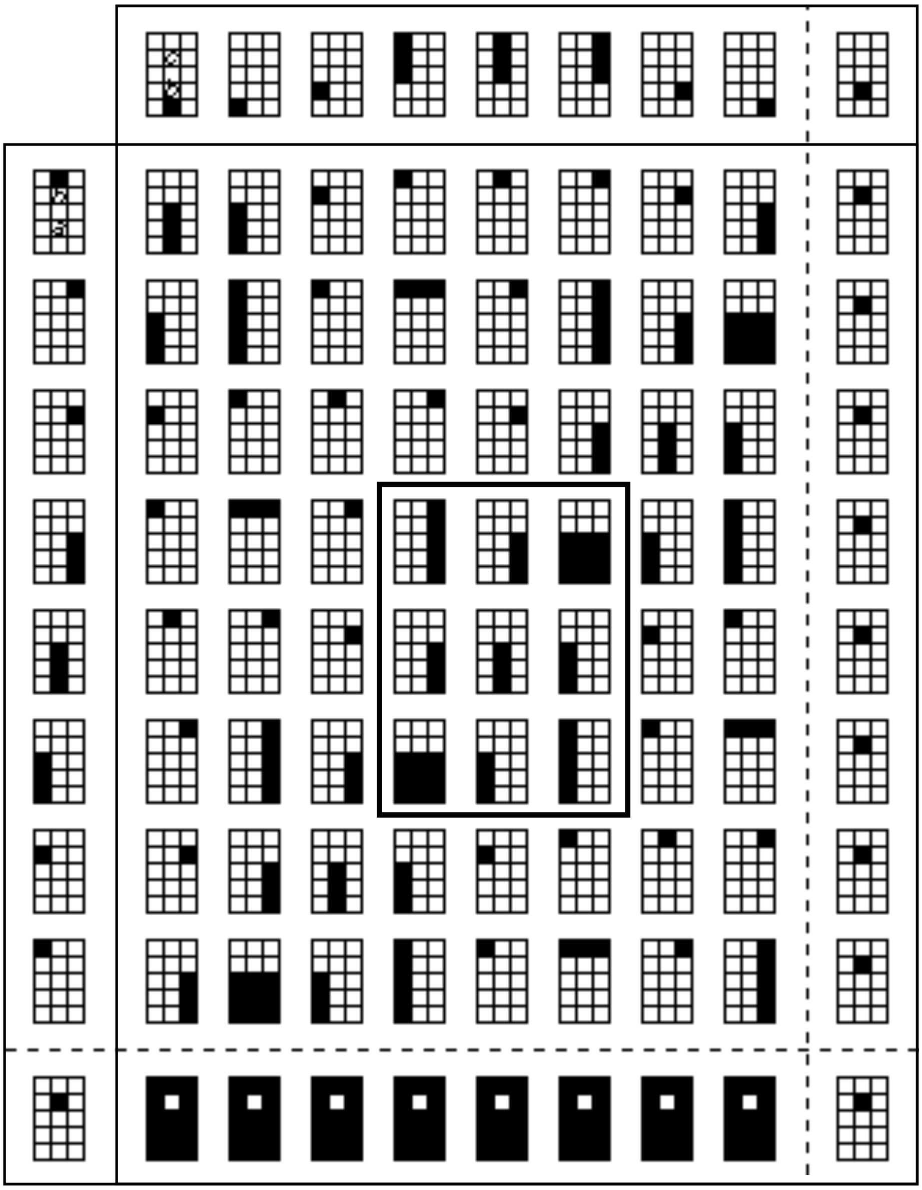


Fig. 7. Iconic composition table for nine location/orientation relations.

The entries in the composition table for the orientations follow a simple formation rule. Let *r* denote the orientation of *c* wrt. ***ab*** and *s* the orientation of *d* wrt. ***bc***. The resulting orientation *t* wrt. ***ab*** then is:

$$t = \left\{ \begin{array}{ll} r + s & \text{for } r \text{ or } s \text{ even} \\ (r+s\text{-}1) \ldots (r+s+1) & \text{for } r \text{ and } s \text{ odd} \end{array} \right\} \bmod 8$$

where *(r+s-1) … (r+s+1)* denotes a range of possible orientations.

Although in one fourth of the cases there is some uncertainty as to which specific qualitative orientation holds – in these cases there is a range of three neighboring possibilities which effectively increase the range of possible angles from 0˚ or 90˚ to 180˚ – we always have certainty about the resulting uncertainty. This is very important, since in certain situations the precision of the result may matter, in others it may not.

Note that the composition table would look more symmetrical if we merged the three lower rows of the icons into one (without loss of information). The expanded graphical notation is used for consistency with the representation for reasoning with higher resolution.

The conclusions obtained through the reasoning procedure can be used for further inferences. Not all conclusion patterns, however, can be found in the composition tables; some conclusions correspond to disjunctions of initial conditions. Accordingly, correct inferences for those patterns are found by forming the logical disjunction of the corresponding compositions. This operation can be visually carried out by superimposing the corresponding icons in our pictorial notation. Alternatively, the composition table could be expanded to explicitly include the complex cases or the conceptual neighborhoods could be exploited for a coarse reasoning approach. These techniques are discussed in detail in Freksa [1992].

4.2 Higher Resolution Reasoning

The reasoning procedure presented in the foregoing section was based on the left/right dichotomy and a single front/back dichotomy for each oriented entity. In this section, we will illustrate how the inferences can be refined by making use of the second front/back dichotomy introduced in section 2.3. This dichotomy corresponds to splitting up rows 4 to 6 of the composition table into three sub-rows each and columns 4 to 6 into three sub-columns each. At the intersection of these rows and columns (marked in Figure 7) we now can make more precise inferences, i.e, we can restrict the range of possible orientations (or locations) of *d* wrt. ***ab***. The result is depicted in Figure 8.

Inferences also can be refined by processing evidence from multiple sources with the same composition table and combining the results. For example, from *c right-front (1)* ***ab*** and *d left-back (5)* ***cb*** follows *d right (1, 2, 3)* ***ab***. From *c' right-front (1)* ***ba*** and *d left-front (7)* ***bc'*** follows *d front (7, 0, 1)* ***ba***. If both descriptions of *d* hold, their conjunction also holds; thus *d left-front* ***ba***. The inference chain is depicted in Figure 9.

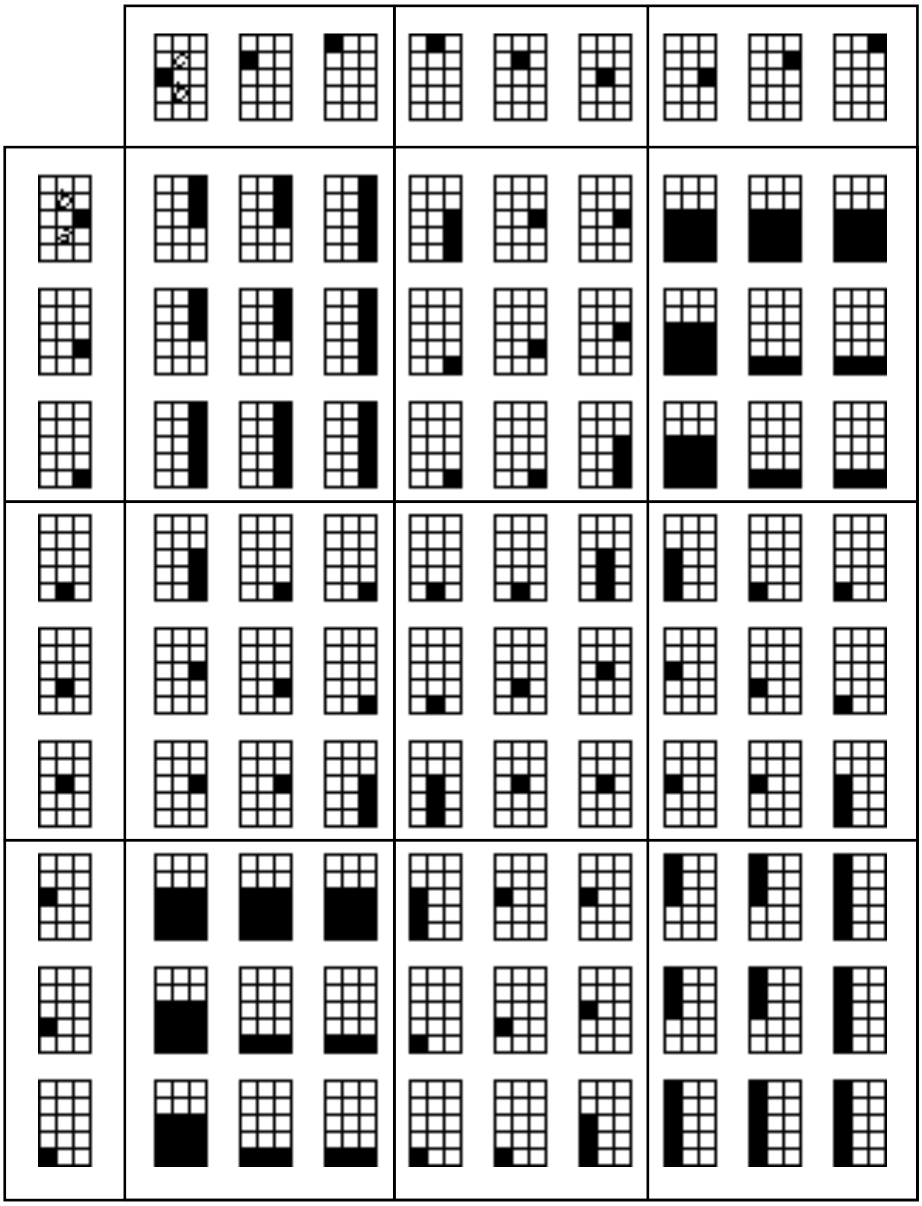


Fig. 8. Fine grain composition table for the marked region in Figure 7.

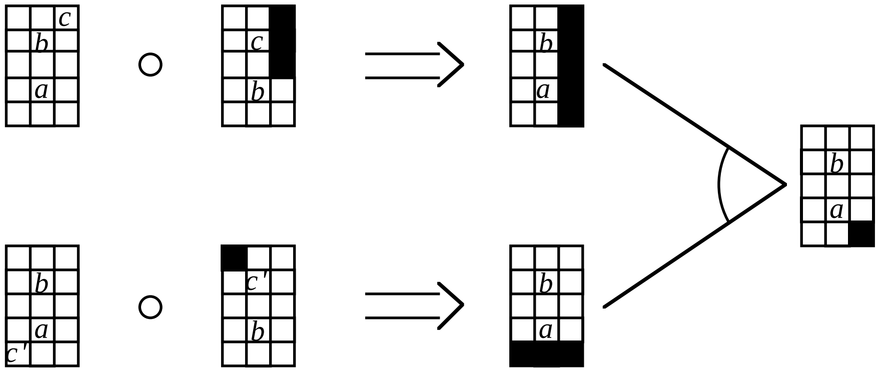


Fig. 9. Refining an inference through multiple evidence.

4.3 Applications

A simple example for an application of orientation-based qualitative spatial reasoning is the process of determining a location in space on the basis of our own location and another location we know. Suppose, we walk from start location *a* to location *c* and we have reached the intermediate location *b*. We can describe orientation and distance of location *c* qualitatively with reference to vector ***ab***, i.e, we compare the road segment ***bc*** to the road segment ***ab*** with respect to their orientation. At position *c*, we can compare the next road segment ***cd*** with the previous stretch, the section ***bc***. The inference step then determines the goal location *d* with respect to the initial road segment ***ab***.

Such an inference can be relevant for a wayfinding process. Suppose, we have a route description from a known location to an as yet unknown place in terms of orientation information (left, straight, right; forward, neutral, backward). We would like to determine the location of the unknown place and the direct route to this place. The described approach can perform this task in qualitative terms, i.e., it can specify a region in which the place can be found.

Suppose, we have two different route descriptions – for example our own description and that of another person. The approach allows us to determine if both routes may lead to the same place; this is the case when the regions described by the inference have a non-empty intersection. Conversely, if we know that both routes in fact lead to the same place, it may be possible to derive a more precise description of the location of this place.

5 Discussion

The approach outlined in this paper is motivated by considerations about spatial knowledge of cognitive systems. More specifically, it is based on the insight that spatial knowledge of natural cognitive systems tends to be qualitative rather than quantitative in nature. The qualitative approach is particularly useful for identification tasks, e.g. for object location tasks, which represent a large fraction of cognitive activity. Furthermore, directional orientation is easily available through perception processes and appears to play an important role for cognitive systems, as the more general meaning of *orientation* suggests. Thus, the presented method applies the qualitative reasoning approach to orientation knowledge.

The present paper only discusses the basic approach. The neighborhood-based approach also is suitable for coarse reasoning, another important ability of cognitive systems. Coarse reasoning allows for drawing inferences under uncertainty and does not require the evaluation of disjunctions, provided that the uncertainty range is a conceptual neighborhood of alternatives (compare Freksa [1992]). The approach can easily be extended to allow for a certain kind of fuzzy reasoning: for an identification task, we may have a description which may or may not apply in the strict sense; when we can not identify the described object by means of the strict interpretation, the neighborhood structure provides information for relaxing the interpretation in an appropriate way. Neighborhood-based reasoning also has computational advantages, specifically for processing perception-based knowledge. For the case of orientation-based reasoning, however, specific analyses have not yet been carried out.

We have discussed in this paper only one of a set of possible spatial inferences one might want to draw: from $c\ R_1$ ***ab*** and $d\ R_2$ ***bc*** we inferred $d\ R_3$ ***ab.*** This inference pattern requires a particular sequence of input relations for reasoning through a chain of inference steps. For certain applications, the input knowledge and/or the desired inference may require a different inference pattern. For example, we may want to infer $d\ R_4$ ***ac***, $b\ R_5$ ***ac***, $b\ R_6$ ***ad***, etc. instead. Such inferences require new composition tables which share important properties with the one discussed here. Other variations are conceivable and should be explored.

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