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Abstract: This paper is concerned with representing spatial structures in object-based knowledge representation systems (OKR systems). Spatial structures are defined as sets of objects related with qualitative spatial relations. We focus on topological relations from the RCC-8 theory, their recognition on raster images, and their reification in an OKR system. Spatial structures and relations have been implemented and used in a knowledge-based system for satellite image interpretation.

Keywords: topological relations, lattice of relations, object-based knowledge representation, relation reification, satellite image interpretation.

Introduction

Our work focuses on representing and classifying spatial relations and structures in order to analyze and interpret satellite images. We work on the design of a knowledge-based system aimed at helping agronomists to recognize and classify landscape spatial structures. This system should contain: the models of the structures to be recognized; the models of the elements (objects, relations, quantifiers) of which the spatial structures are made; a method to match images and models, i.e. a classification method. According to these needs, we have chosen to use an object-based knowledge representation system (or OKR system), which allows both programming and knowledge representation and which includes a classification mechanism [Napoli *et al.*, 1994]. We have extended the representation capabilities of the OKR system in order to represent spatial relations as "first-class citizen", i.e. objects with their own properties. In our proposition, relations are represented by classes having attributes and facets; they are organized within a hierarchy. The classification mechanism in the OKR system has been modified accordingly to take reified relations into account.

The paper is organized as follows. We first present the spatial relations we have used, then the OKR system. The third part is about relation representation and the fourth about the representation of spatial structures. The fifth part is a conclusion.

1 Spatial relations

Our approach is based on the RCC-8 theory [Randell *et al.*, 1992]. The relations are computed on the images thanks to point set operations as it is done in [Egenhofer, 1989; Egenhofer and Sharma, 1993]. We consider four operations between two objects x and y (an object x is made of two sets, the interior, x°, and the boundary, ∂x): intersection of the interiors, $x^\circ \cap y^\circ$, intersection of the boundaries, $\partial x \cap \partial y$, differences of the interiors, $x^\circ - y^\circ$, $y^\circ - x^\circ$. The result of these operations is considered to be empty or not empty. We have defined accordingly eight conditions whose conjunctions are equivalent to the eight relations of the RCC-8 theory. Then, computing a relation on the image is the same operation as verifying a set of conditions (see Fig. 1). For instance, the relation "x is externally connected with y", $EC(x, y)$, is associated to the following set of conditions:

$$\mathcal{C}(EC) = \{x^\circ \cap y^\circ = \emptyset, \partial x \cap \partial y \neq \emptyset\}$$

We have chosen these operations rather than those of Egenhofer (i.e. $x^\circ \cap y^\circ$, $\partial x \cap \partial y$, $x^\circ \cap \partial y$, $\partial x \cap y^\circ$) because we have defined the boundary

$$
\begin{array}{rc}
EQ(x,y): & \{x^\circ - y^\circ = \emptyset,\ y^\circ - x^\circ = \emptyset\} \\
NTPP(x,y): & \{x^\circ - y^\circ = \emptyset, y^\circ - x^\circ \neq \emptyset, \partial x \cap \partial y = \emptyset\} \\
TPP(x,y): & \{x^\circ - y^\circ = \emptyset,\ y^\circ - x^\circ \neq \emptyset, \partial x \cap \partial y \neq \emptyset\} \\
NTPP^{-1}(x,y): & \{y^\circ - x^\circ = \emptyset, x^\circ - y^\circ \neq \emptyset, \partial x \cap \partial y = \emptyset\} \\
TPP^{-1}(x,y): & \{y^\circ - x^\circ = \emptyset, x^\circ - y^\circ \neq \emptyset, \partial x \cap \partial y \neq \emptyset\} \\
PO(x,y): & \{x^\circ \cap y^\circ \neq \emptyset, x^\circ - y^\circ \neq \emptyset, y^\circ - x^\circ \neq \emptyset\} \\
EC(x,y): & \{x^\circ \cap y^\circ = \emptyset, \partial x \cap \partial y \neq \emptyset\} \\
DC(x,y): & \{x^\circ \cap y^\circ = \emptyset, \partial x \cap \partial y = \emptyset\}
\end{array}
$$

Figure 1: Computing the RCC-8 relations: each relation is associated to a set of conditions.

of a image region in a specific way: we consider "abstract pixels" which have the same surface as "real pixels" but which cross four real pixels; thus, two meeting regions ($EC(x,y)$) have the same boundary.

Moreover, the eight conditions correspond to eight so-called *primitive relations* that are:
$P(x,y)$, "x is a part of y": $x^\circ - y^\circ = \emptyset$
$P^{-1}(x,y)$, "x contains y": $y^\circ - x^\circ = \emptyset$
$Dx(x,y)$, "x is not a part of y": $x^\circ - y^\circ \neq \emptyset$
$Dy(x,y)$, "x does not contain y": $y^\circ - x^\circ \neq \emptyset$
$O(x,y)$, "x overlaps y": $x^\circ \cap y^\circ \neq \emptyset$
$DR(x,y)$, "x is discrete from y": $x^\circ \cap y^\circ = \emptyset$
$A(x,y)$, "x shares a boundary with y": $\partial x \cap \partial y \neq \emptyset$
$NA(x,y)$, "x does not share any boundary with y": $\partial x \cap \partial y = \emptyset$

Many other topological relations are useful to describe spatial structures, as for instance "x is a proper part of y ', $PP(x,y)$. This relation is a generalization of "x is a tangential proper part of y" and "x is a non tangential proper part of y". Finally, according to our classification purpose, we have defined a set of relations organized in a lattice structure (Fig. 2) that is built according to the Galois correspondence [Davey and Priestley, 1990] between the base relations of the RCC-8 theory and the eight conditions. Each element $\mathtt{E}$ of the lattice expresses a spatial relation R which is a disjunction of RCC-8 base relations; $\mathtt{E}$ is also associated to a set of conditions whose conjunction is equivalent to R. The partial ordering in the lattice is equivalent to the logical implication on the relations and is defined as follows:

$$(\mathtt{E}_1 \sqsubseteq \mathtt{E}_2) \equiv (\forall(x,y), R_1(x,y) \rightarrow R_2(x,y))$$

This lattice structure provides interesting properties for reasoning purpose. Any two of the elements of the lattice have a greatest lower bound (*glb*, denoted $\frown$), and a least upper bound (*lub*, denoted $\smile$). The *glb* of two elements is equivalent to the conjunction of these two elements. By contrast, this equivalence is not true for the *lub*, and the disjunction of two elements only implicates the *lub* of the two elements [Mangelinck, 1998]. Considering for instance the $TP(x,y)$ and $TP^{-1}(x,y)$ relations (which are expressed by $\mathtt{TP}$ and $\mathtt{TP}^{-1}$ on the left of the lattice, Fig. 2) we obtain:
$\mathtt{TP} \frown \mathtt{TP}^{-1} = \mathtt{EQ}$ and $\mathtt{TP} \smile \mathtt{TP}^{-1} = \mathtt{OetA}$
$\forall(x,y),\ EQ(x,y) \leftrightarrow TP(x,y) \wedge TP^{-1}(x,y)$
$\forall(x,y),\ TP(x,y) \vee TP^{-1}(x,y) \rightarrow OetA(x,y)$
$\forall(x,y),\ OetA(x,y) \rightarrow$
$TP(x,y) \vee TP^{-1}(x,y) \vee OetAetDy(x,y) \vee OetAetDx(x,y)$

The composition of any two relations can also be deduced from the lattice structure as it is done in [Randell and Cohn, 1992].

2 OKR systems

Up to now there are no completely satisfying reifications of relations in object-based representation systems [Rumbaugh, 1987; MacGregor, 1993], whereas the description logics propose representation formalisms and capabilities with a number of advantages: relations between classes are represented by roles to which are associated contructors introducing restrictions on the role, e.g. range of the role, cardinality, universal and existential quantification. Description logics have already been used to represent spatial reasoning, as in [Haarslev *et al.*, 1998]. Never-

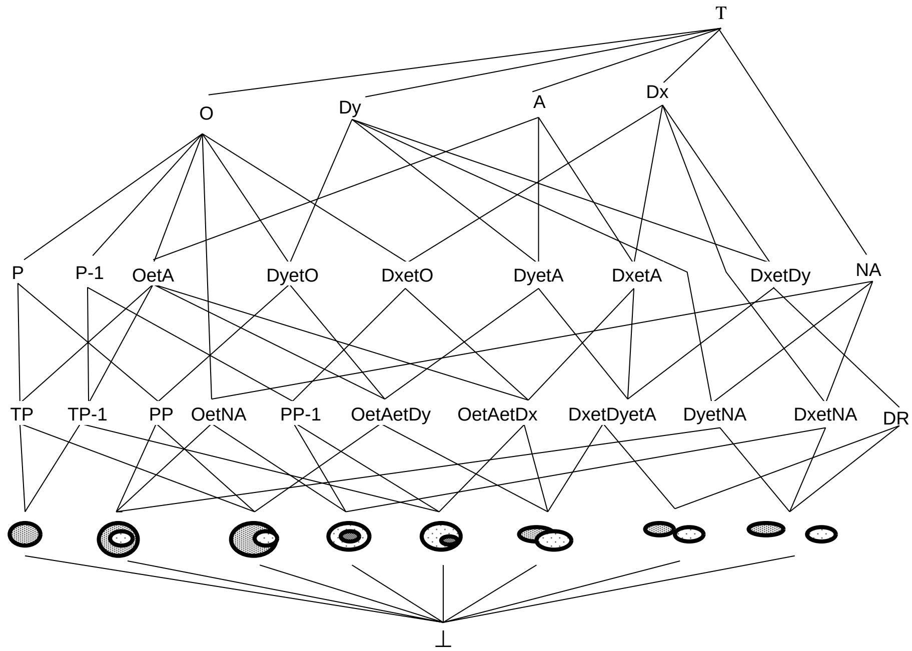

Figure 2: A Galois' lattice of topological relations: the eight relations of the RCC-8 theory are drawn at the bottom of the lattice; the eight primitive relations are at the top of the lattice (P, $\texttt{P}^{-1}$, O, Dy, ...) [Mangelinck, 1998].

theless, we have chosen to use an OKR system rather than description logics because we needed computation methods on the image.

We have used the Y3 system, which is an object-based representation system with a graphical interface, named YAFEN, and a programming language, named YAFOOL [Ducournau, 1991]. YAFOOL is a frame language written in Lisp. All objects (classes and instances) are represented by *frames*; frames are composed of *slots*, representing both attributes and methods. Attributes can be characterized by declarative and procedural *facets*: the former are used to represent the range and the value of the attribute while the latter are used to specify local behaviors. Attributes, facets and methods are objects. Binary relations are special kinds of attributes which are characterized by the fact that their range is a user-defined class. Relations are specializations of the special class `RELATION`. A relation may have an inverse relation and the system is in charge of managing their interrelated values. The classification and inheritance mechanisms are based on attribute unification. When classifying an object into a class, the systems checks whether the (attribute, value) pairs in the object are conform to the pairs in the reference class; if this is the case, the object can be classified as an instance of the reference class.

3 Representing topological relations

We have defined a generic class, named `SPATIAL-RELATION`, which contains the attributes and the methods common to all classes representing topological relations (see Fig. 3). There are three main methods. The `verify-relation` method checks whether a given relation (e.g. EC) exists between two regions of an image. It uses the `search-conditions` method that returns the set of conditions which is associated with the relation (e.g. $\mathcal{C}(EC) = \{x^\circ \cap y^\circ = \emptyset, \partial x \cap \partial y \neq \emptyset\}$). If the `verify-relation` method succeeds (all conditions of $\mathcal{C}(EC)$ are true), it creates an instance of the relation class. If it fails (one of the conditions of $\mathcal{C}(EC)$ is false, e.g. $\partial x \cap \partial y \neq \emptyset$), it searches which relation is associated with the set of conditions it has computed and creates an instance of this relation class (e.g. $\{x^\circ \cap y^\circ = \emptyset, \partial x \cap \partial y = \emptyset\} = \mathcal{C}(DC)$). The method `incompatible` checks whether two relations are compatible ($R_1 \frown R_2 \neq \bot$) or not. Those three methods use the lattice structure of the relation set to find out:

- the set of conditions associated to a relation.
- the relation associated with a set of conditions.
- the greatest lower bound of two relations

The attributes of the class SPATIAL--RELATION mainly describe relations between the relations (see Fig. 3): the value of the negation attribute of a relation R_1 is the relation R_2 which is false whenever R_1 is true (and reciprocally):

$$\forall(x, y), R_1(x, y) \leftrightarrow \neg R_2(x, y)$$

The symmetry attribute of a relation R_1 gives the relation R_2 which is true for (y, x) whenever R_1 is true for (x, y) (and reciprocally):

$$\forall(x, y), R_1(x, y) \leftrightarrow R_2(y, x)$$

The value of the attribute local-condition is the condition which is equivalent to the relation. This value is filled only when the relation is a primitive one.

```
(defclass SPATIAL-RELATION
    (is-a RELATION)
    (negation (a . SPATIAL-RELATION))
    (symmetry (a . SPATIAL-RELATION))
    (incompatible (method (RS)
                    (not (pgcd frame* RS))))
    (specialize (method (RS)
                    (...)))
    (local-condition (a . CONDITION))
    (search-conditions (method () (let ()...)))
    (verify-relation (method (O1 O2)(...)))
```

Figure 3: The SPATIAL-RELATION class coded in Y3.

Every class representing a topological relation is a specialization of the generic class SPATIAL--RELATION and inherits its properties. For instance the classes EC, PP^{-1}, DC, respectively representing the relations $EC(x, y)$, $PP^{-1}(x, y)$, $DC(x, y)$, are subclasses of SPATIAL-RELATION (see Fig. 5).

4 The spatial objects and structures

In our application the spatial objects are the regions of an image. Each region corresponds to a particular land-use category (forest, meadow, corn, barley, village, etc.) or a village territory. The spatial objects are recognized on the image using various methods and indices: labeling (regions have been previously labeled according to the land-use category), surface threshold, Voronoï diagrams... Every model of an object, e.g. crop field, is represented as a class. The recognition method (named recognize) associated with a particular spatial object is attached to the corresponding class (see Fig. 4). Whenever a spatial object is recognized on an image, the corresponding class is instantiated.

```
(defclass LARGE-FIELD
  (is-a FIELD)
  (recognize (method ()
    (subcar (lambda (anobject)
      (if (>= (:: surface-object anobject) 50)
         (put-recognize LARGE-FIELD anobject)
        (put-recognize SMALL-FIELD anobject)))
      (li-recognized FIELD))
   )) )

(defclass SMALL-FIELD
  (is-a FIELD)
  (recognize (method ()
    (recognize LARGE-FIELD)
   )) )
```

Figure 4: Classes of spatial objects coded in Y3: large and small fields are classified according to their surface.

Spatial structures are sets of objects related with qualitative spatial relations. Their models are represented by classes whose attributes are particular relations, instances of the topological relations classes, as illustrated by the examples given in Fig. 5. According to spatial structures and topological relations, classes representing the spatial structures can be specialized in three different ways:

- Adding a relation: for instance, the GROUP class is specialized into GROUP-EC-FOREST or GROUP-DC-FOREST (a *group* is a set of connected fields).
- Specializing a relation: for instance,

the TERRITORY-PP^{-1}-GROUP class can be specialized into TERRITORY-TPP^{-1}-GROUP (*territory* stands for village territory).

- Specializing the range of a relation: for instance, the TERRITORY-PP^{-1}-GROUP class is specialized into TERRITORY-PP^{-1}--GROUP-EC-FOREST.

These various specialization mechanisms must be taken into account within the classification process. Actually, the classification of an instance requires the classification of the objects which are related to it and the classification of the relations that link these objects to it (see Fig. 5). We have accordingly modified the classification mechanism of Y3.

```
(defclass GROUP-EC-FOREST
    (is-a GROUP)
    (g-conn-f (is-a . EC)
              (a . FOREST)))

(defclass GROUP-DC-FOREST
    (is-a GROUP)
    (g-dcn-f (is-a . DC)
             (a . FOREST)))

(defclass TERRITORY-PP-1-GROUP
    (is-a TERRITORY)
    (t-cont-g (is-a . PP-1)
              (a . GROUP)))

(defclass TERRITORY-TPP-1-GROUP
    (is-a TERRITORY-PP-1-GROUP)
    (t-tcont-g (is-a . TPP-1)
               (a . GROUP)))

(defclass TERRITORY-PP-1-GROUP-EC-FOREST
    (is-a TERRITORY-PP-1-GROUP)
    (t-cont-gf (is-a . PP-1)
               (a . GROUP-EC-FOREST))
```

Figure 5: Using topological relations to represent spatial structures. The attributes (e.g. g-conn-f, t-cont-g) are instances of the relations classes (e.g. EC, PP^{-1}).

Conclusion

Our aim is to build an image interpretation system: the image regions are to be classified according to the models of spatial structures. These models are sets of spatial objets related with qualitative spatial relations. Objects, structures and relations have been implemented with an OKR system. The interpretation of an image region is done thanks to a classification algorithm which takes reified relations into account [Mangelinck, 1998]. Finally the system has been implemented and used with satellite images of the Lorraine region (East of France). It takes about five minutes to analyze the image of a village territory (on an Ultra Sparc SUN station). The result of the analysis is a collection of classes of which the territory is an instance. Two territories which are instances of the same classes are supposed to share the same spatial structure. According to these results, the territories of an image are grouped into regions which are mapped and analyzed by the agronomists. Up to now the system has shown interesting results (75% of correct matching, according to the expert analysis).

In the future, improvements have to be made regarding to relation reification: the current state is sufficient for our application but it lacks generality. Considering the application, improvements could be made in two ways: adding indices to characterize spatial objects and adding spatial relations to characterize spatial structures (qualitative distance, extended topology, orientation).

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