Towards Collective Spatial Awareness Using Binary Relations

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Abstract

In this paper, we present an architecture for recognizing spatial relationships between real-world objects with integrated computing capabilities. The aim is to develop mechanisms for providing collectives of such artifacts with an awareness about spatial relations to other artifacts of the same collective. Therefore, an approach for recognizing binary relationships by a pairwise comparison of the spatial contexts of artifacts, as well as a novel algorithm which takes advantage of the relation properties in order to make all artifacts of the collective spatially-aware, are presented. The scope is on orientation- and distance-relationships, which are represented in a qualitative way. A general focus of this work is on the efficiency of the solutions with regard to their application in embedded systems. We expect the presented approach to be valuable for the interaction among artifacts and humans, as well as for acquiring high-level context information about artifact collectives.

1. Introduction

Nowadays, we are confronted with a huge, increasing number of real-world objects with integrated computing capabilities. This development is driven by technological advances, which already allow to shrink sensors and actuators as well as processing and wireless communication technologies to a size that enables their integration not only into everyday objects like cars, mobile phones and household appliances, but also into watches, spectacles and even clothes. In the following, we will use the term *artifact* for such technology-enhanced physical objects.

With virtually ubiquitous computing capabilities, novel applications and ways to interact with computers are emerging. A research field tackling related challenges is *Ubiquitous Computing*, whose scope is the fusion of computing capabilities with the environment such that the technology disappears. A crucial contributor to this field is the consideration of *context* [1] [2], namely information about the state and surroundings of persons, places or objects.

As real-world artifacts are by nature distributed throughout physical space, *spatial relationships* are promising context information for developing new means of *interaction* among artifacts and humans, as well as for inferring *high-level contexts*. Of special interest are *positional relations*, determining orientation and distance in relation to other artifacts or the environment. In this work, we use the term *spatially-aware* for artifacts that are able to acquire and use spatial orientation- and distance-relationships.

We are especially interested in providing *collectives of artifacts* (i.e. artifacts that are working together) with an awareness about spatial relationships to other artifacts of the collective, to which we refer to as *collective spatial awareness*. It opens up many potential fields of application, as spatial relationships are significant for many applications. Especially *spatial orientation* is of relevance, as it is an important property of real-world objects that is available through perception processes or natural language descriptions [3], and enhances the representation of static states and motions in physical space [4]. For the sake of simplicity, in this paper we consider all artifacts that are connected directly or via other artifacts to be members of the same collective.

A promising field is *car-to-car communication*, where such an awareness would allow cars for example to send messages to all cars *in front* which are *not near* and go in the *same direction*, be it for safety applications or for traffic flow improvements by notifying about dangerous driving situations like skidding or observed congestions. Another field of application that shows the significance of spatial relationships is *human-computer-interaction*, where orientation- and distance-relationships can be used for achieving more *implicit interaction*, for instance by taking advantage of where the user currently *looks*, or which one the *nearest* display on his *right-hand side* is. Spatial relationships are particularly important for *tangible user interfaces* [5], where interaction takes place by modifying physical objects in the real world.

Our main concern is on the recognition of spatial relationships and their representation. We decided to use qualitative spatial models for our work due to their advantages [6] compared with high-precision quantitative ones. A related field of research that deals with qualitative spatial relationships is *Qualitative Spatial Representation and Reasoning* [7] [8], which is concerned with abstractions of continuous spatial properties of the physical world including different aspects of space like distance, relative orientation and shape on the one hand, and with inferring knowledge from given spatial relationships on the other hand.

The long-run objective of our work is the utilization of qualitative spatial relations for *self-organizing systems*, which have recently received much attention in the research community [9] [10] [11]. A characteristic of self-organizing systems is that they do not have a central coordinator, and complex collective behavior emerges from *contextual local interactions* between components by the help of *local rules and observations*. We consider spatial relationships to be highly valuable contextual information for self-organizing systems, as most of the known phenomena of self-organization and -adaptation in nature are phenomena of self-organization in space [12].

This paper presents concepts towards making artifacts aware about their spatial relationships among each other. First, Section 2 emphasizes the scope of our work on spatial awareness, and presents a general architecture therefore. Afterwards, Section 3 discusses the recognition of spatial relationships from sensor data in short, and a novel approach for distributing relationship information among a collective of artifacts is presented in Section 4. The paper concludes with an overview about related work and an outlook on future challenges in the sections 5 and 6, respectively.

2. Towards Spatial Awareness

2.1. Research Scope

The *spatial awareness of artifacts* comprises several areas of research. We are primarily concerned with qualitative spatial orientation- and distance-relationships between artifacts on the one hand – size, shape and topology are not considered, and their utilization for providing spatial services on the other hand. Thus, each artifact compares quantitative spatial data from its own sensors with those from surrounding artifacts, and recognizes qualitative spatial relationships to other artifacts therewith. In this regard, we consider *binary* and *egocentric* [13] relations only, which means that the spatial relations are represented with respect to the perspective of the artifact which recognizes them. Consequently, all artifacts only consider relations *to* others, and *not between* them, which allows for lightweight implementations in embedded systems.

We narrow down the scope of our work as follows:

- Focus on *orientation- and distance-relationships*
- Consideration of *egocentric binary relations* only
- Abstraction of spatial relationships through *qualitative representations*
- Restriction to *local interaction* without any kind of centralized instance
- *Distribution of relationship information* among a collective of artifacts
- Development of a *lightweight* and *extensible* architecture for providing spatial services

2.2. General Architecture and Contributions

Figure 1 shows our software architecture for providing *spatial awareness* to artifacts. For acquiring spatial relationship information, the artifact requires its own spatial context as well as the contexts of surrounding artifacts. With the term *spatial context* we refer to quantitative information about the spatial situation of an artifact.

Each artifact is equipped with sensors therefore, for example with a GPS receiver and a digital compass for acquiring position and orientation with respect to the earth reference frame, respectively. The *sensing module* transforms sensor data to *standardized spatial information* about the artifact, which makes it independent of sensor technologies.

In order to make artifacts aware of the spatial contexts of surrounding ones, the *communication module* is concerned with exchanging this spatial information via so-called *self-descriptions* with those of artifacts within range. This means, that each artifact collects its own spatial context only, and gets aware about the others through an exchange of self-descriptions – the spatial contexts of surrounding artifacts are thus not acquired directly with local sensors.

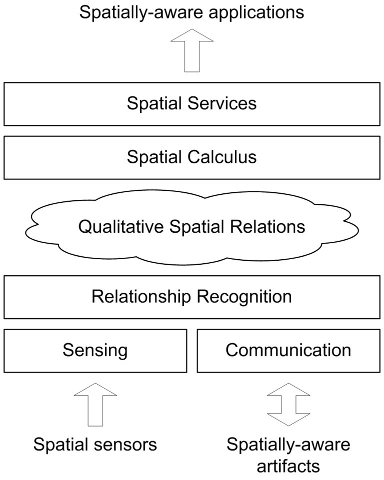

Figure 1. General architecture.

The core of the architecture is the *relationship recognition module*, which performs a pairwise comparison of the local self-description with the received one in order to recognize spatial relations to surrounding artifacts. Separately for each received self-description, locally stored *relation functions*, which are defined on quantitative spatial data contained in the self-descriptions, determine when a certain spatial relationship between two artifacts exists. This however can only be determined if the two self-descriptions contain the required sensor data.

In addition to quantitative spatial data as described above, self-descriptions may also contain qualitative relationships that are already known by the respective artifact. For example, if artifact a is aware that artifact b is on its left-hand side, then this relation is contained in the self-description of a. By taking advantage of the properties of relations, additional relations can be inferred without requiring quantitative sensor data. It enables artifacts to be aware of relations they cannot recognize directly by comparing sensor data of self-descriptions, for example due to missing data or because of the fact that the respective artifacts are out of communication range. Both ways of acquiring relations are explained in detail in the sections 3 and 4.

Each artifact stores known relationships in a database called *relations repository*, and a *spatial calculus* defines operations on the relations. Examples are the logical composition operators *and*, *or* and *not*, which allow to apply the set operations intersection, union and complement [14], respectively.

At the top of the architecture, *spatial services* are provided to *spatially-aware applications*. An example is a communication service for exchanging messages with artifacts to which a certain spatial relationship exists. The communication between the different levels of the architecture is *based on events*.

However, as the paper contains work at an early stage, there is no implementation of the architecture yet, and the specification of a *spatial calculus* as well as *spatial services* are also subject of future work. The contributions of this paper can be stated as follows:

- A *software architecture* for achieving spatial awareness of artifacts is presented
- Spatial relationships are recognized through a *pairwise comparison of self-descriptions*
- An *algorithm* is discussed which takes advantage of the *properties of spatial relations* for achieving *collective spatial awareness*

3. Spatial Relationship Recognition

3.1. Acquiring Spatial Contexts

At the lowest layer of the architecture, a sensing and a communication module are concerned with acquiring spatial contexts from local sensors and exchanging them with surrounding artifacts. The sensing module therefore transforms and combines sensor readings in order to get spatial context information that is conform to the specification of self-descriptions. A *self-description* is an XML-based document that contains standardized quantitative data about the spatial context of an artifact, together with information about known relationships to others. By comparing their own with received self-descriptions, artifacts are able to acquire spatial relationships to others.

Self-descriptions thus build up a *standardized interface* for exchanging spatial information, and they contain the following information:

- A *header* with an *identification* of the artifact as well as a *process-number*
- *Quantitative spatial data* from local sensors
- *Qualitative spatial relationships* to artifacts

It can be seen, that an artifact communicates two kinds of spatial data. First, the *quantitative spatial data* is used for recognizing relations to others within range by comparing sensor data of the two self-descriptions. Second, the *qualitative spatial relationships* are relationships the broadcasting artifact is aware of, which are given by *qualitative relation names* identifying the relations and *tuples of artifacts* between the respective relations exist. This information enables artifacts to infer additional relationships to others by taking advantage of the three relation properties *reflexivity*, *symmetry* and *transitivity*. The *process-number* contained in the header identifies a *relationship distribution process*, which is the process of inferring and distributing certain relations in order to make all artifacts of a collective spatially aware with respect to the relations defined in the self-description.

3.2. Recognizing Spatial Relationships

As mentioned in Section 2.2, the recognition of relationships is based on a *pairwise comparison* of self-descriptions, or – more precisely – on the quantitative sensor data contained therein. Detected relations between artifacts are stored locally in the relations repository, together with the respective process-number of the received self-description.

If an artifact receives a self-description of another one, it first generates its own with actual sensor data. Afterwards, it performs a recognition of all those relations to surrounding artifacts, which are contained in the received self-description. A relation is defined by the following information, which must be available at all artifacts:

- *Qualitative name*: expresses the semantics of a relation (e.g. $Left$)
- *Computational procedure*: is defined on quantitative data of the self-descriptions and returns true if the relation is fulfilled, false otherwise
- *Relation properties*: declare which of the properties of an equivalence relation – i.e. reflexive, symmetric and transitive – are fulfilled

4. Spatial Relationship Distribution

4.1. Binary Spatial Relations

The *distribution* of relationship information, namely the inference of additional relationships and their exchange among artifacts, depends on the properties of binary relations. A *binary relation* is an association of elements between two sets. We just consider spatial relations over a single set of artifacts A, in which each artifact $x \in A$ is associated with another artifact $y \in A$ to which an orientation- and distance-relation R exists; in this case, it holds that $(x, y) \in R$. Such a relation is often denoted as $R(x, y)$, and it is read as "x is in relation R to y".

Binary relations R over a set A can have the following *relation properties* P:

- *Reflexivity*: $\forall x \in A : (x, x) \in R$
- *Symmetry*: $\forall x, y \in A : (x, y) \in R \Rightarrow (y, x) \in R$
- *Transitivity*: $\forall x, y, z \in A : (x, y) \in R \wedge (y, z) \in R \Rightarrow (x, z) \in R$

Table 1. Spatial relations and their properties.

Spatial Relation	reflexive	symmetric	transitive
$Front$			x
$Back$			x
$Left$			x
$Right$			x
$Above$			x
$Below$			x
$Near$	x	x	
Far		x	

Table 1 shows a selection of spatial orientation- and distance-relations taken from [15], together with their properties. For example, the relation $Left$ is transitive, as an artifact x, that is left of y, is also left of z only if y is left of z, but it is neither symmetric nor reflexive. On the other hand, the relation $Near$ is both symmetric (if x is near y, then y is also near x) and reflexive (as x is inherently near to itself), but not transitive.

The relations given in table 1 are *extrinsic relations*, i.e. referring to an external reference system like the earth or a building. *Intrinsic relations* on the other hand refer to inherent properties of artifacts, which are defined by their physical shape or the placement of sensors. A distinction between different frames of reference can be found in [16].

The relation properties for these two frames of reference may be different. For example, an artifact x may be in relation $Front$ to y by using a magnetic compass, but independent of the artifact's orientation in space. In this extrinsic case, the fixed earth reference frame is used. On the other hand, if the intrinsic front of artifact x is of interest – for example to detect if another artifact is in focus of a camera, which is mounted on x and defines its axis of orientation – the relation $Front$ is no longer transitive, as it depends on each artifact's spatial orientation.

4.2. Processing Closures of Binary Relations

An algorithm for achieving *collective spatial awareness* – i.e. an awareness of all artifacts of a collective about certain spatial relations – is presented in the following. The core idea is that each artifact of the collective not only recognizes relations by a comparison of quantitative data, but additionally utilizes the *relation properties* for inferring additional relationships as described below. To state more precisely, the *closure* with respect to each property P is processed iteratively for every relation R over a collective of artifacts A. Thereby, each artifact exchanges self-descriptions (containing quantitative spatial data and qualitative spatial relations) *locally* with artifacts within communication range only, and not by routing them via multiple hops through the artifact collective.

Three different *closures* are distinguished with regard to the relation properties presented in section 4.1:

- *Reflexive closure*: $r(R) = R \cup \Delta$ with $\Delta = \{(x, x) | x \in A\}$
- *Symmetric closure*: $s(R) = R \cup R^{-1}$ with $R^{-1} = \{(y, x) | (x, y) \in R\}$
- *Transitive closure*: $t(R) = \bigcup_{i \in \mathbb{N}} R^i$ with $R^i = R^{i-1} \circ R$ for all $i \in \mathbb{N}$ and $R \circ S = \{(x, z) | \exists y \in A : (x, y) \in R \wedge (y, z) \in S\}$

Thus, each artifact x infers additional relations as defined by the respective closure. To find the *reflexive closure*, x infers the relation $(x, x) \in R$. For the *symmetric closure*, x infers $(x, y) \in R$ for every known relation $(y, x) \in R$. In case of the *transitive closure*, artifact x infers the relation $(z, x) \in R$ if it is already aware about $(y, x) \in R$ and learns about the qualitative relationship $(z, y) \in R$ through a received self-description of artifact y. Each artifact eventually adds newly inferred relations to its relations repository.

4.3. Distributing Relationship Information

In the following, the *distribution process* for obtaining the closures is explained in detail. It starts with an artifact $x \in A$ by *broadcasting* its self-description SD_x to others within range. SD_x contains a unique process-number pn and qualitative relation names $rel_1 \dots rel_n$ identifying the relations for which the closures should be processed.

Each receiving artifact $y \in A$ first generates its own self-description SD_y with actual spatial data from local sensors, the process-number pn and qualitative relation names contained in SD_x, as well as the respective artifact tuples y already became aware of during the distribution process pn. Artifact y then recognizes its relations $rel_1 \dots rel_n$ to x. The recognition is achieved by a quantitative comparison of their self-descriptions SD_y and SD_x, which is performed only once per broadcasting artifact and distribution process pn. Artifact y then infers additional relationships by taking advantage of their properties as described above.

Independently for each relation rel, the local repository of each artifact y that received SD_x is updated with the set R of artifact tuples (x, y) between which rel exists. This means, that new tuples contained in R are added to the repository, which are associated with the respective relation name rel and the process-number pn.

Each artifact y then broadcast its own self-description SD_y with the same relation names $rel_1 \dots rel_n$ as contained in SD_x, together with the distribution process number pn and all artifact tuples it became aware of during pn. However, y broadcasts SD_y if and only if pn is new (i.e. no self-description formerly received by y had the same process number) or if the repository changed (i.e. new tuples were added). If none of the artifacts of the collective A recognized or inferred further relations, the distribution process terminates.

Algorithm 1 shows the operations an artifact y performs upon receiving the self-description of artifact x.

Algorithm 1 self-description-received(SD_x)

```
$SD_y \leftarrow$ generate-self-description($SD_x$);
$pn \leftarrow$ process-number contained in $SD_x$;
for all relations $rel \in SD_x$ do
    if $SD_x$ received first during process $pn$ then
        $R \leftarrow$ recognize($rel$, $SD_y$, $SD_x$);
    end if
    $P \leftarrow$ relation-properties($rel$);
    for all properties $prop \in P$ do
        $R \leftarrow R \cup$ infer($rel$, $prop$, $SD_y$, $SD_x$);
    end for
    if $R \neq \emptyset$ then
        $changed_{rep} \leftarrow$ add-repository($R$, $rel$, $pn$);
    end if
end for
$new_{pn} \leftarrow$ check if $SD_x$ contains new $pn$;
if $new_{pn}$ or $changed_{rep}$ then
    $SD_y \leftarrow$ update-relationships($SD_y$);
    broadcast($SD_y$);
end if
```

4.4. Discussion

The Figures 2 and 3 demonstrate how the algorithm works, exemplary for the transitive relation $Left$ as well as the reflexive and symmetric relation $Near$. The vertices of the graphs represent a collective of five wirelessly communicating artifacts $a \dots e$ that are placed in *two-dimensional Euclidean space*, and edges between vertices indicate that the respective artifacts are within communication range. Broadcasts of self-descriptions are illustrated with dotted arrows from one vertex to another one, and the relations stated besides the vertices show the current spatial awareness of the respective artifact at a certain iteration of the distribution process.

In this example, the relations $Left$ and $Near$ are defined as follows, where d is a certain distance representing $Near$, and $x_i, y_i \in \mathbb{R}$ indicate the position of artifact $i \in A$ in two-dimensional Euclidean space:

- $(a,b) \in Left \Leftrightarrow x_a < x_b$
- $(a,b) \in Near \Leftrightarrow (x_a - x_b)^2 + (y_a - y_b)^2 < d^2$

In Figure 2, artifact d first broadcasts its self-description SD_d, which contains a unique process-number as well as the relation name $Left$. The artifacts c and e receive SD_d, and independently process the algorithm presented in section 4.3. While artifact e *recognizes* artifact d to be on the left hand side, artifact c does not recognize any relationship. Both artifacts c and e then broadcast their own self-description (as SD_d contained a *new* process-number), whereby SD_e already contains the newly recognized relationship $Left(d,e)$.

In step (4) of Figure 2, artifact d *infers* the two additional relationships $Left(a,d)$ and $Left(b,d)$, as $Left$ is *transitive* and therefore it holds that $Left(a,c) \wedge Left(c,d) \Rightarrow Left(a,d)$ and $Left(b,c) \wedge Left(c,d) \Rightarrow Left(b,d)$. Due to the *changed* relations repository of artifact d, it again broadcasts its self-description. This in turn also makes artifact e aware about its relations to a, b and c.

Figure 3 shows a similar picture for the relation $Near$. However, due to different relation properties, the inference of relationships is different. This can be seen in step (1) of the distribution process, where artifact c first recognizes $Near(d,c)$ and then infers the relations $Near(c,d)$ due to the *symmetry* of the relation $Near$, and $Near(c,c)$ due to its *reflexivity*.

In both cases, the result is a *collective of artifacts*, where every one is aware about its $Left$- or $Near$-relations to the other artifacts of the collective. From a mathematical viewpoint, the *transitive closure* of the relation $Left$ as well as the *reflexive closure* and the *symmetric closure* of the relation $Near$ have been determined.

5. Related Projects

The presented work on spatial relations touches several fields and projects. The issue of representing and reasoning about qualitative spatial information is addressed by the interdisciplinary research center *Spatial Cognition: Reasoning, Action, Interaction*[1], which deals with knowledge about spatial environments and currently spans several projects ranging from the investigation of human spatial cognition to mobile robot navigation. Many publications have been produced in the field of qualitative spatial representation and reasoning, which deal with spatial calculi [14], representing spatial knowledge for human-robot interaction [17] and developing linguistic and spatial ontologies [15] [18].

A project that deals specifically with positional relationships is the project *RELATE*[2], which addresses the measurement of such relationships between mobile objects and algorithms for distributed localization in sensor networks, among others. A software framework and an ultrasonic sensing system are presented in [19] [20], and applications can be found in [21] and [22].

Although much work on similar topics can be found in literature, there is no publication about recognizing binary and egocentric spatial relations by a pairwise comparison of the spatial contexts of artifacts as presented in Section 3. Furthermore, the approach of taking advantage of relation properties for inferring additional relationships between artifacts and distributing them in order to achieve a collective spatial awareness as described in Section 4, is – to the best of our knowledge – also new.

6. Conclusions and Outlook

In this paper, we presented a novel approach and a software architecture for achieving spatial awareness of artifact collectives. It is based on a pairwise comparison of their self-descriptions, which contain quantitative spatial data for recognizing binary and egocentric spatial relations, as well as qualitative relationship information that allows for inferring additional relationships by taking advantage of their properties. An algorithm for making all artifacts of a collective spatially-aware was discussed, where our focus is on orientation- and distance- relationships; however, the presented concepts are not restricted to spatial context information, but can be used for arbitrary binary relations. We consider our work very promising for developing new ways of local contextual interaction between artifacts, and eventually for their application to self-organizing systems.

There is plenty of future work, first of all the refinement and implementation of the architecture as well as a practical evaluation of the relationship distribution algorithm presented in Section 4. Services for spatially-aware interaction are planned to be developed, which will build up a basis for self-organizing behavior. The general idea is to utilize spatial relationships e.g. for selecting groups of artifacts to and from which messages should be sent and received, respectively. Further lines of work are to extend the presented concepts with a notion of *time* for representing and reasoning about trajectories of spatial relations, and to

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1. http://www.sfbtr8.uni-bremen.de

2. http://ubicomp.lancs.ac.uk/index.php/home

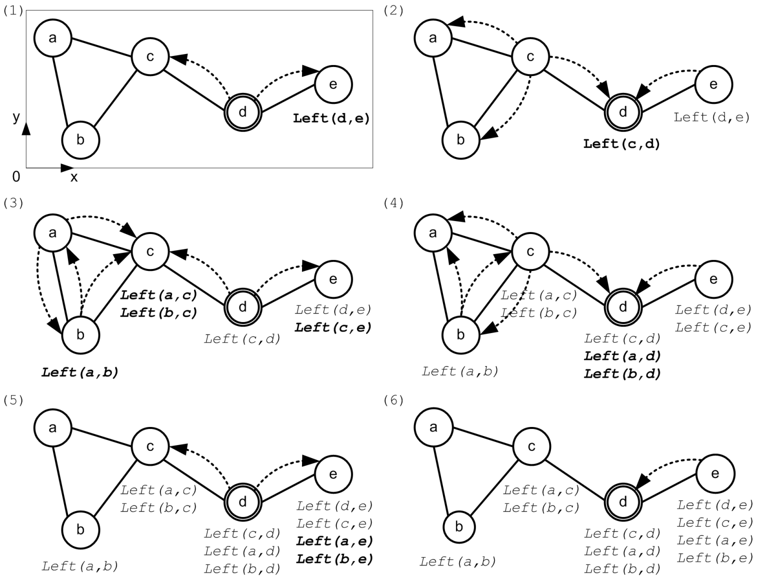

Figure 2. Distribution process for the transitive relation $Left$.

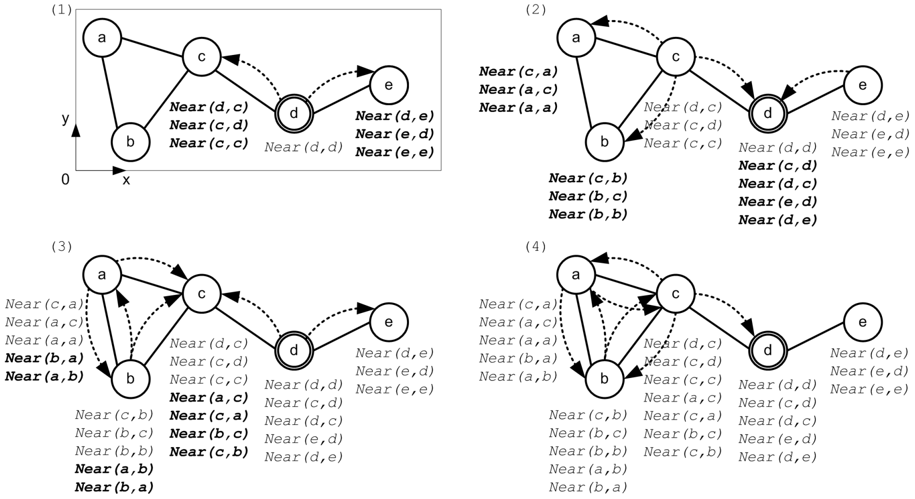

Figure 3. Distribution process for the symmetric and reflexive relation $Near$.

infer additional relationships by taking advantage of operations like *inverse* and *successor* that are defined on binary spatial relations.

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