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Show Me How You Act on a Diagram and I'll Tell You What You Think (or: Spatial Structures as Organizing Schemes in Collaborative Human-Computer Reasoning)

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Abstract

Collaborative human-computer reasoning creates asymmetric reasoning situations in which the human and the computational partners possess dissimilar and, to some extent, even incomparable reasoning faculties. In order to produce a satisfactory performance, collaborative human-computer reasoning requires that predictive cognitive processing models of the human reasoning partner are integrated with the computational part. Keeping track of cognitive process flows thus becomes essential. To this end, basic spatial mechanisms are suggested for control of focus in reasoning with diagrams, and they are complemented by other approaches.

Diagrams and Reasoning

It is not just since Larkin & Simon's (1987) investigation of the proverb that "a diagram is worth ten thousand words" that diagrams, sketches, and alike have been attributed with particular perceptual, cognitive, representational, and computational advantages over sentential representations, at least with respect to certain classes of tasks. In fact, much of earlier research had centered on questions of specific mental representational formats for specific types of content, including issues of dual-coding (Paivio, 1971), visual mental images (Kosslyn et al., 1978), or mental models (Johnson-Laird, 1983).

Representational Properties of Diagrams

With respect to reasoning, the special properties of diagrams have been linked to how information is spatially organized (i.e. to how it is grouped) and to how this organization allows for computationally easy ways of information indexing (cf. Larkin & Simon, 1987). Diagrammatic representations require high degrees of representational specificity (Stenning & Oberlander, 1995), and they exhibit effects such as graphical constraining (i.e., only certain types of inferences are permitted about the world that is represented in the diagram; Scaife & Rogers, 1996). Specificity and structure of diagrammatic representation formats frequently permit the drawing of perceptual inferences; for example, information can be read off a diagram that was not explicitly encoded during its construction (Shimojima, 1996; Freksa & Barkowsky, 1999).

Diagrams and Images

Specifically, diagrams have been related to visual mental images, either by computational or representational metaphors. Cognitive mechanisms involved in the inspection of diagrams and those involved in the construction and inspection of mental images are found to interface at later (Kosslyn & Sussman, 1995) and earlier stages of mental processing (Ishai & Sagi, 1995; 1997). This view is further supported by similar patterns of eye movements (i.e. *scanpaths*) in perception and imagery (Brandt & Stark, 1997), and by comparable functional roles of the movements under both conditions (cf. Laeng & Teodorescu, 2002). With respect to attention, common cognitive mechanisms have recently been suggested for the orienting of spatial attention to extrapersonal scenes on the one hand and on mental representations held in working memory on the other (Nobre et al., 2004).

Reasoning with Diagrams and Images

Diagrams and sketches play important roles for carrying out a variety of cognitive tasks: They may, for example, simplify the choices that a reasoner faces while reasoning or they may help him employ the spatial dynamics in the environment (cf. external computation; Kirsh, 1995). Diagrams can be the second part in a *dialectics* between a reasoner's mental processing and the external world (Goldschmidt, 1991, 1995), in an *eternal loop* (Gorayska & Mey, 1996) in which mental constructions are externalized, internalized again, externalized, and so on.

In the dialectic process, the constant re-representations of contents are usually seen as a driving force in imagery-based graphical reasoning, as variants of structure favor different mechanisms of inference and lead to the introduction of new operators and operands. Purcell and Gero (1998), for example, describe how, in design processes, this iteration can indeed lead from unstructured sketches to detailed, well-structured design.

Mental images are constructions that are already interpreted (Logie, 2001) as they are based on working memory content and inherit part of its semantic and organizational structure. Where diagrams serve as externalizations of mental representations, their semantic and organizational heritage is similar to that of images, however, the binding between a diagram's content and its interpretation requires constant mental effort and is more volatile than in the case of images. This is comparable for associated sensorimotor representations, such as scanpaths. It is further in-line with findings that certain operations which are hard to perform with images (e.g. restructuring) become much easier when tried with sketches (Verstijnen et al., 1998).

Reinterpretations of sketches often lead to aspects of the represented problem to be conceptualized in more abstract ways (Schon & Wiggins, 1992). In design tasks, novices and experts have been reported to differ in the use of their own sketches: an expert designer's sketches are generally more structured and offer more clues for perceptual and cognitive inferences than those of a novice; perhaps a reason why own sketches seem to be more ambiguous for novices than for expert designers (Kavakli & Gero, 2001). The graphical patterns used in the reflexive dialogue between the novice and his own sketch and their interpretations may simply be less refined and less stable.

Effects of Diagram Use on Problem Complexity

Reasoning that involves mental imagery processes, externalization and visual perception processes seems effective for many tasks, including such that involve different kinds of visuo- or temporal-spatial configuration, and tasks with elaborate sketching, as in various fields of designing. Generally, this effectiveness is attributed to the close coupling between imagery and visual perception (Finke, 1990; Kosslyn & Sussman, 1995). In this respect, using external diagrams in reasoning tasks can be seen as one strategy to overcome limitations of mental processing (i.e. regarding storage, activation, or attention capacities). Diagrams are apprehended visually and spatially, and the importance of computational offloading of content and processes from the mental to the external world has been frequently stressed (Kirsh, 1995; Wilson, 2002). Specifically, diagrams and sketches are used to keep track of reasoning during decompositional problem solving: complex problems are broken down into parts that can be treated easily enough, and partial results are integrated later on (cf. Hunt, 1991). The parts may either lead to diagrams in their own rights, or exist only virtually and temporarily by means of focusing attention on parts of a larger diagram. Where problem solving is sequential, this may imply using the result of the previous step for the current one (compare the 'piecemeal' strategy along the causal chain of events in the mental animation of simple mechanical systems as described by Hegarty, 2000).

Another way of breaking a problem's complexity down with diagrams is by focusing on certain *aspects* of a problem (especially for problems with open problem spaces such as frequently found in design tasks, cf. Bertel et al., 2004). In problem solving, aspectual diagrams serve as filters that emphasize certain feature dimensions of a problem and lead to the omission of others.

Collaborative Reasoning

When humans work in teams, the result and format of their work may differ from products of individuals. For instance, when asked to assemble pieces of furniture, people working in pairs have been found to be faster and more accurate than individuals; however, when asked to provide detailed assembly instructions afterwards, the pairs produced significantly less diagrams, and less effective ones, even by their own ratings (Heiser & Tversky, 2004). Why there is much to speculate about whether this particular result is caused by a preference for speech over diagrams in social interaction, there is no doubt that in complex tasks collaboration between individuals is essential for a successful problem solving, such as in many design or engineering tasks where much expertise is required (Moore, 2000). It seems likely (yet is empirically unverified) that the effect found by Heiser & Tversky would lessen with more complex problems whose solution puts more stress on cognitive systems (i.e. regarding storage) and, thus, requires more use of external representation formats.

Diagrams for Communication

Diagrams and sketches are frequently employed for communication purposes in teams (cf. Healey et al., 2002). In this case, the stability of interpretations in sketches seems to have an influence on the development of interpersonal graphical codes as stable codes can lead to a reduction in the cognitive loads involved in interpretation (Giordano, 2002).

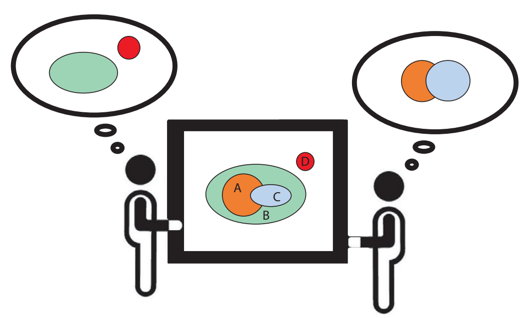

Figure 1: Example of diagram-based reasoning in teams. The task is to visualize a set of topological relations given in the RCC-8 calculus (Randell et al, 1992): {NTPP(A,B), PO(A,C), DC(B,D)}. One of the possible models is jointly constructed on the common external representation in the center. (NTTP = non-tangential proper part; PO = partial overlap; DC = disconnected).

Human-Human Joint Reasoning

When two humans with similar levels of problem solving expertise work together we can assume that, basically, their repertoires of reasoning actions are comparable, although their actual reasoning strategies and preferences may be quite different. Figure 1 illustrates a human-human joint reasoning system in which the reasoners work on a common external representation (shown in the center). Communication and synchronization occur largely through the common representation. At a given time, the reasoners' respective mental representations reflect single solutions (or aspects thereof) rather than representations of the entire problem space. Results from research on mental model construction in spatial and temporal reasoning (e.g. Knauff et al., 1995; Schlieder & Hagen, 2000) suggest that human problem solving of such problem classes is subject to preferences (including interpersonal ones) and usually more resembles an informed depth-first search than broader set search patterns.

Human-Computer Joint Reasoning

We find a different situation where one of the human reasoners is substituted by a computational model (e.g. by a system meant to assist the remaining human with solving the reasoning problem): Frequently, not all constraints of a problem are amenable to formalization, resulting in partially unformalized constraint problems (cf. Schlieder & Hagen, 2000). With such problems, only a subset of the existing constraints can be outsourced to automated constraint solving routines; as a result, the human reasoner and the computational model have to collaborate in the reasoning process. Situations in which constraint solving may not be fully automatically treated include such where certain constraints relate to the human's implicit preferences or knowledge.

The situation in the joint reasoning system thus becomes an asymmetric one[1], in which both partners have different roles stemming from their respective communication and reasoning faculties. Figure 2 depicts such a situation: the human reasoner's mental representations still reflect a single model (or aspects thereof) while the computational partner in the process is (only) capable of keeping track of the reasoning progress with respect to the entire formalizable subspace of the problem space.
In this respect, human and automated constraint problem solving seem dissimilar, at best: to some extent complementary, at worst: somewhat incomparable or incompatible. It is the task of the assistive system's designer to come up with interaction schemes that link up and exploit those faculties of the two sides that are complementary, and to establish and communicate to both the formalizable subsets of constraints in the problem which allow for collaboration to take place.

One way to establish a working communication is by defining a sequence of distinct phases in which only one partner (i.e. the human or the computational assistant) can act on the common external diagram. An example with just two phases can be found in a computational tool for the critiquing of architectural free-hand sketches presented by Oh and co-workers (2004); In it, the architect enters a sketch of a floor plan that is subsequently analyzed against a pre-defined set of constraints by a computational system. The architect is then presented with a list of constraints that are violated and these also get visually annotated in the sketch. Any possible changes to the plan that may be initiated by the outcome of the analysis are left to the human part.
It is easy to see how such a system could be extended to cover more than just one human-to-computational_system-to-human reasoning cycle. What seems much less straight-forward is to incorporate functionality that would allow for both collaboration partners to act concurrently, or for the computational part to make suggestions based on the problem's aspects that are currently attended to by the human reasoner. This could lead to more appropriate suggestions on the part of the computational partner and to a closer collaboration between both. The underlying assumption is that what would follow are a more appropriate assistance to solving diagrammatic reasoning tasks and, thus, better assistive systems.

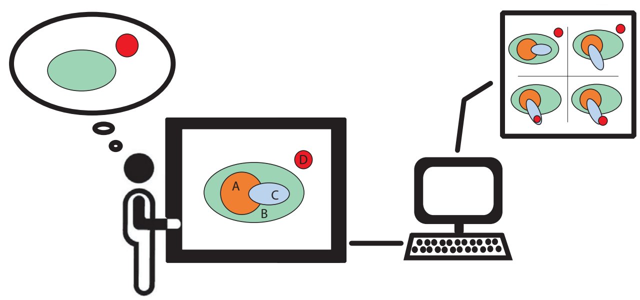

Figure 2: Example of a joint human-computer reasoning system. The task is the same as in Fig.1. One of the four possible models is jointly constructed on the common external representation in the center.

Need for Cognitive Processing Models

With respect to joint human-computer solving of spatio-temporal planning tasks, Seifert et al. (2004, p.9) state:

> Clearly, the performance of an interactive human-computer reasoning system does not only depend on the use of computational resources in the computational part but also on that of human cognitive resources. [...] Human intelligence is one of the bottlenecks in the process; in order to get good collaboration and to allow for better predicting current cognitive stresses in the human reasoner cognitive processing models are required within the computational part.

However, what should be included in these cognitive processing models? And, on which grounds should predictions be made as to a human reasoner's current cognitive state, reasoning strategies, or his current cognitive stresses? There is no promise for simple answers to these questions. What seems necessary as a step towards predicting a current cognitive state and reasoning strategy, however, are reliable models of the reasoner's mental processes which operate his attentional focus: Given a visuo-spatial configuration problem, an external diagram, and a history of previous reasoning steps (i.e. as being manifest in the changes to the external diagram), which aspects of the problem will be most likely tackled next by the user? And why? The following section suggests partial and multiple answers to the latter two questions based on a set of simple spatial organizing principles and mechanisms, as well as on other approaches.

Spatial Structures in Reasoning with Diagrams

It has been recently suggested that, on a functional level of abstraction, a set of spatial organizing principles exist which are shared by diverse mental subsystems collaborating in mental spatial reasoning (Engel et al., 2004). This suggestion is in-line with a distributed account of executive control that relies on functional general basic mechanisms (Cowan, 1999; Hommel et al., 2004).

Common Spatial Principles and Mechanisms

The organizing principles and mechanisms proposed by Engel and co-workers address issues of control of focus on mental representations held in long-term memory, mental models, and images, as well as on diagrams as externalizations of mental representations; they include operations such as grouping and chunking, zooming and scanning, and sequentialization. The basic idea is that spatial properties in mental knowledge representations lead to characteristic spatial mechanisms in the processes which operate on these representations. As the basic spatial organizing principles and mechanisms exist on a functional level throughout many mental representational domains, and in diagrams, they serve to relate representations and processes of different kinds.

As an example, the semantic and organizational structure of knowledge held in long-term memory influences the structuring of mental models built on top of this knowledge in working memory; the organization in mental models in turn affects the construction of mental images that are based on these, and all have an influence on how a diagram gets constructed that visualizes parts of the knowledge contained. In this way, modifications to representations in one domain can trigger mechanisms in another domain. For instance, attentional shifts in a diagram's inspection could propagate back to attentional and activation mechanisms operating on mental representations. For further examples, please refer to Engel et al. (2004).

Actions on Diagrams Reflect Mental Processes

Basic actions performed on an external diagram reflect basic actions carried out mentally, especially when the diagram is the product of an externalization of mental representations, or (to a lesser degree) when the diagram is being perceived. If we could, thus, capture perceptual and manipulative actions performed by a human reasoner on an external diagram we may be able to extrapolate from these basic mental mechanisms carried out on his mental representations. In this respect, observing an interaction with a diagram provides a narrow window on some aspects of inner processing. This is especially important as there exist little means to directly observe shifts of attentional focus on mental representations; one of few exceptions is presented in Nobre et al. (2004). None of these means, however, seem to be suitable for everyday assistance situations to diagrammatic problem solving.

Models of Mental Processing Help Predict Further Reasoning

The reason why an extrapolation of mental mechanisms and of manipulations to mental representations based on observed actions on external diagrams is crucial for the construction of effective collaborative human-computer reasoning systems is that it allows for predicting next steps of reasoning. Specifically, this is the case when seen in the context of a suitable problem representation and a history of previous reasoning steps. Predicting the next step is in turn important as the prediction could be used to generate actions of the computational reasoner that are well tailored to the current chain of reasoning pursued by the human reasoner (i.e. in that the actions of the computational partner address the same aspects of the problem as currently addressed by the human partner).

Observing Actions on Diagrams

It seems crucial for the presented approach that the actions be recorded which the human partner performs on the commonly used diagram. An electronic medium for the diagram (e.g. an electronic whiteboard) facilitates the capturing of drawing actions, and also helps with effecting output produced by the computational partner to the common diagram. Perceptual actions that point to shifts of attentional focus (i.e. eye movements or gestures) can also be tracked with appropriate devices.

With respect to keeping a condensed history log and matching manipulative and perceptual actions against the problem representations, a classification of the actions seems advisable. This could either be in terms of the basic spatial principles and mechanisms discussed above, or, for example, based on coding schemes developed for protocol analyses of diagram-based designing. Suitable approaches include classifications of actions into diverse physical, perceptual, functional, or conceptual action layers (e.g. cf. Suwa & Tversky, 1997; Suwa et al., 1998).

Predicting Actions on Diagrams

Information gathered from observing the human partner's actions can be complemented by information derived from models that provide reasons for why certain actions on the diagram occur (i.e. why the attentional focus gets shifted). The different models each offer but partial explanations, they may at times be wrong, or even contradictory at others. However, where there exists no single comprehensive model that could offer explanations it seems reasonable to consider as many partial models as possible, and to come up with criteria of when to believe which. Four examples are presented in the following.

Overall Spatial Organization. Models that exploit the overall spatio-visual organization of a diagram seem to be a good start: they can be based on various high- and low-level perceptive mechanisms (e.g. on Gestalt principles), and they can, for example, offer explanations for why certain areas in ambiguous figures such as the Necker cube or Wittgenstein duck/rabbit are inspected together.

Visual Scene Analysis. A cognitively motivated computational system for integrating spatial object and visual scene representations with sensorimotor representations has been developed by Schill and co-workers (2001). During the analysis of a visual scene, these integrated representations are used for control of saccadic eye movements. The model extracts salient 2D features, and reasoning is belief-based. Based on the current visual feature and knowledge gained from previous eye movements, the system determines the new feature that promises maximal information towards an identification of the entire scene. Saccadic eye movements based on feature salience and information gain can be explained.

Causal Problem Structure. The sequence of inspection steps will likely not be random. Often, the causal or functional structure of a problem can provide good indication as to how an attentional focus will move through a diagrammatic problem representation, especially on more global levels. The 'piecemeal' strategies along the causal chain of events in mental animation problems (e.g. Hegarty, 2000) provide good examples.

Top-Level Reasoning Strategies. Naturally, top-level strategies for problem solving can also have an influence on how the human reasoner interacts with a diagram. The strategies include top-down decomposition, bottom-up composition, or schematization of representational content. For an overview on some diagram-based, top-level design methods in architectural design see Bertel et al. (2004).

Concluding Remarks

Diagrams and sketches provide unique opportunities for getting a glimpse at the working of mental reasoning. They are a natural means for interaction in human-human collaboration. As such, they also have excellent potential for collaboration between partners as different as a human reasoner and a computational constraint-solving system; a pairing for which many applications exist. However, we should not expect that interaction will be just as smooth as between humans; on the contrary, much modeling effort is required to synchronize the two partners' reasoning. This paper has provided arguments for a synchronization based on basic spatial mechanisms in diagram; many other approaches seem reasonable, and are almost certainly also needed as simple adequate model of the complex mental processes that make up human diagram-based problem-solving likely do not exist.

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[1] a term used by Christoph Schlieder in an invited talk at the *Spatial Cognition 2004* conference in Frauenchiemsee