Similarity of Spatial Configurations in Interactive Layout

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Abstract

A usability requirement for interactive layout assistance systems is the *principle of least astonishment* (Borning et al. 1987) which states that the system should arrange the layout in a way that conforms to the user's expectations.

This paper presents a framework for transformation-based similarity between two-dimensional spatial configurations. Here, similarity is intended to measure the user's expectations when he is presented with a system-side generated layout. The framework is based on results in cognitive science. Firstly, it can serve to validate existing layout algorithms with respect to their ergonomic adequacy. Secondly, it is demonstrated how it can help to design new algorithms respecting the principle of least astonishment. The practical use of the framework is illustrated with UML class diagrams as example domain.

Introduction

In computer assisted layout tasks such as editing UML class diagrams, the user usually modifies a diagram manually until he asks the assistance system to rearrange the layout with the intention to obtain a clearer and aesthetically satisfying layout. The assistance system then should generate a layout with these qualities and that additionally satisfies the user's expectations about the positions of the layout objects.

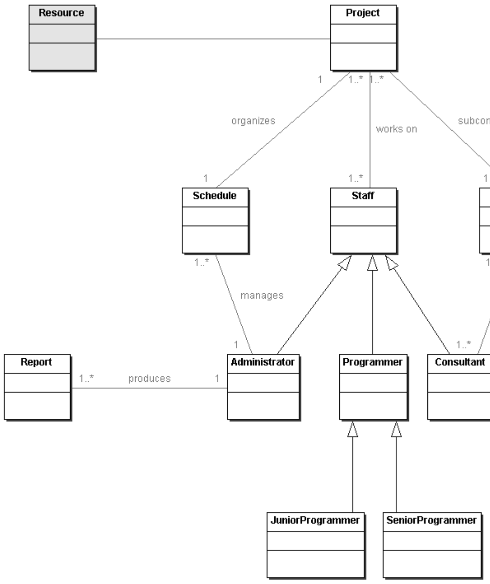


Fig 1 A class diagram

Fig 1 shows a simple class diagram that had been layouted automatically with a widely used CASE-tool (Together ControlCenter). Then the user has added the highlighted class "Resource". When asked for an automatic re-layout, the CASE-tool returned Fig 2 and made drastic, completely unnecessary changes to the layout. Note, that this is frequent system-behaviour.

Based on psychological findings and a cognitive modelling of the transformation of spatial mental models, this paper presents a cognitively motivated framework for the measurement of similarity of two-dimensional spatial configurations. The notion of similarity is chosen in a way that a similar layout, returned as system response, will satisfy the user's expectations about the changed positions.

Special attention is paid to the fact that users often deal with huge diagrams that are difficult to keep in memory.

The organisation of the paper is as follows. The first section presents the similarity framework. Then, its practical use is demonstrated by editing UML class diagrams. The subsequent section sketches how layout algorithms can be designed minimizing the user's astonishment and maximizing the clarity of the new layout. The last two sections present related work and the conclusion.

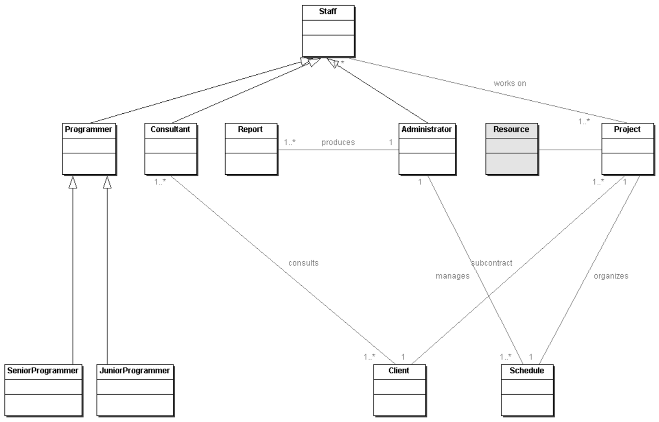


Fig 2 The same diagram after rearranging the layout

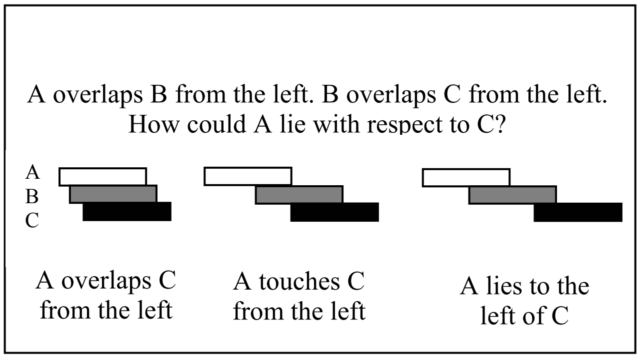
A Framework for Measuring Similarity

The presented framework makes specific assumptions about mental representations and processes operating on them. The proposed notion of similarity is defined on the basis of the cognitive effort necessary to transform the mental model of the original layout into a mental model of the system-generated layout.

Mental representations are influenced by perception, posing domain-independent constraints, as well as domain-specific knowledge. The framework permits this, because it is configurable, mainly with respect to the relevant spatial information and its mechanism that builds groups of the representations of primitive layout objects.

Transformation of Mental Models

Spatial relational inference has been studied by cognitive psychologists for about twenty years. A typical spatial reasoning task is the three-term series task consisting of two premises Xr_1Y, Yr_2Z, and a conclusion Yr_3Z that has to be generated or verified. X, Y, Z denote spatial objects while r_1,r_2,r_3 represent binary spatial relations. Rauh et al. (2000) used such tasks with Allen's (1983) 13 interval relations. An example is shown in Fig 3.



A overlaps B from the left. B overlaps C from the left.
How could A lie with respect to C?

Fig 3 Reasoning task with solutions

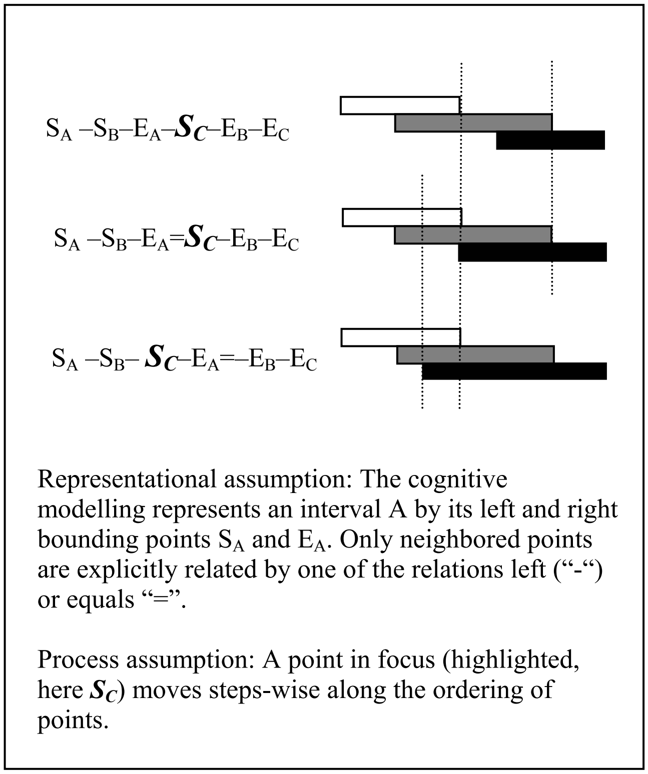
The reasoning strategy most subjects adopt in order to find alternative solutions to spatial relational reasoning problems (e.g. Johnson-Laird and Byrne 1991) consists in the stepwise modification of an initial mental model.

A computational simulation (see Fig 4) of the processes of mental model transformation (Rauh et al. 2000) is in good agreement with the findings. It makes several representational assumptions. The first one is that spatial mental models are not random-access data structures. Access is mediated by a focus which rests on an element of the mental model. If the mental model needs to be accessed (or modified) elsewhere, the focus must be shifted from the element to immediately neighboring elements until it reaches the element in question. These shifts conform to conceptual neighborhoods on Allen's interval relations (Freksa 1992). Interval relations r1 and r2 are said to be conceptual neighbors if a model of intervals X and Y satisfying X r1 Y can be continuously transformed into a model of intervals X' and Y' satisfying X' r2 Y' such that during the transformation no model arises in which a relation different from r1 and r2 holds. In the example task (see Fig 3 and Fig 4), "left of" is neighbored to "touches from the left" that is neighbored to "overlaps from the left".

A second representational assumption consistent with the findings is that the mental model does not encode all relational information explicitly, but only relations between neighbored elements.

The combined effect of implicitly represented relations, spatial focus and a set of local change transformations determines the cognitive effort required to modify the mental model. Effort increases with the number of performed focus shifts and change operations. The modeling reflects an essential property of spatial mental models. They are finite relational structures containing only information that is relevant for the problem to be solved.

Schlieder (1998, 2001) hypothesized and presented first empirical evidence that mental models of two-dimensional configurations of *n* points are organized diagrammatically, i.e. the graph of points and relations is planar. This assumption implies that only $O(n)$ relations (between neighbored points) instead of possible $O(n^2)$ are explicitly encoded which permits a more compact representation. The importance of a compact representation becomes clear in the following section.



Representational assumption: The cognitive modelling represents an interval A by its left and right bounding points S_A and E_A. Only neighbored points are explicitly related by one of the relations left ("-") or equals "=".

Process assumption: A point in focus (highlighted, here $\boldsymbol{S_C}$) moves steps-wise along the ordering of points.

Fig 4 Cognitive modeling (Rauh et al. 2000)

Implications from Working-memory Limitations

Human short-term memory is characterized by its capacity limitations. A reasoning strategy to reduce working memory load is *chunking*, the process of integrating separate pieces of information into units of higher order. The resulting hierarchical structure is more compact and thereby allows keeping in memory more pieces of information (Miller 1956).

Metrical information like precise position, distance, or angle fades away in short-term memory within splits of seconds. Afterwards only vague and incomplete information remains. We account for this by using qualitative spatial relations (e.g. Hernández 1992).

Representation

In the following, we integrate these findings into a framework for two-dimensional configurations.

The representation (see Fig 5) is a relational structure with two hierarchical levels, primitive objects and groups of primitive objects.

According to the common practice e.g. in spatial databases, the form of a primitive layout object or a group is defined as a polygon. This allows approximating the form of most types of layout objects in graphical applications while easily computing spatial relations between them. The polygon of a group represents its outline, e.g. realized as its convex hull.

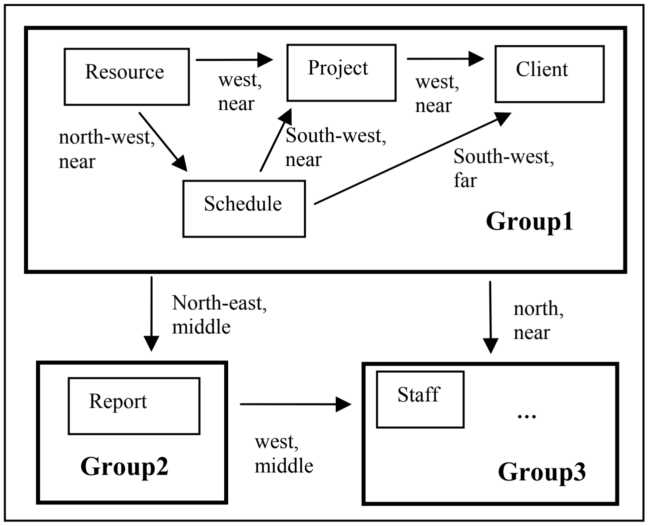


Fig 5 A cut-out of the representation of the grouped class diagram in Fig 6

The next important question is what elements shall be related. Following Schlieder's hypothesis we relate only neighbored objects.

Neighborhood between primitive objects is defined on the basis of the Voronoi-diagram with recourse to the points of the polygons representing their form. Firstly, the Voronoi-diagram is built for the configuration of the vertex-points of all polygons. From this diagram the neighborhood of two primitive objects P1 and P2 is inferred: P1 is neighbored to P2 if there is a vertex-point p1 of P1 and a point p2 of P2 whose Voronoi-regions have a common border.

Accordingly, two groups G1 and G2 are neighbored if there are two neighbored members p1 of G1 and p2 of G2.

Groups are created bottom-up according to the following rule. The neighborhood-graph of primitive objects is partitioned by deleting neighborhood-edges. Each of the resulting connected components becomes a group. Finally, neighborhood-relations between groups are established as described above. The partitioning procedure does not determine the resulting partitioning. This is outsourced to a domain-specific grouping-mechanism.

Now it is clear what elements – neighbors – are related, but not what qualitative spatial information is represented. The use of a system of qualitative spatial relations depends on two criteria. It must represent information like topology, orientation, or distance that is relevant for the diagram type of interest and it must be cognitively adequate, i.e. the relations correspond to cognitively relevant concepts. Up to now, only few relation systems have been experimentally evaluated for their cognitive adequacy, such as the RCC-relation systems (Renz, Rauh, and Knauff 2000) or Allen's interval relations (Knauff 1999).

Therefore, the choice of the appropriate relation systems is not a fixed part of the framework, but object to a suitable configuration depending on the diagram type of interest. A neighborhood-relation may be annotated with an arbitrary number of qualitative relations.

Representing and preserving locally organized groups of layout objects allows the user to quickly find layout objects of interest with a two-step procedure: Firstly, he searches for the group, an element of interest belongs to, and then he "zooms" into the group for a local search.

Transformation-based Similarity

Similarity is a very important concept in cognitive science, and a number of formal approaches have been developed (for an overview see Hahn, Chater, and Richardson 2003). Recently, transformation based similarity has received increasing interest, again (Hahn, Chater, and Richardson 2003). A special type that is similar to Levenshtein edit distance is based on distance of graphs. A graph is transformed into another by applying subsequently one out of as set of basic transformations (e.g. deletions, insertions, substitutions of a graph's nodes or edges). Then distance is defined as the minimum of the costs of all such transformation sequences changing one graph into another.

We propose a notion of distance which is a modification of the edit-distance concept. Edit-distance does not reflect the type of local processing induced by the spatial focus since it allows sequences of transformations where successive transformations may occur at arbitrary relations in the model without consequences for the distance-value. This is in conflict with the representational assumption that transformations may only occur at the current focus position. Therefore, in addition to transformation operators, we need to take into account an operator for focus shifts which also contributes to the costs of an operator sequence. We define the distance between two structures as the minimum of the costs of all operator-sequences (change operators and shift) which transform one structure into the other.

The neighborhood relations can be annotated with several qualitative relations. For each type of relation, the substitution costs are defined as the distance in the graph of the corresponding conceptual neighborhood.

For extended flexibility, transformation costs depend on the weights of the neighborhood-relations.

Note, that due to the fine granularity of the transformation operators, a result of a transformation needs not to be a consistent relational structure, i.e. there exists a configuration of visual objects satisfying all relations.

Application to UML Class Diagrams

UML class diagrams which are supported by all up-to-date CASE-tools basically consist of two types of layout objects, nodes (boxes) and edges. A basic assumption made for applying the framework to the domain of class diagrams is that memory traces essentially encode the positions of the boxes. Spatial neighborhood relations, not functional relations are relevant for minimizing the user's astonishment. This is not surprising, if we take into account that a good layout of graph-like diagrams tries to satisfy limitations of human perceptive faculty by placing functionally related objects close to each other.

It makes sense to assume that only layouts are compared fulfilling a minimal requirement: nodes are pair wise disjoint. Therefore, topological information needs not to be represented. The relative positions of nodes are represented with a qualitative distance measure (zero, near… far) and orientation relations with eight distinctions (north, north-west, west, etc.). For a number of systems of qualitative spatial relations and their conceptual neighborhoods see Hernández (1992).

In class diagrams, not all relations are always equally important. For example, a set of classes inherited from the same superclass typically are positioned side-by-side below this class. While the position below the superclass reflects semantics it will more likely remembered than the exact relative positions of the subclasses. The framework can represent this by different weights of the corresponding neighborhood relations.

Class diagrams lack a natural hierarchical structure with respect to groups of layout objects. This gives leeway to choose an automatic grouping mechanism of interest. We propose to allow the user to partition the configuration himself according to his needs in cooperation with the following mechanism: Elements are grouped together according to the *law of proximity* (see Fig 6). Each group is a connected graph with respect to the neighborhood relations, and the distance between two neighbored group members falls below a predefined threshold. This approach contradicts the widely accepted layout criterion that nodes should be evenly distributed (Purchase et al. 2003).

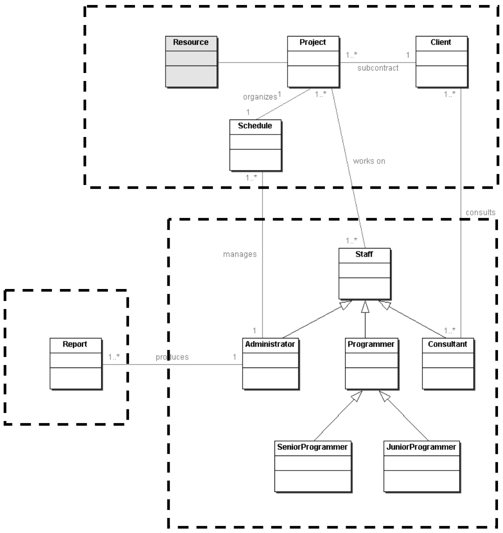


Fig 6 A possible grouping of the diagram

Least-astonishment Layout

In interactive layout, the overall quality of a layout presented as system response depends on two factors: the clarity of the layout itself and the clarity of the change from a user-created to a system-generated layout. Constraint-based layout provides a natural way to integrate both types of requirements. If one wants to control the quality of change, it suggests itself to generate candidate layouts and test them for similarity. The performance of such an algorithm critically depends on purposeful candidate creation. Constraints that should preferably be satisfied by such candidates can be extracted from the relational structure of the user-created layout. In order to enable the user to perform the mentioned two-step coarse-fine localisation of objects, constraints should be chosen such that

1. preserving groups without their internal structure has highest priority,
2. then spatial relations between groups,
3. and finally the internal structure of the single groups.

Preserving a group usually will have to be represented as a set of constraints, e.g. all members of a group have to be inside the same rectangle, while the bounding rectangles of different groups must be disjoint. This implies that constraints cannot be treated separately but in groups.

In order to achieve this, the semantics of the used qualitative relations and, based upon this, the influence of focus movements have to be translated into the language of the constraint solver.

Related Approaches

As it seems, independently from Mental Model Theory in cognitive psychology, applied computer scientists working on interactive diagram layout introduced a similar notion, the user's *mental map* of a diagram (Misue et al. 1995), layout information that may not be changed when adjusting a diagram's layout. Since then, explicit considerations about the nature of the relevant layout information in a diagram became more important in interactive layout. But, until now, the notion mental map is always closely related to the special layout problem of interest and relies on the intuitions of their authors.

Recently, Eichelberger and Gudenberg (2003) applied the idea of the mental map to class diagrams by preserving the positions of unchanged nodes.

In constraint-based interactive layout, there are two approaches considering an interaction scenario, where the user makes local changes to the layout while the system prevents him from violating the given constraints. Marriot et al. (2001) present a class of algorithms that is able to handle certain disjunctions of linear constraints. A similar approach (Schlieder and Hagen 2000) for constraints defined on rectangle-relations is based on results on mental models (Rauh et al. 2000). Starting from a solution, it presents the user with a preview of neighbored solution alternatives. Both methods share the same limitation. If the solution space is not connected, one cannot navigate between solutions in different connected components with the allowed edit operations. These limitations can be overcome with an additional complementary interaction and the presented similarity notion: The user is allowed to modify the layout such that it violates the constraints. Then the assistance system returns a most similar layout that satisfies them again.

Formal concepts of spatial transformation-based similarity using qualitative relations have been investigated also in the area of GIS (Bruns and Egenhofer 1996). In contrast to this paper, they take into account the relations between all visual objects and do not consider the possibility of creating groups of objects.

Conclusion

The initially mentioned usability problem is the question how to satisfy the user's expectations about the positions of layout objects in a rearranged layout. The presented approach has two useful characteristics.

Since, due to costs of focus-movements, the differences of the chosen configurations tend to be local, the user will easier assess all differences between the configurations and be prevented from overlooking some. Furthermore, the possibility of aggregating objects to groups allows a two step search strategy that becomes especially useful in huge diagrams. Firstly, the user looks for the group of an object of interest. When he has found the group, he only needs to localize it within the group. As the example of UML class diagrams shows, grouping can be successfully used even if the type of configuration or diagram does not allow a complete automatic determination of appropriate groups.

Although we underpinned our argumentation as far as possible with psychological findings, additional hypothetical assumptions were needed to obtain a complete framework. Therefore, an empirical validation will be necessary. Currently, an experiment for the evaluation of the similarity framework with class diagrams is in preparation.

The presented framework shows that in certain situations it makes sense to design assistance systems in a way that mental processes on internal representations of diagrams correspond to external processes on diagrams. It is an example of how to use findings in cognitive science to build real life applications.

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