A representation of contextual relationships knowledge in images

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Abstract

This report is focused on the study of methods for image retrieval in collection of heterogeneous contents. The spatial relationships between entities in an image allow to create the global description of the image that we call the image context. Taking into account the contextual spatial relationships in the similarity search of images can allow improving the retrieval quality by limiting false alarms. We defined the context of image as the presence of entity categories and their spatial relationships in the image.

By studying statistically the relationships between different entity categories on LabelMe, a symbolic images databases of heterogeneous content, we create a cartography of their spatial relationships that can be integrated in a graph-based model of the contextual relationships, the principal contribution of this report. This graph describes the general knowledge of every entity categories. Spatial reasoning on this knowledge graph can help improving tasks of image processing such as detection and localization of an entity category by using the presence of another one. Further, this model can be applied to represent the context of an image. The similarity search based on context can be achieved by comparing the graphs, then, contextual similarity between two images is evaluated by the similarity between their graphs. This work was evaluated on the symbolic image database of LabelMe. The experiments showed its relevance for image retrieval by context.

Keywords : Image, similarity search, spatial relationships, image context.

1 Introduction

The interpretation of images by a machine requires to have a representation of images preprocessed manually or automatically. This representation can be built from visual features (such as color, shape of elements in images) or higher level information (such as spatial relationships between elements or models of these elements). To date, it is still difficult to build a robust model for automatic image
interpretation. On the contrary, humans prove their effectiveness in image processing tasks. We can say that what makes such humans’ possible aptitudes is their ability to interpret visual features of images by using prior knowledge. Prior knowledge is very often related to the presence of multiple entities in an image and to the spatial information linking them, that can be called the context of the image. Humans can incorporate this knowledge to analyse the image and to create personal semantic concepts. According to [8], image interpretation can be classified into three levels of complexity:

- Level 1: interpretation is based mainly on primary features such as color, texture, shape, segmented regions, interest points and/or the spatial location of image elements. These features are rather objective and their estimation is performed directly, it does not require any knowledge base. Many approaches of image retrieval or of image categorization can be classified into this level (e.g. Bag of Features and all its derived approaches).

- Level 2: interpretation involves some degree of logical inference concerning the image content. At this level, queries are performed in order to retrieve entities of a given type or to retrieve a specific entity from another. The need of a processed knowledge base is obvious. This knowledge base can contain low-level information of entity categories (e.g color, shape), relationships between categories (e.g. correlations, conditional probabilities, spatial relationships), and more.

- Level 3: interpretation is based on symbolic features. At this level, a significant amount of high-level reasoning about the meaning and purpose on the entities or on background of images can be involved. The result of this processing is that an image can be linked to a concept by a subjective judgement. To date, humans are only ones who can propose an effective interpretation of an image at this level.

Most of the approaches proposed lie between levels 1 and 2. It is still difficult to lie between levels 2 and 3 that refer to high-level semantic image retrieval [12]. The main effort is to connect low-level features to high-level semantics of images. The effective approaches to date are:

1. using machine learning methods in order to associate high-level concepts to low-level features,
2. taking into account user feedback in order to improve subjective concepts,
3. inferring visual content based on textual information extracted from image context,
4. using entity ontology in order to define high-level concepts.

Most content-based image retrieval systems exploit a combination of two or more of these methods in order to perform high-level semantic image retrieval (see [24, 8, 18, 27, 6]). Although the results obtained are promising, designing systems that really understand image content at semantic level is still an open problem.

In this paper, we propose a model to represent a general knowledge about relationships such as spatial ones between entity categories existing in an image database. Furthermore, this model can be used to describe the context of a given image. The definition of image context is discussed in the section 2.2. Finally, we observe that an image may be linked to multiple subjective interactions, then, we hope to attribute a semantic meaning to each context image that can facilitate image retrieval or recognition tasks. Our work falls in the third and fourth categories of approaches listed above. In the
limit of our framework, we do not investigate the learning of concepts using machine learning methods and consider that these concepts are known.

In the section 2, we present the definition of image context and several spatial relationships between categories. The section 3 presents the concepts and definitions of our graph model. In the next, we discuss the evolution capacity of the graph to the new knowledge and spatial reasoning in the section 4 and 5. Finally, in the section 6, we present several experiments to evaluate our graph model.

2 Initial definitions

In this section, we present several definitions like spatial relationships and image context before presenting our principal work.

2.1 Spatial relationship

In our framework, we are firstly interested in the representation of spatial relationships between symbolic objects in images, called entities. In CBIR, embedding such information into image content description provides a better representation of the content as well as new scenarios of interrogation. The spatial relationships can be the unary, binary, and ternary relationships.

We call unary relationship, the relationship between an entity and its localization in an image, where localization is defined as a region or an area of the image. Areas of an image can be represented in different ways like quad-tree or quin-tree, see for example [20, 28]. Since we do not have any knowledge a priori of the location of the categories in the images, we propose to split images in a fixed number of regular areas (i.e. equal size areas). First, we divide each image in a fixed sized grid. Each cell of this grid, called atomic area, is represented by a code. Fig. 1 and 2 depict a splitting in 9 or in 16 different basic areas and theirs codes, respectively. We then combine these codes to present more complex areas, by example for 9-area splitting, code 009 represents area (□) grouping together areas 001(□) and 008(□).

<table>
<thead>
<tr>
<th>001</th>
<th>008</th>
<th>064</th>
</tr>
</thead>
<tbody>
<tr>
<td>002</td>
<td>016</td>
<td>128</td>
</tr>
<tr>
<td>004</td>
<td>032</td>
<td>256</td>
</tr>
</tbody>
</table>

**Figure 1** – Codes in unary relationship by splitting an image in nine areas.

<table>
<thead>
<tr>
<th>00001</th>
<th>00016</th>
<th>00256</th>
<th>04096</th>
</tr>
</thead>
<tbody>
<tr>
<td>00002</td>
<td>00032</td>
<td>00512</td>
<td>08192</td>
</tr>
<tr>
<td>00004</td>
<td>00064</td>
<td>01024</td>
<td>16384</td>
</tr>
<tr>
<td>00008</td>
<td>00128</td>
<td>02048</td>
<td>32768</td>
</tr>
</tbody>
</table>

**Figure 2** – Codes in unary relationship by splitting an image in 16 areas.

A binary relationship links two entities of distinct categories together in an image. In last years,
there have been many approaches proposed for representing binary spatial relationships. They can be
classified as topological, directional or distance-based approaches (see [11] for more details), and can
be applied on symbolic objects or low level features. Here, we have focussed on relationships between
the entities of the database described in terms of directional relationships with approach 9DSpa [17],
of topological relationships [9, 10] and of a combination of them with 2D projections [19]. We do not

A ternary relationship describes a relationship of a triplet of categories. To our knowledge, a few
approaches were proposed to describe triangular relationships of three symbolic entities. We can
mention TSR approach [13] and our approach Δ-TSR (see [16]). By applying to a set of heterogeneous
symbolic entities that do not have fixed shape and size, these approaches cannot described fully tri-
angular spatial relationships between symbolic entities since they take into account only the center of
each entity as representation of it.

2.2 Image context

In an image, the recognition or detection of entity category requires different information from the
raw image data. According to [26], in the real world, there exists a strong relationship between the
environments and entities found within it or between the entities. Entities are never in isolation. They
can tend to co-vary with others entities and particular environments for providing a rich collection
of contextual associations. The recognition or detection will be accurate and quick if entities usually
appear in a familiar background. Then, initially, we can define that the context of an image describes
all possible types of relationship between the entities in this image, or between the entities and back-
ground of this image. The use of image context can bring a strong interest not only for recognizing
or detecting the entity category but also for image retrieval. For the recognition or detection of an
entity category, it is evident to examine the general context of image if the local features are insuffi-
cient (e.g. entity is small, or appears partially). For image retrieval, the comparison of image contexts
can help to filter out the false alarms before enter in the step of comparison of visual contents of images.

By using the visual features in image, the context can be described by relationships between local
informations and global information of the image. This context definition can drive to a hard work
of image processing. Another natural way of representing the context of an image is using the co-
ocurrence relationships of its entities. In the real world, the co-occurrence might happen at a global
level, for example a bed room will predict a bed, or at a local level, for example a table will predict
the presence of a chair. A probabilistic problem can be also associated in this case. More complex, the
spatial relationships between entity categories in images can be taken into account. In general, that is
difficult to have an exact definition of context ; each case of use can depend on a particular context
definition.

Here, we try to study different relationship that could be present in images. According to [14],
entities in an image can be THINGS (e.g. car, people) or STUFF (e.g. road, buildings, more precise that
are the regions in images). In general, we can have five types of relationship:
- Thing-Thing: co-concurrent relationships, spatial relationships, etc.
- Stuff-Thing: texture regions that allows to predict the present of an entity category.
- Stuff-Stuff: relationships between regions of images.
- Scene-Thing: scene information such as scale, global direction that allows to determine the location of an entity category.
- Scene-Stuff: scene information such as scale, global direction that allows to determine the location of a region.

In our framework, we do not differentiate the entities present in image as "Thing" or as "Stuff" because we are interested in symbolic objects that are represented by polygons. These entities are classified simply by category. We define the image context by the presence of entity categories in image and by the spatial relationships between these entity categories. The presence of at least an instance of an entity category will confirm the presence of this one. The spatial relationships between categories in image will be represented in a general way (e.g. probabilities). There are two principal ways of using the context in a vision system:

- A priori: in this way, the context serves to locate the entities, to limit the searching region, and to decrease the retrieval time (for example the approaches proposed by [26, 14, 25]).
- A posteriori: the context serves to object recognition if the local information is not sufficient, it can help to reduce the ambiguities of the presents of objects in the same scene (for example the approaches proposed by [23, 22, 5]).

There has been a growing interest in exploiting contextual information for image retrieval, classification or object detection, recognition. Different techniques have been exploited to describe the context of image for this purpose. Intuitively, the spatial locations of objects and background scene from global view can be used as inside-image context. Further, the combination of object detection and classification tasks together can provide natural comprehensive context for each other without any external assistance. Moreover, a knowledge database, considered as a external element, based on machine learning SVM or probabilistic technique, allows to enhance other tasks as localization, detection, etc. Our approach proposed in the next sections is a priori one.

3 A Graph-based Knowledge Representation

In this section, we present how to represent a knowledge between entity categories in images by using a graph. The concepts and definitions of this graph are presented in section 3.1. To avoid building an unreadable graph, the attributes of node and the graph constraints are discussed in section 3.2 and 3.3 respectively. Finally, section 3.4 presents a brief example of the use of the graph.

3.1 Concept and definitions

In reality, events can be expressed by two notions: entity and relationship. For example, if we have an event "our laboratory invited a professor last month", then this event can be represented by two entities: "our laboratory" and "a professor" that have a relationship "invite" of attribute "last month". We know that a general knowledge presents a general event based on concrete events which happened. For example, based on the previous event, a general event could be formed: "Laboratories
invite professors sometimes". "Laboratory" and "Professor" may be considered as entity categories that may be linked by a relationship of type "invite". Based on this argument, we would like to represent the learnt knowledge by using a graph concept developed only on two notions of "category" and of "relationship". In this graph, the instance of category (an entity) is not meaningful to guarantee a general representation of a knowledge. However, entities are always examined before building a graph. The reason was explained previously: a general event is based on particulars events.

Normally, in a classic graph, a vertex (or a node) represents a category and an edge represents a relationship. We observed that a "relationship" may be unary, binary, ternary or n-ary relationship, then a "relationship" can concern one or many categories. A classic graph can represent only the binary relationships between two vertices. By using a hypergraph, a generalization of a graph [4], an edge can connect any number of vertices (see Fig.3(a)). However, this connection of a set of vertices is represented by only an edge. We know that, between two or more "categories", there are many "relationships". It means that different edges can have the same end nodes, then a multigraph [1] can be another alternative graph. However, a multigraph allows to describe multiple relations between two and only two vertices (see Fig.4(a)). For our concept, we would like to use the advantages of these two graph models, and we know that a bipartite graph [29] can model the more general multigraph and hypergraph (see examples of representation of hypergraph in Fig.3(b) and of multigraph in Fig.4(b)).

![Hypergraph](image1)

(a) Hypergraph

![Bipartite graph](image2)

(b) Bipartite graph

**Figure 3** – An example of hypergraph and its bipartite representation.

![Multigraph](image3)

(a) Multigraph

![Bipartite graph](image4)

(b) Bipartite graph

**Figure 4** – An example of multigraph and its bipartite representation.

We would like to present multiple relations between multiple vertices, that is why we decided to represent a relationship by a node. Our graph, denoted $G$, is a bipartite graph and contains two types
of nodes: a category node, denoted \( C \) and a relationship node, denoted \( R \). We give a definition to each type of node in our graph \( G \):

- A category node \( C \) represents the existence of a set of categories in a same environment, i.e. in the same database. For a set of categories \( K = \{ \text{cat}_i \} \), its representation node is \( C_{\{\text{cat}_i\}} \) or \( C_K \). \( C_K \) can own different attributes describing some information of \( K \) such as visual features or a dedicated object detection algorithm.

- Similarly, a relationship node \( R \) represents a type of relationship between categories in a set \( J = \{ \text{cat}_j \} \), we denote this node \( R^\text{type}_j \). From a \( R^\text{type}_j \), we can learn all possible configurations of relationship type involved from \( J \). In our framework, we are especially interested in spatial relationships, for example, relationship type can be the topological spatial relationship [10] that describes different configurations: disjoint, joint, overlaps, insides, etc.

Now, graph \( G \) is defined as:

\[
G = (V, E)
\]

(1)

Knowing that \( V \) is the set of nodes in the graph:

\[
V = \{C_K\} \cup \{R_J\}
\]

(2)

This graph is an undirected graph. Then, \( E \) is the set of edges:

\[
E = \{e(C_K,R_J)| \forall C_K, R_J \in V \land K \subseteq J \}
\]

\[
\forall C_K, R_J \in V; e(C_K,R_J) \Rightarrow e(R_J,C_K)
\]

\[
\forall C_K, C_J \in V; \exists e(C_K,C_J)
\]

\[
\forall R_K, R_J \in V; \exists e(R_K,R_J)
\]

(3)

Figure 5 gives an example of graph (at 3 levels).

3.2 Attributes of a node

On the other hand, our requirement is that graph-based representation must be simple to compute, clear to understand, and extendible to represent a new complex general knowledge. From this question, we define specific attributes associated to each node, category or relationship, in sections 3.2.1 and 3.2.2.

3.2.1 Level attribute

To avoid building an unreadable graph, based on the idea that say that a complex knowledge is developed from a set of basic ones, we split our graph into many different levels. A graph level indicates the number of categories concerned \( :|\{\text{cat}_i\}| \) meaning cardinality of set \( \{\text{cat}_i\} \). Thus, each level of graph
Figure 5 – An example of a 3-level graph. The green, violet, and orange colors illustrate nodes at level 0, 1, and 2 respectively.

is composed of a set of $C$ and $R$ nodes that have the same $|cat_i|$. Thus, we can consider the level as an attribute of the node, denoted $lev$, that is defined as: $lev = |cat_i| - 1$. Our idea is that a higher level node can be built from lower level nodes. A low level node can connect only to one higher level by edges between $C$ nodes of lower level and $R$ nodes of higher level.

In consequence, we redefine set $E$:

$$E = \{e(C_K, R_J) \mid \forall C_K, R_J \in V \land K \subseteq J \land (C.lev = R.lev \lor C.lev + 1 = R.lev)\} \quad (4)$$

Note that we can expand the number of levels in the graph as we need. If we study $N$ categories, then at the level $l$, we can have in maximum $\frac{N^l}{(N-l)!}$ nodes $C$. A high number of levels can increase considerably the number of nodes in the graph, however, in reality, we can find many categories that never occur together. For example, in [15], by studying 86 different entity categories in a dataset of heterogeneous content, we found 879 couples of categories that never occur together among a set 7310 of possible couple and only 38031 present triplets in total among 102340 possible triplets.

In Fig.5, we show the concept for a 3-level graph. Concretely, we can model unary, binary, and ternary relationships with this graph.
3.2.2 Status attribute

We know that a knowledge can be either true, or false, or uncertain. In fact, for example, we are not certain to confirm the existence of aliens because of the limit of our scientific knowledge. "The earth is a square" is a false definition. In addition, a true confirmation could become a false one; for example, nowadays the confirmation "the earth is a center of universe" is not true. To complete the graph conception, we propose to add an attribute on such status for each node of graph, denoted stat. A node in graph can be either true, or false, or uncertain. These statuses can be modified to deal with a new situation if necessary. Figs. 5, 8, and 9 show examples of true nodes. To represent a uncertain node, we use a discontinuous line node as shown in Fig.6(a). Finally a false node is represented by a strike-through node as shown in Fig.6(b). Note that false and true statuses are considered as confirmations, though, uncertain status will be used as induction that is not verified yet.

(a) Uncertain node representation  (b) False node representation

Figure 6 – Two additional statuses of a node.

A C node must own only one status at one time in the graph. In fact, for example, it is impossible that two confirmations: true and false about one category are present in parallel in the same graph. However, we know that a C node can be connected to many R nodes. A R is assigned to a set of categories J and has type, each R node determines a set of configurations Φ that are learnt from J. When adding stat attribute to R node, one remark is that three R nodes can own three different statuses but the same J and type can present in parallel to complete a knowledge of a type relationship studied from J but for different configurations. We denote the set of configurations in $R_{j}^{type} : R_{j}^{type}$.Φ. Let type.Φ be the set of all possible configurations of the relationship type. In consequence:

$$R_{j|stat=true}^{type} \cup R_{j|stat=uncertain}^{type} \cup R_{j|stat=false}^{type} \subseteq \text{type.}\Phi$$

(5)

And:

$$R_{j|stat=true}^{type} \cap R_{j|stat=uncertain}^{type} \cap R_{j|stat=false}^{type} = \emptyset$$

(6)

Note that a configuration of relationship type belongs to only one R node among three different status R nodes of J and type (see Fig.7 for an example).

By adding a status to a node, there are two possible scenarios to represent a knowledge base:

- We begin our knowledge representation with a graph containing all possible combinations on categories and on relationships of universe (i.e. there is no limitation on the number of entity categories and of types of relationship). It is evident that these nodes are uncertain initially. Initially, the graph is very huge. The studying of several content databases will confirm or deny
these nodes. But this scenario is complex and will not be taken into account in our framework.

- A knowledge graph is built directly from a given database. An initial graph contains only the true or false nodes. The number of categories and the types of relationship are limited. This graph evolve by adding new knowledge. Our work in the following will respect this scenario.

3.3 Graph constraints

Here another challenge is that the comparison of two graphs may not involve a costly computation. To avoid to complicate the graph that can impact on graph computation such as comparison, some constraints must be associated to it, on nodes (section 3.3.1), on statuses (section 3.3.2) and on edges (section 3.3.3).

3.3.1 Node constraints

The presence of a set of entity categories is represented by one C node only. Thus, a C node must be unique. It can be identified with a unique identification, denoted id and computed by function of equation 7 : \( C_{K}.id = F^{ID}_{C}(K) \). Note that a cat, can be identified by a unique id (that is an integer) and that \( N^{Catag} \) is the total number of categories examined in system. The id attribute of the C node is an integer computed from the id of cat,\( cat_i \in K \). It will allow to locate quickly a C node in the graph by using a hash function.
\[ F_{C}^{ID}(K) = \sum_{i=1}^{|K|} \text{cat}_i.id \cdot (\text{N}\text{Cat}_\text{eg})^{(i-1)} \quad \forall \text{cat}_i, \text{cat}_j \in K; i < j \Rightarrow \text{cat}_i.id < \text{cat}_j.id \]  \hspace{1cm} (7)

In consequence, we obtain: \( \forall C_K \in V : \#C_J \in V | C_K.id = C_J.id. \)

Similarly, a \( R_J \) node must be unique also. Its uniqueness is represented by a unique \( id \). Differently to the \( id \) of the \( C \) node, this \( id \) is defined by three elements: set \( J \) of categories, \( \text{type} \) of relationship, and status \( \text{stat} \) of a node. It is computed by the function in equation 8:

\[ F_{R}^{ID}(K) = \text{type} + \text{toString} (\text{stat}) + \text{toString} (F_{C}^{ID}(K)) \]  \hspace{1cm} (8)

where \( \text{toString}(s) \) allows to transform a data type (boolean, number, etc.) to a string. Then the \( id \) of a \( R \) node is a string that is unique. Thus, we obtain:

\[ \forall R_J, R_K \in V : (J \neq K) \lor (J = K \land R_J.type \neq R_K.type) \lor (J = K \land R_J.type = R_K.type \land R_K.stat \neq R_J.stat) \]  \hspace{1cm} (9)

It is evident that, for a type of relationship, there may be many different \( R \) nodes. It means there are many instances of \( R^{\text{type}} \) for a given \( \text{type} \). Nowadays, a computer can have a large memory, storage optimization is not the main subject. It is not necessary to look for a way to associate many \( C \) nodes to a \( R \) of given \( \text{type} \) efficiently. We address the computation optimization problem in the graph (e.g. comparison, node matching, etc.). In a large graph, it is always easy and quick to find a node by its \( id \).

In our graph, one lower level is connected to only one next higher level. There is another important constraint on the link between \( R \) nodes and \( C \) nodes. Given a \( R \) node at level \( l \), \( R \) is always connected to \( l + 1 \) nodes \( C \) that are at level \( l - 1 \), and is linked to only one \( C \) node at level \( l \) (see Fig.5).

### 3.3.2 Status constraints

To be able to compare the three statuses, we impose that \( \text{true} > \text{uncertain} > \text{false} \). Finally, to avoid absurd representations in the graph, we propose three constraints concerning \( \text{stat} \) definition:

- The first constraint concerns the \( C \) and \( R \) nodes that are connected and at a same level:
  \[ \forall C_K, R_J \in V : (I = J \Rightarrow C_K.stat >= R_J.stat) \]  \hspace{1cm} (10)

Note that: \( I = J \) can be replaced by \((\exists e(C_K,R_J) \in E \land C_K.\text{lev} = R_J.\text{lev}).\)

- The second constraint concerns the lower level \( C \) node and the higher level \( R \) node that are connected:
  \[ \forall C_K, R_J \in V : I \subset J \Rightarrow C_K.stat >= R_J.stat \]  \hspace{1cm} (11)
Here note that: \( I \subset J \) can be replaced by \((\exists e_{(C_K,R_J)} \in E \land C_K.\text{lev} = R_j.\text{lev} - 1)\).

- The third constraint concerns two \( C \) nodes of two different levels:

\[
\forall C_K, C_J \in V : I \subset J \Rightarrow C_K.stat \geq C_J.stat
\]  \( (12) \)

We can observe that the status of a category node plays an important role. It is certain that the status of a \( R \) node depends on the status of a \( C \) node. We cannot deny that the non-existence of a \( C \) node will reject all \( R \) nodes linked with it. For example, we can say that there are many researches concerning relationship between alien category and earth category; and one day, if we confirm that this alien category do not exist (this category has a false status), then all associated relationships become false. Furthermore, it is also evident that the status of a higher level node depends on the status of a lower level node. For example, if we confirm that in an environment, there is no \( A \) category \((C_{\{A\}}.stat \) is false\), then it is impossible for a couple of categories \((A,B)\) to be present in this environment (thus, \( C_{\{A,B\}}.stat \) becomes false too).

3.3.3 Edge constraints

We impose two constraints for the edges between \( C \) nodes and \( R \) nodes:

- The first constraint is for two nodes of same level. Node \( C_K \) can be linked to node \( R_J \) at the same level if and only if they are assigned to the same set of categories, it means too \( K = J \):

\[
\forall R_J \in V : \exists C_K \in V | C_K.\text{lev} = R_J.\text{lev} \land K = J \land \exists e_{(C_K,R_J)} \in E
\]  \( (13) \)

- The second constraint is for two nodes of different levels. A node \( C_K \) of a lower level can be linked to a node \( R_J \) of a next higher level if and only if \( K \subset J \):

\[
\forall R_J, C_K \in V | (R_J.\text{lev} = C_K.\text{lev} + 1) \land (K \subset J) : \exists e_{(C_K,R_J)} \in E
\]  \( (14) \)

This last constraint confirms the fact that one lower level is connected to only one next higher level.

3.4 Examples

To make clear the model of our graph, we propose two examples in Fig. 8 and 9. In the first example, we describe spatial binary relationship, represented with the topological approach \([9, 10]\) (see section 2.1), between two different categories: car and person. We show the possibility of association of many \( R \) nodes to one \( C \) node. In the second example, the presence of triplet (car, person, building) is confirmed by a presence of three couples of categories in a lower level that have a spatial ternary relationship, represented with the approach \( \Delta-TSR \)[16](see section 2.1), between them. In general, if the number of categories is small, the graph is simple. However, the graph can evolve dynamically, supplement nodes can be added any time when a new knowledge is learnt.
Figure 8 – Example of knowledge representation of relationships of two categories in two first levels by using different relationships: 9-area or 16-area relationships for unary relationships on location in the image, topological relationships or correlation for binary relationships.

Figure 9 – Example of knowledge representation of three categories at level 2 by using Δ-TSR relationships that represent ternary relationships between entities.

4 Management of the graph

In this section, we present several possible manipulations on our graph-based model. The evolution capacity of the graph to the new knowledge is represented in section 4.1. Our graph-based model can be used also to describe the context of an image. This application will be presented in section 4.2. The advantage of this representation is to allow to accelerate the similarity computation of two images by comparing their graphs.
4.1 Evolution of the graph

Section 4.1.1 discuss the operation to update the node status. Section 4.1.2 present how to infer the new knowledge from an existing one.

4.1.1 Update of node status

It is evident that a knew knowledge may change the status of a node. This modification can have some consequences. Here, we say that a node degrades its status while the value of its status is decreased; on the contrary, a node upgrades its status. For example, a $C_K$ node degrades its status from true down to false and then upgrades its status false up to uncertain. Here, we denote $DG$ and $UG$ the operations of status degradation/upgradation of a node respectively. There are two scenarios of status modification, one for $C$ nodes and one for $R$ nodes:

- While a $C$ node changes its status, other nodes may change their status too in order to respect the three constraints of equations 10, 11, 12 p.11, 11, 12. These nodes can be $R$ or $C$ nodes. There are two cases:
  
  1. The first case is when a node $C_K$ realises a $DG$. Then, every $R$ node connected with it and having a status higher than the new status of $C_K$ must undergo a $DG$. Every $C$ node at the next level must undergo a $DG$ too. Algorithm $DG$ is defined as in Algo.1 p.15. Note that while a $R$ node degrades/upgrades its status, it is probable to have two $R$ nodes owning the same id, then it is necessary to merge these two $R$ nodes into one.

  2. The second case is when a node $C_K$ realises a $UG$. Here, we can have a paradox while a higher level $C$ node upgrades its status to a status higher than lower level $C$ node’s one. To respect the imposed constraints, should the lower level $C$ nodes upgrade their statuses too? We examine an example below. Let suppose that in an given environment, an object detector cannot identify the existence of category $A$ but confirms that $B$ exists. Then, we obtain false nodes $A$ and $(A, B)$ in the graph. Then, we see with our own eyes in this environment the existence of couple $(A, B)$ together. Consequently, $A$ must exists in examined environment. Thus, a new confirmation can reject an old confirmation. However, if we say $(A, B)$ maybe exist together, that is not a confirmation, then this uncertain opinion cannot change the non-existence of $A$. From this example, we impose that a $C$ node can upgrade its status only to true status or to the lowest status of lower level $C$ nodes concerning it. This $UG$ operation is defined in Algo.2 p.15.

- On the contrary, we think that status modification of $R$ node does not change the presence of $C$ node. Therefore, a $R$ node can undergo a $UG/DG$ of its status such as its new status respects the three constraints of section 3.2.2. It means a $R$ node cannot upgrade its status to a new status that is higher than one of any $C$ node connected with it. Furthermore, these operations will not impact the status of any $C$ nodes in the graph.

In summary, only the status modification of a $C$ node can impact the status of every $R$ or $C$ nodes of lower/higher levels having a link with it. We can develop a recursive status modification of some
Algorithm 1: DG degradation algorithm of $C_K$ node.

Data: $C_K$, newStatus
Result: downgrade $C_K.stat$ down to newStatus

$C_K.stat \leftarrow newStatus$

for $(R_J | (R_J.lev = C_K.lev \lor R_J.lev = C_K.lev + 1) \land \exists e(C_K, R_J))$ do
  if $(R_J.stat > C_K.stat)$ then
    $R_J.stat \leftarrow newStatus$
    if $(\forall R_K | K = J \land R_K.type = R_J.type \land R_K.stat = R_J.stat)$ then
      $R_J \leftarrow merge(R_J, R_K)$
    end
  end
end

for $(C_Z | (Z \subset I))$ do
  if $(C_Z.stat > C_K.stat)$ then
    DG$(C_Z, newStatus)$
  end
end

Algorithm 2: UG upgradation algorithm of $C_K$ node.

Data: $C_K$, newStatus
Result: upgrade $C_K.stat$ upto newStatus

lowestStatus $\leftarrow$ FALSE.val

for $(C_J | (J \subset I))$ do
  if $(C_J.stat < lowestStatus)$ then
    lowestStatus $\leftarrow C_J.stat$
  end
end

if $(newStatus \neq TRUE.val \land newStatus > lowestStatus)$ then
  return;
end

$C_K.stat \leftarrow newStatus$

if $(newStatus > lowestStatus)$ then
  // newStatus = TRUE.val
  for $(C_Z | (Z \subset I) \land (C_Z.stat \neq newStatus))$ do
    UG$(C_Z, newStatus)$
  end
end

nodes from a $C$ node status change.

Let us study the complexity of each operation. Let $N^R$ be the average number of $R$ nodes connected with one $C$ node. Let $N^C$ be the average number of $C$ node connected with one $C$ node by a $R$ node. Let $N^L$ be the total number of level in the graph. An upgradation operation of a $C$ node at level $l$ impacts only the $C$ nodes of lower levels, thus, the complexity of upgradation is $O((N^C)^{(l-1)})$. On the contrary, an degradation operation of a $C$ node at a level $l$ impacts the $C$ and $R$ nodes of higher levels. Its complexity can reach $O((N^R)^{(N^C-l)} + (N^C)^{(N^R-l-1)})$. 
Let us examine the example of Figure 7 p.10. Suppose that the \(C_{\text{car}}\) node degrades its status (see Fig.10 p.16):

1. \(C_{\text{car}}\) node degrades its status to \textsc{uncertain}.
2. Consequently, respecting constraints on the status conducts that every \textsc{true} \(R/C\) nodes concerned by \textsc{car} must change their statuses to \textsc{uncertain}.
3. A \textsc{true} \(R\) node downgrades its status, it will merge to existing \textsc{uncertain} ones.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure8}
\caption{The initial graph is presented in Fig.7. \(C\) node assigned to \textsc{car} category degrades its status down to \textsc{uncertain}.}
\end{figure}

In fact, if we are uncertain about the presence of \textsc{car}, we cannot be sure about the presence of couple \textsc{car-person}. Further, every relationships concerning \textsc{car} are not certain too or do not exist. On the contrary, a higher level \(C\) node cannot impact the lower level \(C\) node when it degrades its status as we can see with the example of Fig.11 p.17.

We present another example on impact of \textsc{UG} operation of a \(C\) node. From the initial situation in Fig.12(a), a status upgradation of higher level \(C\) node can modify the status of lower level \(C\) node as shown in Fig.12(b). Note that, according to the above constraints, a higher level \(C\) cannot upgrade to \textsc{uncertain} if it exists at least one false lower level \(C\) node concerned to this higher one. The \textsc{UG} operation of \(C\) node will not impact \(R\) nodes and higher level \(C\) nodes.
Figure 11 – The initial graph is presented in Fig.7. A node assigned to \( \text{\textsc{car-person}} \) degrades its status down to FALSE.

### 4.1.2 Inference knowledge

The first utility of our graph is to represent a set of knowledges on entity categories and on their relationships. From an image database, after the analysis of its visual content, we can construct such knowledge graph. This graph can help us to save, to organize, and to infer all statistical informations on the trends of spatial relationships involving entity categories effectively encountered in the database, with the aim of exploiting them in future CBIR applications, for improving tasks such as object recognition or retrieval.

To infer new knowledge from an existing one, several rules can be defined:

- A **true** higher level \( \text{\textsc{car}} \) node can implicate **true** lower level \( \text{\textsc{car}} \) nodes assigned to a subset of its set of categories. For relationship **type** between these \( \text{\textsc{car}} \) nodes, we can add an **uncertain** \( \text{\textsc{R}} \) node containing all configurations of **type** that are not yet represented. Fig.13 illustrates this rule. Let \( K \) be the set of categories represented by \( \text{\textsc{car}} \). Let \( l \) the level of \( \text{\textsc{car}} \). The complexity of this inference is \( \prod_{i=0}^{l} \binom{|K|}{i}. \)

- We can infer the relationship between two **true** \( \text{\textsc{car}} \) nodes based on confirmed relationships between these two \( \text{\textsc{car}} \) nodes and the third intermediate **true** \( \text{\textsc{car}} \) node. Note that for **uncertain** \( \text{\textsc{R}} \) node, we can associate each configuration to some probabilities or to a expected values. Fig.14 illustrates this rule. Here, to avoid complicate structure graph and useless knowledge, we would not like to introduce an implication based on existing **uncertain** nodes. It means that we cannot
(a) Initial graph

(b) Impact of status modification of a higher level C node on lower level C node.

Figure 12 – An example on relationships between two categories car-person, and the impact of a status modification. Relationships are spatial binary relationships described with a topological model.

do a recursive implication, thus, the complexity of this inference is $O(1)$.

4.2 Graph-based representation of image context

In section 2.1, we have defined the context of an image as the representation of every categories in this image and of their spatial relationships. Thus, the graph concept defined in previous sections can be applied to describe the context of an image. For example, the context of the image in Fig.15(a) can be represented by the graph shown in Fig.16. In this image, four entity categories: sky, sun, sea, mountain are detected. Suppose that we study only topological relationships. Note that the existence of the category nodes in level 1 allows to extend this graph to a higher level by studying ternary relationships. In this section, we explain how to compare the context of two images based on graph representation.

Section 4.2.1 defines the similarity between 2 category nodes, section 4.2.2 defines the one between 2 relationship nodes while section 4.2.3 defines the one between 2 graphs.
Figure 13 – Example of automatic inferences in the graph. The discontinuous line rectangles represent the sets of new nodes inferred from existing nodes.

4.2.1 Similarity between two category nodes

We can say that two similar contexts necessarily contain common entity categories. Therefore, firstly, to evaluate the similarity of context of images $I_i$ and $I_j$, we evaluate the similarity of their entity categories.
Figure 14 – Example of automatic inferences in the graph.

Figure 15 – Example of two images that may have similar contexts in terms of entity categories and of topological relationships.

$G_i, G_j$ are the graphs of $I_i, I_j$ respectively. We denote $SC(G_i, G_j)$ the set of matched category couples that are in common between $I_i$ and $I_j$ : $SC(G_i, G_j) = \{(C_{K_i}^{G_i}, C_{K_j}^{G_j})\}$. We split this set in two subset : a set of $(TRUE,$ FALSE$)$ confirmed couples ($SC^{TF}$)and a set of uncertain couples ($SC^U$). Our idea is that the computation of the similarity between two graphs is based on the weighted evaluation of these two sets. Let :

$$SC^U(G_i, G_j) = \{(C_{K_i}^{G_i}, C_{K_j}^{G_j}) | C_{K_i}^{G_i}.stat = \text{UNCERTAIN} \lor C_{K_j}^{G_j}.stat = \text{UNCERTAIN} \}$$

$$SC^{TF}(G_i, G_j) = \{(C_{K_i}^{G_i}, C_{K_j}^{G_j}) | C_{K_i}^{G_i}.stat \neq \text{UNCERTAIN} \land C_{K_j}^{G_j}.stat \neq \text{UNCERTAIN} \}$$
Figure 16 – Image context representation by a graph for images of Fig.15.
Thus, $SC(G_i, G_j) = SC^U(G_i, G_j) \cup SC^TF(G_i, G_j)$. Let $u = |SC^U(G_i, G_j)|$, $tf = |SC^TF(G_i, G_j)|$. Then, $u + tf = |SC(G_i, G_j)|$, it is also the number of nodes $C$ in each graph that participate to the matching. We call $\text{sim}^{SC}(G_i, G_j)$ the category similarity function of two graphs, that can be defined as:

$$\text{sim}^{SC}(G_i, G_j) = \frac{2 \times (u + tf)}{|G_i, \{C_K\}| + |G_j, \{C_J\}|} \times e^{CN}$$

Knowing that:

- $e^{CN} = p^U \times \sum_{k=1}^{u} \text{sim}^{CN}(SC^k(G_i, G_j)) + (1 - p^U) \times \sum_{k=1}^{tf} \text{sim}^{CN}(SC^k(G_i, G_j))$

where:

- $SC^k(G_i, G_j)|X \in \{U, TF\}$ is the $k^{th}$ couple of entity categories of $SC^X(G_i, G_j)$,
- $G_i, \{C_K\}$ the set of the $C$ nodes in $G_i$,
- $p^U$ is weight parameter on evaluation of uncertain part.

$\text{sim}^{CN}(SC^k(G_i, G_j))$ varies in $[0, 1]$, it evaluates the similarity of couples $SC_k$, then $\text{sim}^{SC}(G_i, G_j)$ also varies in $[0, 1]$. $\text{sim}^{SC}(G_i, G_j) = 1$ when two images contains the same set of entity categories. If $\sum_{k=1}^{SC(G_i, G_j)} \text{sim}^{CN}(SC^k(G_i, G_j)) = |G_j, \{C_J\}|$, then $I_i$ contains all of categories of $I_j$. Here, we can define the similarity of two $C$ nodes in two graph as:

$$\text{sim}^{CN}(C_i^G, C_j^G) = \begin{cases} 0 & \text{if } K \neq J, \text{otherwise} \\ \text{sim}(C_K, \text{stat}, C_J, \text{stat}) \end{cases}$$

$\text{sim}(C_K, \text{stat}, C_J, \text{stat})$ evaluates the similarity of status of $C_K$ and $C_J$.

For example, $\text{sim}(C_K, \text{stat}, C_J, \text{stat}) = 1$ when $C_K, \text{stat} = C_J, \text{stat}$ or $\text{sim}(C_K, \text{stat}, C_J, \text{stat}) = 0$ when $C_K, \text{stat} = \text{true} \land C_J, \text{stat} = \text{false}$.

However, if we take into account other attributes for category node in each graph, in this case, we have to consider the comparison of image visual contents also. We can redefine the $\text{sim}^{CN}$ as:

$$\text{sim}^{CN}(C_K^G, C_J^G) = \begin{cases} 0 & \text{if } K \neq J, \text{otherwise} \\ \sum_{k \in \text{SetOfAttributes}} \frac{\text{sim}(C_K, \text{attribute}_k, C_J, \text{attribute}_k)}{|\text{SetOfAttributes}|} \end{cases}$$

where $C_K, \text{attribute}_k$ is the $k^{th}$ attribute of $C_K$ and $\text{sim}(C_K, \text{attribute}_k, C_J, \text{attribute}_k)$ the similarity of the $k^{th}$ attribute between $C_K$ and $C_J$. These attributes are status, furthermore, they can be the size, shape, or color histogram of $I$ (in this case, the similarity is computed from the intersection of two histograms of two nodes or any usual description of graph).

The matching of category nodes in two graphs is not complex, it can be realized based on their id and by using a hash table. This operation has a complexity of $O(N)$ with $N = \min(|G_i, \{C_K\}|, |G_j, \{C_J\}|)$.
4.2.2 Similarity between two relationship nodes

The comparison of context of two images can be studied deeper by taking into account $R$ nodes in the two graphs of these images. Then, similarly to the comparison of $C$ nodes in the two graphs, we define the similarity function to compare $R$ nodes. We denote $SR(G_i, G_j)$ the set of matched relationship node couples from $I_i$ and $I_j$: $SR(G_i, G_j) = \{(R_{iK}^G, R_{jK}^G) | R_{K}.type = R_{K}.type\}$. Here, because of the existence of different statuses of the $R$ node, we impose a constraint of matching:

- a true $R_{K}.type$ node in $G_i$ can be matched with a true $R_{K}.type$ node in $G_j$,
- a false $R_{K}.type$ node in $G_i$ can be matched with a false $R_{K}.type$ node in $G_j$,
- a uncertain $R_{K}.type$ node in $G_i$ can be matched with any $R_{K}.type$ node in $G_j$.

In the same way, we can split $SR(G_i, G_j)$ in two subsets $SR^U(G_i, G_j)$ and $SR^{TF}(G_i, G_j)$. Let $NR^{G_i}$ the number of $R$ nodes in $G_i$ and $NR^{G_j}$ the number of $R$ nodes in $G_j$ that participate to the matching. Consequently, we call $sim^{SR}(G_i, G_j)$ the relationship similarity function of two graphs that can be defined as:

$$sim^{SR}(G_i, G_j) = \frac{NR^{G_i} + NR^{G_j}}{|G_i\{R_K\} | + |G_j\{R_K\}|} \times e^{RN}$$

Knowing that: $e^{RN} = p^U \times \sum_{u=1}^{u} sim^{RN}(SR^U_u(G_i, G_j)) + (1-p^U) \times \sum_{u=1}^{U} sim^{RN}(SR^{TF}_u(G_i, G_j))$

$sim^{RN}(SR_k(G_i, G_j))$ is the function that allows to evaluate the similarity of two $R$ nodes. Then, we can take into account any information from these nodes such as frequency of each $conf_i \in \Phi$.

4.2.3 Similarity between two image graphs

Finally, we can evaluate the similarity of two image graph based on the similarity of category nodes and relationship nodes. We call $SIM(G_i, G_j)$ the function evaluating similarity between two graphs. Then:

$$SIM(G_i, G_j) = p \times sim^{SC}(G_i, G_j) + (1-p) \times sim^{SR}(G_i, G_j)$$

Knowing that $p$ is a weight parameter and $SIM$ varies in $[0..1]$.

For example, we compare the contexts of the two images from Fig.15. Suppose that we study only the topological spatial relationships and choose $p = 0.5$ (equation 19) to give equal importance to categories and relationships. The context representation of these two images can be seen in Fig.16. We obtain $sim^{SC}(G_i, G_j) = 1$ and $sim^{SR}(G_i, G_j) = 1$. Finally, $SIM(G_i, G_j) = 1$, we can say these two images have the same context.

We can add other attributes for category nodes in each graph, for example information on size to each category node (sky, sun, sea, mountain). In the first image, sky and sea occupy around 39.2% and 58.3% of image respectively. In the second image, they occupy around 45.6% and 54.2% respectively. Suppose that we define $sim^{A}(C_i.size, C_j.size)$ as:

$$sim(C_i.size, C_j.size) = 1 - \frac{2 \times |C_i.size - C_j.size|}{C_i.size + C_j.size}$$

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<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C$</td>
<td>category node</td>
</tr>
<tr>
<td>$R$</td>
<td>relationship node</td>
</tr>
<tr>
<td>$lev$</td>
<td>level of node</td>
</tr>
<tr>
<td>$stat$</td>
<td>status of node</td>
</tr>
<tr>
<td>$type$</td>
<td>type of relationship</td>
</tr>
<tr>
<td>$\Phi$</td>
<td>set of configurations</td>
</tr>
<tr>
<td>$F_C^{ID}(K)$</td>
<td>function computing the id of the $C$ node from a set of entity categories</td>
</tr>
<tr>
<td>$F_R^{ID}(K)$</td>
<td>function computing the id of the $R$ node from a set of entity categories</td>
</tr>
<tr>
<td>$UG_i/DG_i$</td>
<td>upgrade/downgrade the status of a node</td>
</tr>
<tr>
<td>$SC(G_i,G_j)$</td>
<td>set of matched category couples from graphs $G_i$ and $G_j$</td>
</tr>
<tr>
<td>$SIM(G_i,G_j)$</td>
<td>similarity between two image graphs (section 4.2.3)</td>
</tr>
<tr>
<td>$SC(G_i,G_j)$</td>
<td>set of matched relationship couples from graphs $G_i$ and $G_j$</td>
</tr>
<tr>
<td>$sim^{CN}(G_i,G_j)$</td>
<td>similarity between two $C$ nodes from graphs $G_i$ and $G_j$ (section 4.2.1)</td>
</tr>
<tr>
<td>$sim^{SR}(G_i,G_j)$</td>
<td>similarity between two $R$ nodes from graphs $G_i$ and $G_j$ (section 4.2.2)</td>
</tr>
<tr>
<td>$G_K$</td>
<td>knowledge graph</td>
</tr>
</tbody>
</table>

Table 1 – Meaning of symbols used.

Consequently, we obtain $sim^{SC}(G_i,G_j) \approx 0.93$. We can find too a different score if we add other spatial relationships like 9DSpa which describe directional relationships [17].

5 Spatial reasoning

In this section, we present two ways for automatically building an image context graph by using the knowledge graph: graph building based only on the knowledge graph in section 5.1 and graph building based on the knowledge graph and the annotation of image in section 5.2. An overview of these main algorithms proposed is presented in section 5.3. From this strategy, several scenarios of query based on the image context graph can be applied, we present them in section 5.4.

5.1 Image context graph building based only on knowledge graph

We present how to build the context graph of an image $I$, denoted $G_I$, based only on visual content of $I$ and on a knowledge graph $G_K$. We suppose that we have built $G_K$ from a training image database and that $G_K$ contains several categories of entities and useful knowledge on unary, binary relationships on them as well as on their visual features (e.g. color histograms, interest points, etc.) or a dedicated algorithm of category detection (the visual attributes of a category in $G_K$ can be for example learnt
from the set of visual attributes of $N$ instances of this one). Note that, every nodes in $G_K$ have a **true** or **false** status because we suppose that the training database $G_K$ represents the universe and that all knowledge collected from this database is verified. The presence of an entity category, a couple or a triplet of categories together at least in an image can be represented by a **true** $C$ node. The relationships between them can be represented by a **true** $R$ node. However, for multiple categories and a given configuration of a relationship type, if we cannot find at least one example in the training database, this configuration is presented in a **false** $R$ node.

The building of $G_I$ is based on the knowledge of $G_K$ by exploiting the visual features of $I$, for the confirmation of the existence of an entity category in $I$. Differently to $G_K$, a final $G_I$ will contain only **true** or **uncertain** nodes. Certainly, if the presence of an entity category in $I$ is not confirmed with a high probability by a detection tool for example, we represent this one by a **uncertain** $C$ node. On the other hand, every categories from the training database that are not present in $I$ can be represented by **false** $C$ nodes in $G_I$. However, this last representation is useless and complicate the representation of $G_I$ because of a great number of absent categories and then we do not put such nodes in $G_I$. Consequently, the absence of $C$ node in $G_I$ expresses the absence of entity category associated with it in $I$.

Algo.3 describes the main steps of this construction. Before starting Algo.3, we have to define the five following parameters:

1. Type of unary relationship $type^u$ to be studied in $I$, for example, $type^u \in \{9$-area, $16$-area$\}$ (see section 2.1);
2. Type of binary relationship $type^b$ to be studied in $I$, for example, $type^b \in \{9$Dspa, topological$\}$ (see section 2.1);
3. Probability threshold $\varphi_p/0 < \varphi_p \leq 1$: this parameter allows to filter all configurations of a given type of relationship with a low frequency or a low presence probability in $G_K$. For example, by using unary relationship, in $I$, we can begin by verifying the presence of a category on areas where its presence probability learnt from $G_K$ is higher than $\varphi_p$;
4. Probability threshold $\varphi_l/0 < \varphi_l \leq 1$ for deciding of the **true** status of a category or a relationship node in $G_I$: when the detection probability of an entity of given category $cat_i$ reaches $\varphi_l$ by using the visual features of an area in $I$ in comparison with the visual features associated with category node in $G_K$, a **true** category node assigned to $cat_i$ can be created in $G_I$. It means that category $cat_i$ is present in $I$;
5. Probability threshold $\varphi_u/0 < \varphi_u < \varphi_l$ for deciding of the **uncertain** status of a category or a relationship node in $G_I$: similarly to $\varphi_l$, when the detection probability of an entity of $cat_i$ varies in $[\varphi_u, \varphi_l]$, a **uncertain** category node assigned to $cat_i$ can be created in $G_I$. It means that category $cat_i$ may be present in $I$.

These parameters will be used in the following algorithms. The main idea of Algo.3 is that, in $G_K$, each **true** category node at level 0, that is assigned to an entity category, will be examined if it can
be present in $G_I$. A supplementary function, named "checkCN", used by this algorithm is presented in Algo.4. This function allows to verify the presence in $G_I$ of a given category node of $G_K$ by comparing the visual features of $I$ to the visual features contained in this category node. Algo.4 can be used as the algorithm to detect the presence of a given entity category in image $I$. Since its presence is confirmed with a probability, a true or uncertain category node will be added into $G_I$. To reduce the complexity of Algo.3, while a true $C$ node is added to $G_I$, all other $C$ nodes that cannot occur with this node will be deleted from the tail of nodes to be checked. When the level-0 of $G_I$ is completely studied by using $G_K$, the next level of $G_I$ can be studied, i.e. the binary, ternary relationships in $I$. To illustrate the concept, we only study here binary relationships of $type^b$, which are studied in function "buildBinaryRelation" of Algo.3 (and fully described in Algo.5). Note that, to be able to study the binary relationships between two categories, during the building of level 0 in $G_I$, all possible locations detected for these categories can be stocked as meta-data of $G_I$.

**Complexity of Algo.3, Algo.4, Algo.5**: The three algorithms are presented with the paradigm of Object-oriented programming (OOP), they are entirely implementable and applicable. Let study the complexities of these algorithms:

- $N_{Cat}^*$ denotes the number of entity categories presented in $G_K$,
- $N_{Cat}_{Avg}^*$ the average number of categories present in an image,
- $N_{Conf}^*$ the average number of configurations assigned to a $R$ node,
- $N_{Entity}^*$ the average number of instances of a category in an image,
- $O(D)$ the complexity of the detection processing for a category.

In general, the complexity of Algo.4 is $O_2 = O(N_{Conf}_{Avg}^* \times O(D))$, the one of Algo.5 is $O_3 = O(\frac{(N_{Cat}^*)^2}{2} \times (N_{Entity}^*)^2)$. Then, Algo.3 has a maximum complexity of $O_1 = O(N_{Cat}^* \times O_2 + O_3)$. For example, from the statistical studies on the symbolic database studied in [15], we have: $N_{Cat}^* = 86$, $N_{Cat}_{Avg}^* = 5$, $N_{Entity}^* = 33$, $N_{Conf}^* < 138$ with 9-area splitting.
Function: `buildGraph_01`

Input: Image $I$, knowledge graph $G_K$, type of unary relationship $type^u$, type of binary relationship $type^b$, threshold parameters: $\varphi_p, \varphi_l, \varphi_u$

Output: Graph $G_I$ representing the context of $I$

$G_I \leftarrow \emptyset$; # Initialize the context graph of $I$
$L_{CN} \leftarrow G_K.get\_ListOf\_TrueCNode\_AtLevel(0)$;
# Get the set of true category nodes at level 0 from $G_K$

while $L_{CN} \neq \emptyset$ do

$cn_{check} \leftarrow getRandom\_CNode\_From(L_{CN})$;
# $cn_{check}$ is a C node of $G_K$ to be located in $I$

$rn^u_{check} \leftarrow cn_{check}.getRNode\_ByTypeAndStatus(type^u, \text{TRUE})$;
# Get a true $R$ node of type $type^u$ that is connected to $cn_{check}$

if $\exists rn^u_{check}$ then

listConf $\leftarrow rn^u_{check}.\phi$; # Get the list of configurations associated with $rn^u_{check}$

foundTrueCN $\leftarrow$ checkCN($I$, $G_I$, $G_K$, $cn_{check}$, $type^u$, $listConf$, $\varphi_p$, $\varphi_l$, $\varphi_u$);
# Verify if $cn_{check}$ can be present in $G_I$. The status of $G_I.cn_{check}$ depends on $\varphi_l$, $\varphi_u$. checkCNode is defined in Alg.4

if $foundTrueCN = \text{true}$ then

Remove from $L_{CN}$ other $C$ nodes that cannot occur with $cn_{check}$;
# If $cn_{check}$ is present as a true node in $G_I$, we remove all $C$ nodes in $G_K$ that are connected to $cn_{check}$ by only false $R$ nodes.\(^\dagger\)

end

end

$L_{CN}.remove(cn_{check})$; # Since $cn_{check}$ is checked, we can delete it from $L_{CN}$

end

`buildBinaryRelation(G_I, type^b)`;
# Study other spatial relationships from $G_I$ such as binary relationships, see this function in Alg.5

Return $G_I$;

Algorithm 3: Algorithm of context graph $G_I$ building for an image $I$ from a knowledge graph $G_K$. See Tab.2 on page 39 for the definition of the main used variables/methods.

\(^\dagger\) We study the non-occurrence in the same image of two level-0 category nodes in $G_K$. The determination of this situation is quickly done by examining the status of the $C$ node at level 1 that is connected to these level-0 ones. If the status of this node is $\text{FALSE}$, this pair of nodes cannot occur together. It means that every binary relationship nodes between these two level-0 $C$ nodes are $\text{FALSE}$. 

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Function: checkCN

Input: Image I, context graph G_I, knowledge graph G_K, category node cn of G_K to be located in I, type of unary relationship type^u, list of configurations listConf to be verified on cn, threshold parameters: \( \varphi_p, \varphi_l, \varphi_u \)

Output: foundTrueCN indicates if we find a TRUE C node

\[
\text{foundTrueCN} \leftarrow false
\]

# In unary relationship, conf indicates the area and the presence probability at this area of entity category represented by cn

\[
\text{for} \ (\text{conf} \in \text{listConf} \land \text{conf.prob} \geq \varphi_p) \ \text{do}
\]

\[
\text{res} \leftarrow I.\text{detectObject}(\text{conf}, \text{cn}) \quad ; \quad \# \text{This function returns detection probability res.prob and possible location of entity res.location in conf. Note that, in the worst case, the detection tool does not provide the location of the detected object, and then res.location is conf}
\]

\[
\text{nodeStatus} \leftarrow TRUE
\]

\[
\text{if} \ (\text{res.prob} > \varphi_l) \ \text{then}
\]

\[
\text{foundTrueCN} \leftarrow true \quad ; \quad \# \text{If it exists at least one entity of category presented by cn in I, the status of the C node assigned to this category in } G_I \text{ must be True}
\]

\[
\text{end}
\]

\[
\text{else if} \ (\text{res.prob} > \varphi_u) \ \text{then}
\]

\[
\text{nodeStatus} \leftarrow \text{UNCERTAIN}
\]

\[
\text{end}
\]

\[
\text{cn}_{G_I} \leftarrow G_I.\text{getCNode}_\text{ById}(\text{cn.id}) \quad ; \quad \# \text{cn}_{G_I} \text{ can be null or a C node having the UNCERTAIN or TRUE status}
\]

\[
\text{if} \ (\tilde{\emptyset} \text{cn}_{G_I}) \ \text{then}
\]

\[
\text{cn}_{G_I} \leftarrow G_I.\text{newCNode}_\text{AssignedTo}((\text{cn}.\text{getCategory}(0), \text{nodeStatus}) \quad ; \quad \# \text{cn}_{G_I} \text{ is assigned to the same category as cn and has status value of nodeStatus}
\]

\[
\text{end}
\]

\[
\text{if} \ (\text{foundTrueCN} = true) \ \text{then}
\]

\[
\text{cn}_{G_I}.\text{setStatus}(\text{TRUE}) \quad ; \quad \# \text{In all cases, } \text{cn}_{G_I} \text{ must change his status to the TRUE status}
\]

\[
\text{end}
\]

\[
\text{rn}_{G_I} \leftarrow \text{cn}_{G_I}.\text{getRNode}_\text{ByTypeAndStatus}(\text{type}^u, \text{nodeStatus}) \quad ; \quad \# \text{rn}_{G_I} \text{ is a R node connected to } \text{cn}_{G_I}
\]

\[
\text{if} \ (\tilde{\emptyset} \text{rn}_{G_I}) \ \text{then}
\]

\[
\text{rn}_{G_I} \leftarrow G_I.\text{newRNode}_\text{AssignedTo}((\text{cn}_{G_I}.\text{getCategory}(0), \text{type}^u, \text{nodeStatus}) \quad ; \quad \# \text{rn}_{G_I} \text{ is assigned to the same category of } \text{cn}_{G_I} \text{ and has type of unary relationship } \text{type}^u \text{ and status value of nodeStatus}
\]

\[
\text{G_I}.\text{setLink}(\text{cn}_{G_I}, \text{rn}_{G_I}) \quad ; \quad \# \text{G_I} \text{ is the knowledge graph}
\]

\[
\text{end}
\]

\[
\text{rn}_{G_I}.\text{addConf}(	ext{conf}) \quad ; \quad \# \text{We add the meta data concerning location and status of } \text{cn}_{G_I} \text{ to } G_I, \text{ this information can be used to study binary or ternary relationships between categories in I}
\]

\[
\text{end}
\]

Return foundTrueCN

Algorithm 4: Algorithm of the function checkCN(). See Tab.2 on page 39 for the definition of the main used variables/methods.
Function: buildBinaryRelation

Input: Context graph \( G_I \), type of binary relationship \( type^b \)
Output: Context graph \( G_I \) that is completed with binary relationships

\[
L_{CN} \leftarrow G_I\.get\_ListOf\_CNode\_AtLevel(0);
\]

# Get the set of category nodes at level 0 from \( G_I \)

for \( (i \in [0..size(L_{CN}) - 2]) \) do

\[
cn_i \leftarrow L_{CN}.get(i);
\]

for \( (j \in (i..size(L_{CN}) - 1)) \) do

\[
cn_j \leftarrow L_{CN}.get(j);
\]

\[
setCat \leftarrow \{cn_i\.getCategory(0), cn_j\.getCategory(0)\};
\]

# \( cn_i \) and \( cn_j \) are at level 0 then they contain only one entity category.

\[
cn_{ij} \leftarrow G_I\.getCNode\_BySetCat(setCat);
\]

# \( cn_{ij} \) is a category node at level 1 in \( G_I \) and represents the presence of \( setCat \) in \( I \)

if \( \exists cn_{ij} \) then

\[
cn_{ij} \leftarrow G_I\.newCNode\_AssignedTo(setCat, min(cn_i\.stat, cn_j\.stat));
\]

# According to status constraints, a higher level C node cannot have a status superior to the status of lower

end

listMetaData_{i} \leftarrow G_I\.getMetaData(cn_i);
listMetaData_{j} \leftarrow G_I\.getMetaData(cn_j);

# Get all possible meta-data of \( cn_i \) and \( cn_j \) from \( G_I \). This meta data is created in Algo.4

for \( (data_i \in listMetaData_{i}) \) do

for \( (data_j \in listMetaData_{j}) \) do

\[
minStat \leftarrow min(data_i\.getCNode().stat, data_j\.getCNode().stat);
\]

\[
rn_{ij} \leftarrow cn_i\.getRNode\_ByTypeAndStatus(type^b, minStat);
\]

if \( \exists rn_{ij} \) then

\[
rn_{ij} \leftarrow G_I\.newRNode\_AssignedTo(setCat, type^b, minStat);
\]

# \( rn_{ij} \) is a R node at level 1 and is assigned to the same category of \( cn_{ij} \)

\[
G_I\.setLink(cn_{ij}, rn_{ij});
\]

\[
G_I\.setLink(cn_i, rn_{ij});
\]

\[
G_I\.setLink(cn_j, rn_{ij});
\]

end

conf \leftarrow getBinaryConf(type^b, loc_i, loc_j);

rn_{ij}.addConf(conf);

end

end

end

Algorithm 5: Algorithm of the function buildBinaryRelation(). See Tab.2 on page 39 for the definition of the main used variables/methods.
5.2 Image context graph building based on incomplete image annotation and knowledge graph

In this section, we present how to build an image context graph from its annotations and the knowledge graph $G_K$. The annotations are the location of some given categories, they can be manual annotations or the result of an object detection task. The annotations are supposed incomplete, several categories of $G_K$ which can be present in $I$ are not annotated. These annotations will not be put back into question even if they do not coincide with $G_K$. From these annotations, $G_I$ can be initialized: initially $G_I$ contains only true nodes that represent the presence of some entity categories and some unary and binary spatial relationships deduced from the location of the entities annotated in $I$.

We can easily adapt Algo.3 to these new initial conditions, see this adaptation in Algo.6. One main difference between these two algorithms is the input variable $G_I$: in Algo.6, $G_I$ is non empty. Because $G_I$ contains initially some category nodes, we can check only the category nodes in $G_K$ that can occur with these ones. Consequently, the complexity of Algo.6 is reduced considerably compared to Algo.3.

Complexity of Algo.6: Let study the complexity of this algorithm. $N^{Cat}$ denotes the number of entity categories presented in $G_K$, $N^{Cat}_{Filter}$ the number of categories that are consistent with categories present in initial graph $G_I$. Then the complexity of Algo.6 is $O(N^{Cat}_{Filter} \times O_2 + O_3)$ (see the definitions of $O_2$ and $O_3$ in section 5.1) in knowing that $N^{Cat}_{Filter} \ll N^{Cat}$. 
**Function: buildGraph_02**

**Input:** Image $I$, initial context graph $G_I$, knowledge graph $G_K$, type of unary relationship $type^u$, type of binary relationship $type^b$, threshold parameters: $\varphi_p$, $\varphi_t$, $\varphi_u$

**Output:** Graph $G_I$ representing the context of $I$

$L_{CN} \leftarrow G_K.get\_ListOf\_TrueCNode\_AtLevel(0);$

# Get the set of true category nodes at level 0 from $G_K$

for $cn \in G_I.get\_ListOf\_TrueCNode\_AtLevel(0)$ do

  Remove from $L_{CN}$ other $C$ nodes that cannot occur with $cn$;

  # If $cn$ is present as a True node in $G_I$, we remove all $C$ nodes in $G_K$ that are connected to $cn$ by only false $R$ nodes

end

# The following is the same as in Algo.3

while $L_{CN} \neq \emptyset$ do

  $cn_{check} \leftarrow getRandom\_CNode\_From(L_{CN});$

  # $cn_{check}$ is a $C$ node of $G_K$ to be located in $I$

  $rn_{check} \leftarrow cn_{check}.getRNode\_ByTypeAndStatus(type^u, \text{TRUE});$

  # Get a true $R$ node of type $type^u$ that is connected to $cn_{check}$

  if $\exists rn_{check}$ then

    foundConf $\leftarrow rn_{check}.\phi;$

    # Get the list of configurations associated with $rn_{check}$

    foundTrueCN $\leftarrow checkCN(I, G_I, G_K, cn_{check}, type^u, foundConf, \varphi_p, \varphi_t, \varphi_u);$

    # Verify if $cn_{check}$ can be present in $G_I$. The status of $G_I, cn_{check}$ depends on $\varphi_t, \varphi_u$. checkCNode is defined in Algo.4

    if $\text{foundTrueCN = true}$ then

      Remove from $L_{CN}$ other $C$ nodes that cannot occur with $cn_{check}$;

      # If $cn_{check}$ is present as a true node in $G_I$, we remove all $C$ nodes in $G_K$ that are connected to $cn_{check}$

      by only false $R$ nodes.

    end

  end

  $L_{CN}.remove(cn_{check});$  # Since $cn_{check}$ is checked, we can delete it from $L_{CN}$

end

buildBinaryRelation($G_I, type^b);$

# Study other spatial relationships from $G_I$ such as binary relationships, see this function in Algo.5

Return $G_I$;

---

**Algorithm 6:** Algorithm of context graph $G_I$ building from initial incomplete context graph and a knowledge graph $G_K$. See Tab.2 on page 39 for the definition of the main used variables/methods.
Now let us consider the case of binary relationships. We can improve Algo. 6 by using the binary relationships from knowledge graph $G_K$ for better filtering the possible locations of category in check. We define the two following functions; the output of the first function is used as one of the input of the second one:

1. $\text{findLocFromBR}()$: defined in Algo.7, it allows to determinate the set of possible locations in $I$ of a category (presented by C node $cn_{\text{check}}$) from $G_K$ by using the binary relationships learnt from $G_K$ and the existing $C$ nodes in $G_I$. The presence of this category is confirmed by a TRUE or UNCERTAIN $C$ node added in $G_I$. The output of this function is the list of possible locations and probabilities of $cn_{\text{check}}$.

2. $\text{filterLocWithUR}()$: allows to filter all locations predicted in the previous function that do not agree to the unary relationships of $G_K$. This function is presented in Algo.8. In this algorithm, we use a probability fusion method to compute the final probability for each possible location. We will detail this point in the following.

Algo.9 combines these two functions to improve Algo.6. Filtering on the entity location, by using binary relationships, can considerably reduce the number of final possible locations. Consequently, $N_{\text{Avg}}^{\text{Conf}}$ is notably reduced, then also $O_2 = O(N_{\text{Avg}}^{\text{Conf}} \times O(D))$ (see section 5.1).

In function $\text{filterLocWithUR}()$ (Algo.8), we can encounter the following problem: how to combine the different knowledge to determinate the confidence of the results? Fig.17 illustrates this problem. $I$ contains entities of category $A$ and $C$, we would like to verify if entities of category $B$ could be in $I$, knowing that $A, B, C$ and binary spatial relationships between $A$ and $B, B$ and $C$ are known in $G_K$. From $G_K$, based on $A$ and binary relationships between $A$ and $B$, we can deduce three areas 1, 2 and 3 where $B$ may be present with probabilities 0.40, 0.10, and 0.50 respectively. Based on $C$ and binary relationships between $C$ and $B$, there are two areas 1 and 2 with probabilities 0.50 and 0.50 respectively. Furthermore, from $G_K$ with the unary relationship of $B$, we know that $B$ can be present in four areas, as in Fig.17(b). We denote $P(\text{cat}_B | \text{setCat}, A_i)$ the presence probability of category $B$ at area $A_i$ in $I$ when set of categories $\text{setCat}$ is present. According to literature on data fusion [7, 30] there are several strategies to merge these informations and to conclude about $B$

1. Conjunction strategy: for each area in $I$, keep the lowest probabilities and recalculate them by normalizing with the sum of the kept probabilities. For example, Fig.18(a) presents the results of this strategy by applying it on the example of Fig.17. When the probability is absent, we consider the value 0.

2. Disjunction strategy: for each area in $I$, keep the highest probability and recalculate them by normalizing with the sum of kept probabilities. For example, Fig.18(b) presents the results of this strategy by applying it on the example of Fig.17.

3. Compromise strategy: It is based on the idea of the correlated probabilities fusion model of [21]:

$$f(g, h, c) = \frac{g \times h \times e^{m \times c}}{g \times h \times e^{m \times c} + (1 - g) \times (1 - h) \times e^{-m \times c}} \tag{21}$$
where $g$ and $h$ are the probabilities considered, $c$ the correlation, $e$ is the exponential function, and $m \in [0,1]$ is the weight applied on $c$.

We extend this definition to a set of probabilities and define $P(cat_B|setCat, A_i)$ as a fusion function:

$$ FFusion\left(\{p_i\}, c\right) = \frac{\prod_{j=1}^{\#setCat} p_j \times e^{m \times c}}{\prod_{j=1}^{\#setCat} p_j \times e^{m \times c} + \prod_{j=1}^{\#setCat} (1 - p_j) \times e^{-m \times c}} \quad (22) $$

where $setCat$ is the set of categories present in image, $p_j = P(cat_B|cat_j, A_i)$ the presence probability of $cat_B$ at area $A_i$ when $cat_j$ is present, $c = max(correlation(cat_i, cat_j))/cat_i, cat_j \in setCat$.

This strategy contains more information in comparison to the two previous strategies. The use of the correlation between a couple of existing categories (for example, the correlation obtained in [15]) can reinforce or reduce the prediction confidence about the presence of a category considered based on this couple. For example, if couple $(A, C)$ has a high correlation, it means that the confidence of the prediction of $B$ based on $A$ and based on $C$ is reinforced; on the contrary, a low correlation of $(A, C)$ can reduce this confidence. We have the global form of $FFusion$ is $\frac{a}{a + b}$ and the more correlation $c$ increases, the more $a$ increases and $b$ decreases, consequently, the more $FFusion$ increases.

Because we think that the correlation between categories is a relevant information to integrate in the analysis, we choose the compromise strategy to compute the presence probability of one category based on the existing ones (see Algo.8).
(a) By using the conjunctive strategy, probabilities 0.35, 0.10, 0.0, 0.0 are kept for areas 1, 2, 3, 4 respectively. By normalizing with their sum 0.45, we obtain the results above.

(b) By using the disjunctive strategy, probabilities 0.50, 0.50, 0.50, 0.05 are kept for areas 1, 2, 3, 4 respectively. By normalizing with their sum 1.55, we obtain the results above.

(c) By using the compromise strategy, with \( m = 0.5 \) and \( c = 0.7 \), merged probabilities for areas 1, 2, 3, 4 are 0.419, 0.182, 0.0, 0.0 respectively. By normalizing with their sum 0.601, we obtain the results above.

(d) By using the compromise strategy, with \( m = 0.5 \) and \( c = 0.1 \), merged probabilities for areas 1, 2, 3, 4 are 0.28, 0.11, 0.0, 0.0 respectively. By normalizing with their sum 0.39, we obtain the results above.

Figure 18 – Results of the application of three data fusion strategies to the example of Fig 17.
Function: findLocFromBR

Input: Context graph $G_I$, knowledge graph $G_K$, category node $cn_{check}$ of $G_K$ to locate in $I$, type of unary relationship $type^u$, type of binary relationship $type^b$, threshold parameter $\varphi_p$

Output: List of possible unary configurations $LConf$

$LConf \leftarrow \emptyset$

for $(cn_{G_I} \in G_I.get\ ListOf\ TrueCN ode\ AtLevel(0))$ do

$setCat \leftarrow \{cn_{G_I}.getCategory(0), cn_{check}.getCategory(0)\}$;

# $cn_{G_K}$ and $cn_{check}$ are at level 0 then they contain only one entity category. In consequence, $setCat$ has 2 items.
$cn_{G_K} \leftarrow G_K.getCN ode\_BySetCat(setCat)$;

# $cn_{G_K}$ is a category node at level 1 in $G_K$
$rn_{G_K} \leftarrow cn_{G_K}.getRN ode\_ByTypeAndStatus(type^b, TRUE);$ 

for $(conf_{type^b} \in rn_{G_K}.$) do

if $(conf_{type^b}\ .probab > \varphi_p)$ then

$conf_{type^u} \leftarrow get UnaryConfFrom(conf_{type^b}, cn_{G_I})$;

# Determines $conf_{type^u}$ the area in $I$ of $cn_{check}$ from $conf_{binary}$ and $cn_{G_I}$

$conf_{type^u} \leftarrow get ByConf(\ LConf, conf_{type^u})$;

# In set $LConf$, looking for a $conf_{other}$ having the same configuration as $conf_{type^u}$

if $(\exists conf_{type^u})$ then

# Store the detection probability and the category that allows to deduce this one before computing the fusion of probabilities in Alg.8
$conf_{type^u}.addCategory(cn_{G_K}.getCategory(0))$;

$conf_{type^u}.addToListOfProbab(conf_{type^u}.probab)$;

end

else

$LConf.add(conf_{type^u})$;

end

end

end

Algorithm 7: Algorithm of function findLocFromBR(). See Tab. 2 on page 39 for the definition of the main used variables/methods.
Function: \textit{filterLocWithUR}

**Input:** Relationship node \(rn^{type_u}\) taken from \(G_K\), list of possible unary relationship configurations \(LConf\), probability threshold \(\varphi_p\)

**Output:** List of possible unary configurations \(LConf\) after filtering

\begin{verbatim}
for (conf in LConf) do
    conf\textsuperscript{rn} ← getByConf(rn\textsuperscript{type_u}, \phi, conf);
    # In set \(rn\textsuperscript{type_u}, \phi\) looking for the \(conf\textsuperscript{rn}\) having the same configuration as \(conf\)
    if (\#conf\textsuperscript{rn} \lor conf\textsuperscript{rn}.probab < \varphi_p) then
        LConf.remove(conf);
    else
        conf.addToListOfProbab(conf\textsuperscript{rn}.probab);
    end
end

# Compute final detection probability for each \(conf \in LConf\) according to strategy of fusion 3 and equation 22
for (conf in LConf) do
    maxCorr ← computeMaxCorrFrom(conf.getCategories());
    # Get the highest correlation of a couple of categories among the list of categories stored for \(conf\) in Alg.7
    p ← FFusion(conf.listOfProbab, maxCorr);
    # Compute the fusion probability in according to equation 22 \(conf.setFinalProbab(p)\);
end

Sort \(LConf\) by probability;
\end{verbatim}

Algorithm 8: Algorithm of function \textit{filterLocWithUR()}. See Tab.2 on page 39 for the definition of the main used variables/methods.
Function: buildGraph_03

Input: Image $I$, initial context graph $G_I$, knowledge graph $G_K$, type of unary relationship $type^u$, type of binary relationship $type^b$, threshold parameters: $\varphi_f, \varphi_t, \varphi_u$

Output: Graph $G_I$ representing the context of $I$

$L_{CN} \leftarrow G_K.get\_ListOf\_TrueCNode\_AtLevel(0);$

for $cn \in G_I.get\_ListOf\_TrueCNode\_AtLevel(0)$ do

Remove from $L_{CN}$ other C nodes that cannot occur with $cn$;

if $cn,check$ is present as a True node in $G_I$, we filter all C nodes in $G_K$ that are connected to $cn,check$ by only FALSE R nodes $L_{CN}.remove(cn);$

end

while $L_{CN} \neq \emptyset$ do

$cn,check \leftarrow get\_Random\_CNode\_From(L_{CN});$

$LConf \leftarrow find\_Loc\_From\_BR(G_I, G_K, cn,check, type^u, type^b, \varphi_p);$

$rn_{type^u} \leftarrow cn,check.get\_RNode\_ByTypeAndStatus(type^u, true);$ FilterLocWithUR($LConf, rn_{type^u}, \varphi_p);$

$foundTrueCN \leftarrow check\_CN(I, G_I, G_K, cn,check, type^u, LConf, \varphi_t, \varphi_u, \varphi_p);$VERIFY if $cn,check$ can be present in $G_I$. The status of $G_I.cn,check$ depends on $\varphi_t, \varphi_u$. checkCNode() is defined in Algo.4

if $foundTrueCN = true$ then

Remove from $L_{CN}$ other C nodes that cannot occur with $cn,check$;

end

$L_{CN}.remove(cn,check);$

end

buildBinaryRelation($G_I, type^b);$ Study other spatial relationships from $G_I$ such as binary relationships, see this function in Algo.5

Return $G_I$;

Algorithm 9: Improved algorithm of context graph $G_I$ building from initial incomplete context graph and a knowledge graph $G_K$ by using binary relationship knowledge. See Tab.2 on page 39 for the definition of the main used variables/methods.
5.3 Overview of graph building

In Fig.19, we present an overview of the three main algorithms (Algo.3, Algo.6, and Algo.9). Algo.6 improves Algo.3 by filtering the list of categories considered before verifying their presence in I. Algo.9 improves Algo.6 by using the binary relationships learnt from $G_K$ to filter possible locations of a category considered. We report the main object variables and functions used in these three algorithms in Tab.2.

![Diagram](image)

**Figure 19** – An overview of the three graph building algorithms for a given image.
<table>
<thead>
<tr>
<th>Name of variable/method</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G$</td>
<td>Knowledge/image context graph</td>
</tr>
<tr>
<td>$cn$</td>
<td>Object variable of type $C$ node</td>
</tr>
<tr>
<td>$rn$</td>
<td>Object variable of type $R$ node</td>
</tr>
<tr>
<td>$conf$</td>
<td>Object variable of type configuration</td>
</tr>
<tr>
<td>$L$</td>
<td>List of object variables, for example $L_{CN}$ is a list of $C$ nodes</td>
</tr>
<tr>
<td>$L.remove(o)$</td>
<td>Remove object variable $o$ from $L$</td>
</tr>
<tr>
<td>$L.add(o)$</td>
<td>Add object variable $o$ to $L$</td>
</tr>
<tr>
<td>getRandom_CNode_From($L_{CN}$)</td>
<td>Get a $C$ node from list $L_{CN}$ randomly</td>
</tr>
<tr>
<td>$cn.getRNNode_ByTypeAndStatus(type, stat)$</td>
<td>Get a $R$ node that has $type$ and $stat$ as attributes and is connected to $cn$</td>
</tr>
<tr>
<td>$G.getCNodE_ById(id)$</td>
<td>Get a $C$ node from $G$ in function of a given identifier $id$</td>
</tr>
<tr>
<td>$G.getCNodE_BySetCat(setCat)$</td>
<td>Get a $C$ node from $G$ in function of a given set of categories $setCat$</td>
</tr>
<tr>
<td>$G.newCNode_AssignedTo(setCat, stat)$</td>
<td>Create a new $C$ node in $G$ that is assigned to a set of categories $setCat$ and that has a status $stat$</td>
</tr>
<tr>
<td>$G.newRNodE_AssignedTo(setCat, stat)$</td>
<td>Create a new $R$ node in $G$ that is assigned to a set of categories $setCat$ and that has a status $stat$</td>
</tr>
<tr>
<td>$G.setLink(cn, rn)$</td>
<td>In $G$, add an arc between $cn$ and $rn$</td>
</tr>
</tbody>
</table>

Table 2 – Table of some used variables/functions and their meaning in Algo. 3, 4, 5, 6, 7, 8, 9.
From these strategies, several scenarios of query based on the image context graph can be applied, we present them in the next section 5.4.

5.4 Scenarios of interrogation

Suppose that we have a knowledge graph $G_K$ from a training image database where each image is completely annotated, and that we have a test database $DB_{test}$ where each image is not completely annotated. By building the initial graph for each image in $DB_{test}$, by referencing the knowledge on $G_K$, from the previous algorithms, we can imagine forming some scenarios of query as following:

1. Is category $A$ present in the given image $I$, knowing that $A$ is present in $G_K$?
2. What are the images in $DB_{test}$ containing category $A$? Where is the searching area of $A$ in these images? Where is exactly $A$, knowing that $A$ is present in $G_K$.
3. Given two categories $A$ and $B$, what are the configurations $conf$ of the relationship $type$ between them in $DB_{test}$? Which configuration is the most frequent?
4. What are the images where $A$ and $B$ have a $conf$ of relationship $type$?
5. Given category $A$, and configuration $conf$ of relationship $type$ (e.g. $type$ could be 9Dspa, topological), which category $B$ have relation $conf$ with $A$?
6. In image $I$ where $A$ is present, is $B$ present?
7. Given two categories $A$, $B$, and location $L_A$ of $A$ in an image, which configuration $conf$ of relationship $type$ can we found between $A$ and $B$? Where is the searching area for $B$? Where is $B$?
8. Given a query image, what are the images in $DB_{test}$ that are similar to this query one?
9. Given a prototype context (i.e. a context description by a graph), what are the images from $DB_{test}$ that have the similar context?

In the next section, we integrate some of these scenarios into our experiments. The experiments in section 6.1 correspond to queries 1,2 while the ones in section 6.2 correspond to queries 5,6,7. The other queries are studied in section 6.3.
6 Experiments

This section is dedicated to the evaluation of our context graph-based model for object detection and image retrieval by example in a collection of images.

In the following experiments, the knowledge graph, $G_K$, is built from statistical results obtained in [15] on LabelMe\textsuperscript{2} with annotated image database $DB$. This graph presents a general knowledge on 86 different entity categories, on their frequent locations in images (with 9-area/16-area splitting), and their binary/ternary relationships (spatial relationships, co-occurrence relationships).

To describe visual content of each entity category, we use the $\Delta$-TSR description that allows to describe the triangular relationships between interest points (see section 2.1 or [16]). They are stored as description attributes of category nodes in $G_K$. In fact, for each entity present in images of $DB$, we extract all interest points within its boundary (annotated by a polygon). Points are extracted and characterized with SIFT. The size of the visual vocabulary is $N_L = 8000$. In consequence, each entity category can own many $\Delta$-TSR descriptions. The detection of an entity in the query image is done by comparing its $\Delta$-TSR description to each $\Delta$-TSR one of the entity category (this step is encapsulated in function $\text{detectObject}(\text{conf}, cn)$ of Alg. 4 p. 28). The comparison can be stopped immediately when the similarity measure reaches a given threshold.

The test database $DB_{test}$ contains a set of 10000 images randomly chosen from LabelMe in daily contents. The content of these images is very heterogeneous and already annotated. In order to guarantee the quality of the database we verified carefully each annotated image for consistency:

- Firstly, we manually consolidated synonymous labels by correcting orthographic mistakes and merging labels having the same meaning.
- Secondly, we added missing annotations to entities of the considered categories, except for too small size entities or entities belonging to a category having a high frequency of already annotated entities in the image, such as "leaf", "window", "flower", etc. In this way, the statistical results should not be biased by these missing annotations.

In all experiments concerning algorithms presented in section 5 p. 24, we choose threshold $\varphi_p = 0.1$ (the frequency of location), $\varphi_t = 0.3$ (the threshold of true positive), $\varphi_u = 0.15$ (the threshold of uncertainty). These thresholds were determined from different experiments: we vary thresholds $\varphi_p$, $\varphi_u$ and $\varphi_t$ in the interval $[0.05, 0.2]$, $[0.1, 0.3]$ and $[0.2, 0.5]$ respectively, and then we choose the values of thresholds that give the best results in general.

In sections 6.1 and 6.2, we evaluate the ability of describing the image context of the proposed algorithms of section 5. Then, in section 6.3, we evaluate the approach for the image retrieval based on context in using our context graph-base model. This evaluation shows the interest of using this graph-based model in image retrieval in comparison to $\Delta$-TSR approach only.

\textsuperscript{2} LabelMe: http://labelme.csail.mit.edu.
6.1 Evaluation of image context graph building by using unary relationships

In this section, we evaluate the ability of automatic image context graph building with algorithm `buildGraph_01` (Algo.3 p.27) by only using the unary relationships from $G_K$. In section 6.1.1, we present the comparison between the graphs built by this algorithm and ground-truth graphs. Then in section 6.1.2, we evaluate the ability for object detection and localization of `buildGraph_01`. Finally, in section 6.1.3, we present its ability of object detection compared to $\Delta$-TSR.

6.1.1 Global comparison with ground-truth graphs

In this section, we evaluate the similarity between context graphs built with algorithm `buildGraph_01` and context graphs built from image annotations (what we call a ground-truth graph). The similarity measure is computed based on the function of equation 19 p.23. Fig 20 displays the distribution of the similarity measures of 10000 couples of graphs.

The average of similarity measure is 0.531. The highest and lowest measures are 0.79 and 0.27 respectively. The low score is caused by false positives (entity is not present but is detected). Clearly, the absence of an entity category leads to the absence of its relationships that penalizes more the similarity between graphs. However, in average, `buildGraph_01` gives an initial acceptable result.
6.1.2 Ability of object detection and localization vs. ground-truth

By using \texttt{buildGraph\_01}, firstly, we observed that in average for each image, around 42 categories are checked for around 5 different categories detected. Secondly, there are about 14 and 21 location configurations among 138 and 649 different configurations to verify for each category with 9-area and 16-area splitting models respectively. To go deeper, we compare the information contained in the context graph for each image to the one of the annotation. We evaluate the average of precision for each entity category in two cases:

- the category is present in a given location in image,
- the category is absent in a given location in image.

Fig.21 shows the distribution of the mean precision (by number of instances of category) obtained with \texttt{buildGraph\_01} (Algo.3) for each entity category from $G_K$. Fig.21(\textcolor{red}{\#}) indicates the percentage of true positives (according to threshold $\varphi_t$) while Fig.21(\textcolor{green}{\#}) indicates the percentage of false negatives (i.e. entity is present in a given location but it is not detected in this location). The uncertainty of the detection is presented in Fig.21(\textcolor{orange}{\#}). In general, the mean precision of \texttt{buildGraph\_01} reaches 0.526 for true positives, 0.163 for uncertainty and 0.311 for false negatives.

Similarly, we evaluate the precision of \texttt{buildGraph\_01} on the absence of each category. The mean score of false positive is 0.134 (see the distribution in Fig.22), while the mean one of uncertainty is 0.153. Nevertheless, the mean score more than 0.71 of true negatives can confirm a robustness for object detection and localization of our model.
Figure 22 – Average precision of detection step with buildGraph_01 (Algo.3) for each entity category when it is absent.

We illustrate category detection with our approach in Fig.26 of appendix. In this query image, the algorithm detected "car", "tree", "fence" and other categories. The yellow rectangles indicate a confirmation of the detection while the blue ones show an uncertainty.

6.1.3 Ability of object detection and localization vs. Δ-TSR

In this section, we evaluate the impact of using context knowledge for object detection and localization. Firstly, we compare the ability of detection with buildGraph_01 with the one of Δ-TSR. Note that Δ-TSR cannot allow to localize the entity, this method detect only the presence/absence of a category in an image by giving a similarity score. Then, to compare to Δ-TSR, we evaluate buildGraph_01 also on the criterion of presence/absence of a category in a whole image not taking into account its location. The comparison is shown in Tab.3 for Δ-TSR and strategy buildGraph_01 (with and without considering location to be comparable with Δ-TSR).

We observe that detection with Δ-TSR is slightly improved of 1%. This improvement results from the matching of category descriptions on the whole image descriptions. Certainly, buildGraph_01 limits the number of localization to verify, then it collects fewer descriptions from images to compare with category descriptions. Similarly, uncertainty with Δ-TSR are slightly improved of 0.8%, in consequence, the false positive are decreased of 2%. However, this advantage can become an important inconvenient when category $C_i$ is absent. True negative of Δ-TSR decrease of 5%, that means the score of false negative and uncertainty are worse. It results from a false matching between descriptions.
of $C_i$ with other descriptions in the image.

On the other hand, we show that the use of context knowledge can reduce the computation costs notably. We compare the average cost of detection for each category in two models. Note that no indexing structure is used for the two models. The comparison is presented in Tab.4. Logically, by exploiting context knowledge, the object detection of buildGraph_01 reduces considerably the number of comparison while remaining a competitive quality.

<table>
<thead>
<tr>
<th>Category is</th>
<th>buildGraph_01 take into account location</th>
<th>buildGraph_01 do not take into account location</th>
<th>$\Delta$-TSR</th>
</tr>
</thead>
<tbody>
<tr>
<td>True positive</td>
<td>0.526</td>
<td>0.534</td>
<td><strong>0.543</strong></td>
</tr>
<tr>
<td>Uncertainty</td>
<td>0.163</td>
<td><strong>0.158</strong></td>
<td>0.166</td>
</tr>
<tr>
<td>False positive</td>
<td>0.311</td>
<td>0.308</td>
<td><strong>0.291</strong></td>
</tr>
<tr>
<td>False negative</td>
<td>0.134</td>
<td><strong>0.127</strong></td>
<td>0.167</td>
</tr>
<tr>
<td>Uncertainty</td>
<td><strong>0.153</strong></td>
<td>0.159</td>
<td>0.169</td>
</tr>
<tr>
<td>True negative</td>
<td>0.713</td>
<td><strong>0.714</strong></td>
<td>0.664</td>
</tr>
</tbody>
</table>

Table 3 – Comparison of average precisions with the two algorithms.

<table>
<thead>
<tr>
<th>Average number of categories to check (averaged on the set of images)</th>
<th>buildGraph_01</th>
<th>$\Delta$-TSR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>42</td>
<td>86</td>
</tr>
<tr>
<td>Average number of $\Delta$-TSR signatures used per image (averaged on the set of images)</td>
<td>1571</td>
<td>4315</td>
</tr>
<tr>
<td>Average number of $\Delta$-TSR signatures of each category in $G_K$</td>
<td>442</td>
<td>442</td>
</tr>
<tr>
<td>Average number of signatures of each $\Delta$-TSR signatures in $G_K$</td>
<td>73</td>
<td>73</td>
</tr>
</tbody>
</table>

Table 4 – Computation cost comparison between buildGraph_01 and $\Delta$-TSR approaches, in terms of volume of $\Delta$-TSR descriptors and of volumes of categories to manipulate.

### 6.2 Evaluation of image context graph building adding binary relationships

In this section, we study the improvement brought by strategies buildGraph_02 (Algo.6 p.31), buildGraph_03 (Algo.9 p.37) in comparison to building_01 (Algo.3 p.27). Because buildGraph_02 and buildGraph_03 need an initial image context graph, for each image, we choose randomly an annotated entity category from image annotation as the initial information to build its initial context graph. The comparison of these three algorithms is reported in Tab.5.

We observed that:
<table>
<thead>
<tr>
<th></th>
<th>builGraph_01</th>
<th>builGraph_02</th>
<th>builGraph_03</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average number</td>
<td>42</td>
<td>21</td>
<td>21</td>
</tr>
<tr>
<td>Average number of</td>
<td>14/21</td>
<td>14/21</td>
<td>7/12</td>
</tr>
<tr>
<td>location</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>configurations</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>with 9-area and</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16-area splittings</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>True positive</td>
<td>0.526</td>
<td>0.526</td>
<td>0.532</td>
</tr>
<tr>
<td>False positive</td>
<td>0.311</td>
<td>0.311</td>
<td>0.257</td>
</tr>
<tr>
<td>False negative</td>
<td>0.134</td>
<td>0.134</td>
<td>0.116</td>
</tr>
<tr>
<td>True negative</td>
<td>0.713</td>
<td>0.713</td>
<td>0.741</td>
</tr>
</tbody>
</table>

Table 5 – Comparison between builGraph_01, builGraph_02, and builGraph_03.

- builGraph_02 and builGraph_03 reduce considerably the number of category to verify. In average, there are only 21 categories to check for each image.

- builGraph_01 and builGraph_02 approximately inspects, in average, 14 and 21 different location configurations with 9-area and 16-area splitting respectively for each entity category. Meanwhile, in using 9D Spa relationships as binary relationship, builGraph_03 inspects only 7 and 12 different location configurations for each type of unary relationship.

- builGraph_02 does not improve the score of builGraph_01 in terms of detection precision because builGraph_02 only uses co-occurrence relationships to reduce the number of categories to check.

- builGraph_03 improves slightly the score of true positive when a category is present, reduces the one of false positive (the average score is 0.116). When a category is absent, the score of true negative is increased about 3%. The ones of false positive and uncertainty are lowered 2% (see the score of builGraph_01 in Tab.3).

We illustrate category detection with builGraph_03 in Fig.27 in appendix. By giving the information of "building" category, the algorithm shows different locations detected for other entity categories than can have a relationship with "building". We illustrate the algorithm with "car", "fence", "tree". By using binary relationship, builGraph_03 can be used to respond to queries 5, 6 or 7 presented in section 5.4. In comparison with builGraph_01, builGraph_03 reduced the uncertainty in detection for remaining true positive.

6.3 Evaluation for image retrieval

In this section, we evaluate our context graph-based model for the scenario of image retrieval. All the techniques are evaluated under the paradigm of image retrieval by example, in terms of quality of the responses by computing Precision and Recall (P/R) curves (or at least mAP, i.e. mean Average Precision, for secondary results). These measures are averaged over all the images of the tested datasets taken as queries. We propose the evaluation with a database built by giving priority to the annotations.
Figure 23 – Precision/Recall curves of Δ-TSR and context graph-based model for image retrieval.

In this experiment, we classify $DB_{test}$ in different classes defined by the set of annotated categories present in each image (see example of Table 7 in appendix). For example, every images containing "car", "person", "building", "road" belong to the same class. In our framework, we defined randomly many classes by group of categories and chose 20 ones that contain the most images (see Tab.6 in appendix). The number of categories in each class varies between 1 and 5. The comparison of the P/R curves for the two approaches (Δ-TSR and the context graph-based model) gives the Fig.23.

We observe that the graph-based model is superior. Its mAP is 0.79 while mAP of $\Delta$-TSR$_{5D}$ is 0.61. The result of $\Delta$-TSR$_{5D}$ is worse because of the important variability of the visual content in each class of this test database. The similarity measure in the graph-based model is always based on the presence of entity categories and spatial relationships between them, then the better precision is logical.

6.3.1 Example of retrieval

To conclude these experiments, we give an example of image retrieval by example with $\Delta$-TSR in Fig.24 and with the context graph-based model in Fig.25.

7 Conclusion

In this paper, we have presented and evaluated a graph-based model to represent the spatial knowledge existing between entity categories in an image. This graph is totally extensible for adding a new
Figure 24 – The ten first images similar to the query image in terms of visual content ($\Delta$-TSR).

Figure 25 – The ten first images similar to query image in terms of context.
knowledge. The unification of knowledge is guaranteed robustly by using three notions of node situation: true, uncertain, false. Moreover, this knowledge graph helps to localize and detect objects in an image if we can collect some initial information from other categories. And more generally, in the other cases, the location knowledge of an entity category allows to restrict the number of locations for its detection if we do not have any a priori information in the image.

We apply this graph model to represent the spatial context of an image. This representation allows a quick comparison between images based on the context similarity. Each node in the graph has an unique identification, then the matching between two nodes of two graphs can be done quickly with a hashing structure. The context similarity of two images is evaluated on the presence of categories and the similarity of their spatial relationships. So, our graph-based model can be classified with those using the image context a priori for image processing. In that way, for image retrieval for example, the model can strengthen the obtained images filtering, then, the execution time. We have also proposed three algorithms to represent automatically the context of image by using a knowledge graph as external assistance for object detection and localization. We demonstrated also the robustness of these three algorithms for the building of context of image. We have also experimented its relevance for image retrieval by context by comparing our graph-based model to Δ-TSR that allows a similarity search based on visual content.
References


APPENDIX

Figure 26 – Entity categories detected with buildGraph_01 and their locations with 9-area splitting: blue rectangle for uncertain location and yellow rectangle for a sure one.
Figure 27 - Entity categories detected with buildGraph_03 from the given category "building" and their locations: blue rectangle for uncertain location and yellow rectangle for sure one.

<table>
<thead>
<tr>
<th>ID Class</th>
<th>Categories</th>
</tr>
</thead>
<tbody>
<tr>
<td>C01</td>
<td>bicycle, car, road</td>
</tr>
<tr>
<td>C02</td>
<td>bird, grass, lake, tree, path</td>
</tr>
<tr>
<td>C03</td>
<td>bird, plant</td>
</tr>
<tr>
<td>C04</td>
<td>boat, building, lake, sky</td>
</tr>
<tr>
<td>C05</td>
<td>building, car</td>
</tr>
<tr>
<td>C06</td>
<td>building, fence</td>
</tr>
<tr>
<td>C07</td>
<td>car, road, tree</td>
</tr>
<tr>
<td>C08</td>
<td>chair, window</td>
</tr>
<tr>
<td>C09</td>
<td>chimney, roof, building, tree</td>
</tr>
<tr>
<td>C10</td>
<td>door, fence, wall</td>
</tr>
<tr>
<td>C11</td>
<td>flag, road</td>
</tr>
<tr>
<td>C12</td>
<td>grass, flower</td>
</tr>
<tr>
<td>C13</td>
<td>lake, tree, sky</td>
</tr>
<tr>
<td>C14</td>
<td>lamp, tree</td>
</tr>
<tr>
<td>C15</td>
<td>mountain, road</td>
</tr>
<tr>
<td>C16</td>
<td>motobike, table, traffic-light</td>
</tr>
<tr>
<td>C17</td>
<td>person</td>
</tr>
<tr>
<td>C18</td>
<td>sea, sky, mountain</td>
</tr>
<tr>
<td>C19</td>
<td>side-walk, tree</td>
</tr>
<tr>
<td>C20</td>
<td>table, umbrella</td>
</tr>
</tbody>
</table>

Table 6 - 20 image classes in experiment of section 6.3.
<table>
<thead>
<tr>
<th>person</th>
<th>building, car</th>
<th>boat, lake, sky, building</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
</tr>
<tr>
<td><img src="image4.png" alt="Image" /></td>
<td><img src="image5.png" alt="Image" /></td>
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<td><img src="image9.png" alt="Image" /></td>
</tr>
<tr>
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<td><img src="image26.png" alt="Image" /></td>
<td><img src="image27.png" alt="Image" /></td>
</tr>
</tbody>
</table>

Table 7 – Different classes of test database for evaluation in section 6.3.