Model Construction in General Intelligence

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Abstract. In this conceptual paper we propose a shift of perspective for parts of AI – from search to model construction. We claim that humans construct a model of a problem situation consisting of only a few, hierarchically structured elements. A model allows to selectively explore possible continuations and solutions, and for the flexible instantiation and adaptation of concepts. We underpin our claims by results from two protocol studies on problem-solving imagery and on the inductive learning of an algorithmic structure. We suggest that a fresh look into the small-scale construction processes humans execute would further ideas in categorization, analogy, concept formation, conceptual blending, and related fields of AI.

Keywords: Problem representation, model construction, heuristic search.

In their much-acknowledged Turing lecture of 1975 [16], Newell and Simon proposed that heuristic *search* is a cornerstone of AI. The notion of search is partially motivated by the subjective observation that one actively explores different ideas while working on a problem. However, searching and "finding" a solution by *systematically enumerating every possibility* both a) poses a huge and in the general case intractable computational problem, for computers and for humans, and b) largely overstretches the cognitively motivated metaphor. Newell and Simon address this problem and assert that their methods initially only "controlled" the exponential explosion of search instead of "preventing" it. They proposed several ideas for "intelligence without much search" [16] which later flowed into the cognitive architecture Soar [10]: "Nonlocal use of information" and "semantic recognition systems" advert the value of analogies in reusing knowledge that has already been generated at another occasion. They also point out that "selecting appropriate representations" of a problem greatly facilitates finding a solution.

Despite these ambitions, recent projects in simulating human performance, for example IBM's chess-playing computer DeepBlue [9] and question-answering system Watson [4], still are harvesting large knowledge bases. Their impressive success obscures that these systems clearly lack *generality* with regards to the tasks they can solve. Just think of mixing up DeepBlue and Watson, so that DeepBlue suddenly has to compete in Jeopardy!, and Watson plays a game of chess. Obviously this would fail right from the start because each implementation lacks the front-end for parsing the other's input (which is a non-trivial problem!). Even worse, their vast knowledge bases are largely incompatible.

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One difference to human intelligence is that these programs actually *have to access* huge amounts of data before getting meaningful results, while humans are much more selective in the first place. In this conceptual paper we suggest that shifting the perspective from search to *model construction* might be beneficial to understanding this selectivity. We will first introduce psychologically motivated requirements for general intelligence and phrase our suggestion how the construction of temporary models can account for these. We will then present aspects of model construction as observed in two qualitative studies. Last, we will discuss our findings with respect to their explanatory power for organizing human behavior. The view that we construct models and operate on these is not new in the field of AI and AGI, and we will contextualize our findings at the end of the paper. Our aim is to show how actual observations can contribute to further such ideas.

1 Theoretical Considerations

Newell and Simon's article [16] lays out many conceptions that became standards in AI and very early anticipates improvements that seem inevitable from today's perspective. Their dedicated goal was to implement a system capable of 'general intelligent action' as it can be observed in human behavior:

> By 'general intelligent action' we wish to indicate the same scope of intelligence as we see in human action: that in any real situation behavior appropriate to the ends of the system and adaptive to the demands of the environment can occur, within some limits of speed and complexity. [16, p. 116]

In their pragmatic definition, an intelligent organism is being required to be "adaptive" to real world situations. Let us for a moment consider some properties of how a "real situation" is cognitively represented taking the following example by Marr [14, p. 44]:

(A) The fly buzzed irritatingly on the window-pane.
(B) John picked up the newspaper.

Marr states that when one reads both sentences in conjunction, one instantly infers an "insect damaging" *scenario*. If one would read only sentence (B) one would most probably think of John sitting down and reading the newspaper, instead of the implicit action of "fly-swatting". When reading a gardenpath sentence, the understanding of the sentence that has been generated on the fly does not fit, and one therefore has to reconstruct the meaning. In Newell and Simon's conception, the "ends" of the system are being defined by given (possibly self-assigned) "problems". Marr's example shows that a) it is the situation as a whole, which determines the ends of the system in the manner of a Gestalt. And b), the whole situation sets a behavioral disposition without the necessity for reasoning about it. The neuroscientist MacKay makes a similar point:

> we assume that at any moment, an agent's central organizing system can be specified in terms of some total state of conditional readiness [...] for *action* or the *planning of action*. [13, p. 298; emphasis added]

MacKay focuses on the internal representation of "what is the situation about?". With this in mind, we assert that a situation is determined by (i) the stimulus provided by the environment, (ii) the cognitive structures at the organism's disposal[1], (iii) and most crucially, the 'aspect' (a certain goal or interest) under which the organism encounters the situation. At any moment, the organism's dispositions determine what the situation is about, and what might be done next.[2] Based on these reflections we posit that general intelligence is constructing, instead of searching:

1. One constantly constructs and re-constructs a model of a situation by assembling various structures (aspects) from memory under the conditions of the perceived problem. This model represents the "state" of the organism's apprehension of the situation.
2. The purpose of model construction is to bind and order activated cognitive structures into temporary hierarchies.
3. This hierarchical organization is established according to a superordinate, directing structure, i.e. the 'aspect' in (iii).
4. Problem solving is based on this model and proceeds with this "material" at hand. By executing the model, one "explores" whether the construct holds or whether it runs into problems.

The cognitive representations of a single 'concept' is therefore never present in full flesh (in all possible aspects; cf. [15]). Instead, some aspects of it are being assembled in relation to other aspects of the same or of different concepts. We want to call this a *model* of the situation. From one "cognitive scenario" to the next, the model is being modified according to the dispositions for "actions" and for "planning of actions" (and eventual further input). The following section will illustrate our view based on two qualitative protocol studies.

2 Two Examples of Constructing and Thinking with Models

In two case studies [18, 17] we investigated how subjects construct an understanding and solve problems in an imagery and an inductive learning task. The tasks are comparable insofar as both, if one is inclined to do so, can be conceived as search in different problem spaces. We favor the interpretation of model construction and will support our view by highlighting different aspects: frequent reconstruction (study 1), hierarchical assemblies, and mutual modification between hierarchy levels (study 2).

2.1 Study 1: Construal in Mental Imagery

Imagery is widely considered to be functionally involved in and even essential to creative processes [5]. In [18] we presented evidence that imagery does not operate with

[1] Here we use cognitive structure as a general term pertaining to operators, schemata, single pieces of knowledge and the like.

[2] A claim which is being corroborated by the well-known psychological phenomena of priming and functional fixedness.

static images, but requires frequent *reconstruction* of these. Represented figures are not stable; in contrast to actual 2D images they are not easily analyzable for detail and geometric properties, and do not lend themselves ready to reinterpretation. This conflicts with results of Finke, Pinker and Farah [5] who show that mentally synthesized images can be reinterpreted. An exemplary task of theirs is: “Imagine the letter Y. Put a small circle at the bottom of it. Add a horizontal line halfway up. Now rotate the figure 180 degrees” [5, p. 62].

Apparently, one can mentally *assemble* and *recognize* such a figure.[3] In [18] we used figures of related complexity given by verbal description, for example the assembly suggested in Figure 1. The task here was not to recognize the whole figure but to count all triangles in it. Subjects easily found some of the triangles, but struggled to find all. Here is a part of a typical report:

> *I lose the whole image. It isn’t as clear as before any more. (Can you still examine it?) Yes, but I have to build it up anew. And in considering a detail of the image I . . . somehow have to retrace the constituents, for example putting in the diagonal again.*

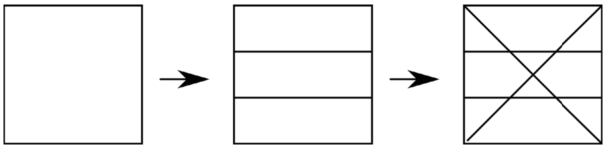

Fig. 1. In mental imagery, the synthesis of this figure is easy to *apprehend*, but *analyzing* it in order to find all triangles contained in it is much harder

Our protocols were full of such accounts. Subjects readily remembered the constituents of the task, but they had to assemble varying parts in order to consider relations between lines that would form triangles. Recognizing triangles is thus deeply entangled with the *attempt to construct these* from the material at hand. Likewise, visual analysis for triangles contained in Figure 1 requires to relate lines.

With respect to model construction we want to highlight that in the presented task a directing structure (in this case a triangle) “consummates” relevant material (various lines) and thereby guides the construction of a particular triangle. When this fails (and no triangle is being recognized) one has to start over again with a new construction. If one relates these reflections to the notion of searching states in a problem space [12], an important point to note is that a state is not “for free”, but has to be constructed and maintained. Imagery drastically shows the human limitation for upholding constructed models; but also in visual analysis one has to keep record of what one “searches for” and of what has been “found” so far. Another point to note is that every constructed state is potentially perceived as “new”. As a consequence, fixed states and problem spaces might be too restrictive to describe the construction of figures in mental imagery.

[3] A process which according to Hofstadter [8] is based on “higher level perception” and which he thinks of as “the core of cognition”.

2.2 Study 2: Inductive Learning of an Algorithmic Structure

Algorithms are a most influential cultural feat. As a tool of thought, they allow the concise and reproducible formulation of observed and constructed, complex regularities. For example, the capability to count arbitrarily far requires the apprehension of a recursive algorithm, that is, a finite system of regularities that can cope with (respectively generate) infinitely many cases. Enumeration in *positional notation* (e.g. the familiar decimal notation) realizes such a system. It allows to generate number strings from a finite set of at least two symbols and a *successor operation* on the symbols (decimal: 0, 1, 2, 3, 4, 5, 6, 7, 8, 9), and the so-called *carry* mechanism, which specifies the order in which the successor function is being applied to different string positions.

In [17] we investigated how subjects make up the regularities of a positional number system by way of example. We "disguised" the surface features of the familiar decimal notation by using a quaternary system with the four symbols A, B, C, D (instead of 0, 1, 2, 3). Subjects were not informed that the task was based on a number system, but were only given an initial symbol sequence (cf. Figure 2) written on a tablet screen and were asked to continue it. No further restrictions were put onto subjects, such that they could continue the sequence while developing their own conceptualization. For the purpose of this paper we want to highlight two interrelated aspects of our findings. First, subjects construct occurrent models of this system as a hierarchical network of metaphors of different scope. And second, these temporary hierarchies scaffold the further development of the subjects' conceptualizations, that is, of the constructed models.

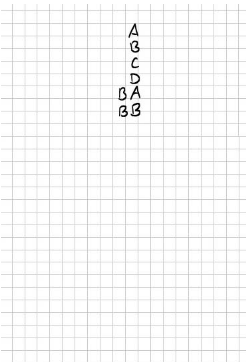

Fig. 2. The sequence was written on a tablet screen by the interviewer until BB. All subjects continued it until BD.

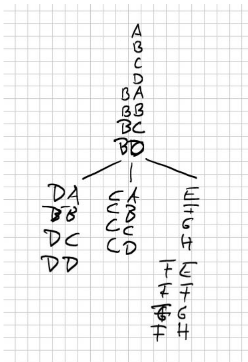

Fig. 3. The screenshot shows three possible branches of the sequence as proposed and written by one subject

All subjects continued the given sequence A, B, C, D, BA, BB by appending BC, BD. Our protocols show that the task was apprehended as to create a linear continuation of two-digits combinations. Subordinated to this comprehensive conceptualization was the way in which combinations were accomplished, namely by repeating the ABCD-series at the right position while after each turn prepending another symbol at the left.

Subjects were irritated though that the first prepended symbol was a B, not an A. They perceived this as an inconsistency ("AA is missing") because they reapplied the ABCD series to the left position. According to the aspects subjects put in focus, continuations after BD showed four major types of coping with this problem, three of which are shown in the tablet screenshot in Figure 3. The left continuation regularly repeats that a symbol is missing. The middle branch defers to cope with the problem, which resulted in later complications (cf. Figure 5). The right continuation avoids the structural problem by appending an analogue version using the next letters of the alphabet. We want to emphasize that in all three cases, the temporal, hierarchical model is the basis of devising and realizing further continuations.

Figure 4 shows the fourth continuation type. In this case the aspect of expanding positions was put in focus. The main idea was that after each repetition of the ABCD series, another symbol is being prepended. This leads to a an expansion that one subject called a triangle, one a pyramid, and yet another associated the related metaphor of "atom splitting". Drawings and gestures (which are being depicted by arrows in Figure 4) also show this metaphorical system comprehension. The trick of this continuation type is that it resolves the A-problem by applying the ABCD series not only vertically, but also diagonally. Compare the following transcript with Figure 4:

> *There is ABCD in the back (position) . . . and then you write B in front, and again the same series (in the back). So at the right the series remains the same throughout (1 - vertical gesture in three batches on the right). At the left there is always one (element) being added, so (2 - diagonal gesture) A, B, C, and here would be D (3 - points at the next position in line).*

The reasoning of the subject goes like this: the sequence starts with A, the first expansion takes a B, the third expansion thus is a C, and fourth a D. This indicates a model with tightly meshed constituents. Nevertheless, the pyramid metaphor is "only" a coarse

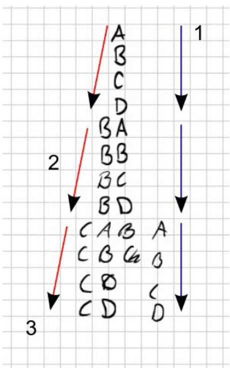

Fig. 4. The metaphor of a pyramid guides the vertical and diagonal application of the ABCD series

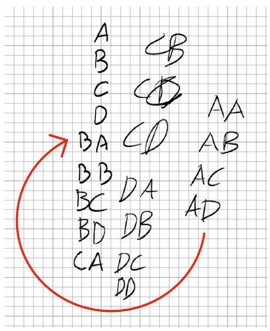

Fig. 5. This continuation temporarily defers coping with the A-problem and later rectifies this by *looping* the initially *linear* progression

directing structure which leaves "blank spaces" in the center, where it does not inform what ought to be done. It only gives a coarse plan of what to do when positions get expanded, but as such, it sets the frame for filling in detail and unfolding other aspects.

The pyramid example shows that focusing on an aspect (position expansion) can bring up a metaphorical structure (pyramid) and thereby modify an earlier structure (the linear succession). The new structure then guides in constructing further detail (fill center digits). Likewise, Figure 5 shows that the deferral of the A-problem leads to completing the linear sequence with AA, AB, AC, AD, followed in turn by BA, BB, BC, BD. This modifies the linear continuation to be a circle, or *loop*. In this example, the subject went on and tried to include the leading, single-digits A, B, C, D into the two-digits combination loop. He thereby reinterpreted these to be two-digits strings as well, prefixed by an invisible "nil-symbol".

Our protocols contain a manifold of such examples, but we want to stop here and summarize how *construction* guides the subjects' coping with the task. In apprehending the given symbol sequence and the underlying generative principle, subjects naturally construct a model consisting of structures of differing scopes. More comprehensive structures employ temporarily subordinated detail structures and thereby not only bring these into relation, but guide their instantiation. As a result, the the model as a whole *determines its further application and development*. But while structures that one puts in focus tend to subordinate and re-arrange other structures, the degree of comprehensiveness does not restrict which structure is being modified. If an instantiation of the assembled model is not readily at hand, *either* detail structure *or* the comprehensive structure may be modified.

3 Discussion: Aspects and Assets of Model Construction

In study 1, problem solving tasks in mental imagery were given to subjects. The subjects' reports indicate that mental images are not analog, 2D-like depictions, but interpreted models, which have to be construed and continuously reconstructed to discover (not "see"!) relations. Study 2 investigated the inductive learning of an algorithmic concept. Similar to study 1, subjects constructed and operated with a model of the given stimuli representing different "parts" of it. But after all, what do we mean by *model construction*?

By model, we mean the temporary, and structurally hierarchized apprehension of the problem situation, which gives an immediate directive of what could be done. The model is being executed until the point where it fails to work. One then has to reconstruct and again, go ahead with testing this new idea. A central feat is that reconstruction usually starts with a very similar approach than before. This process can be viewed as an attempt to fulfill, or *realize* the directive given by the initial model. Otto Selz called this process *complex completion* ("Komplexergänzung") [6]. Construction does not search and find, but instantiates a model according to a certain directive and thereby creates something new. Mutual modification of structures of different coarseness is another, essential property of model construction. On the one hand construction is guided by directing structures, but as with in the pyramid example in study 2 such a structure can also be modified as the result of working on detail structures.

Clearly, *general* intelligence can only be accomplished by an organism which possesses a manifold of *specific* knowledge. This however does not mean that for every concept a mere multiplicity of singular "facts" is being memorized. For example, an emerging comprehensive structure is not necessarily creative or new; quite simple and well-known figures often take the role of directing structures for complex concepts. Components of a temporal construction thus do not inherently belong to one single concept, but are modular, re-usable parts. In their book "Metaphors we live by" Lakoff and Johnson [11]) lively illustrate that we always think in metaphors – that is, in structures which contribute to a multitude of models. Likewise, for instance, the "loop" in study 2 matches the intuitively discovered, comprehensive structure of the famous benzene-ring of Kekulé (and an analogy to a snake biting its own tail).

Each structure in itself can thereby be a quite simple one. As we have seen, a "loop" and a "pyramid" are just *tracks* along which a more detailed understanding is being unfolded. Perceived aspects thus do not necessarily entail the information of a whole, separate domain, but merely some guidance which can be adapted to the respective situation. From a functional perspective, such adaptation is highly profitable because every situation an organism faces is essentially different from any situation it has encountered before. The value of finding (that is, constructing) *analogies* consists in reducing this complexity by clustering possible situations. Thinking of a model of a situation as a construction of multiple, hierarchized aspects allows for flexibility with respect to a contextual embedding, and reciprocally also for stability, because prevalent structures can be flexibly applied.

4 Conclusions

We suggest that construction, in the manner we have exemplified, is at the core of general intelligence. Many classical and recent topics of AI that center around flexible mechanisms with the potential to learn can be viewed as depending on construction, for example the creation of categories and classes, analogical reasoning, concept formation or conceptual blending. Analogies are not simply being found: After initially discovering an analogy the actual relations have to be constructed. These new relations then might constitute something which is new to the intelligent system [7]. It might however also turn out that beside an initial superficial similarity nothing was to be gained and that the analogy could not be established to any interesting depth [20]. The constructive aspect is even more apparent in conceptual blending, where new concepts are created by bringing components of different earlier ones into new relations [3].

Meanwhile, the idea of construction as a central faculty of intelligence has gained some attention – especially in the field of AGI. Thórisson [19] for example emphasizes the necessity to approach what he calls constructivist AI and presents many ideas and arguments that relate to our perspective. Bringsjord and Licato [2] propose a practical test for general intelligence, which requires a candidate program to solve any problem *constructed* from a given set of objects. We want to emphasize that no 'deus ex machina' can present such problems, and that the ability to *construct* "intelligent" problems as well as to *construct solutions to these* are two sides of the same "general intelligence" coin (the indivisibility of which already was anticipated in Selz' theory of complex completion). A solution indeed has to be viewed as a construction in itself. Even when it only consists in a yes/no decision, the problem has to be represented, worked on, and resolved.

We are quite aware that most of the ideas presented here can also be cast in terms of search: Changing a model's hierarchical organization might be seen as re-representation into another problem space, the directing structure could be understood as a certain heuristic etc. Yet, the metaphor of search itself carries along connotations that might overshadow aspects of thought we tried to hint at in this paper. Among others there seems to be the common misapprehension that the knowledge a system actively possesses is described by the transitive closure of its operators (cf. [1]). From this perspective it is tempting to think of the whole problem space as readily available and "awaiting harvesting". The critical problem then is one of intelligently traversing it and containing this process within the realm of tractability. With our constructive perspective we want to emphasize that the actual setup and unfolding of a problem space is arduous cognitive work and in allowing to do so in the first place intricately linked with the question of how to traverse it.

We suggest to take a fresh look on problem solving as model construction, both from a psychological and from an AI perspective. We want to emphasize the importance of small-scale construction processes. It is here where concepts are brought into relation, are being modified, generalized, where analogies are being drawn; on this scale and from these mechanisms, the nature of concepts and of conceptual change should be inferred.

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