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Arguments for the effectiveness of human problem solving

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ABSTRACT

The question of how humans solve problem has been addressed extensively. However, the direct study of the effectiveness of this process seems to be overlooked. In this paper, we address the issue of the effectiveness of human problem solving: we analyze where this effectiveness comes from and what cognitive mechanisms or heuristics are involved. Our results are based on the optimal probabilistic problem solving strategy that appeared in Solomonoff paper on general problem solving system. We provide arguments that a certain set of cognitive mechanisms or heuristics drive human problem solving in the similar manner as the optimal Solomonoff strategy. Specifically, we argue that there is a concrete mathematical background for the effectiveness of human problem solving, and we show how it is connected with several well established components of human cognition. The results presented in this paper can serve both cognitive psychology in better understanding of human problem solving processes as well as artificial intelligence in designing more human-like agents.

Introduction

Problem solving is probably the most common activity of all organisms, especially of humans. We deal with various problems throughout our lives, from infancy to adulthood. Therefore, it is not surprising that an extensive effort has been made to understand the cognitive processes responsible for this ability, and many models of human problem solving have been presented (Hummel & Holyoak, 1997; Ohlsson, 1992; Polya, 1957; Davidson, 1995; Davidson & Sternberg, 1986; Davidson, 2003; Weisberg, 1992; Woods, 2000). Additional models of problem solving and, generally, of human cognitive skills have been proposed by research groups on cognitive architectures like ICARUS (Langley & Rogers, 2005; Langley & Trivedi, 2013; Langley, Laird, & Rogers, 2009; Langley & Choi, 2006), ACT-R (Anderson et al., 2004; Anderson, 1996), SOAR (Laird, 2008; Langley et al., 2009; Nason & Laird, 2005), Polyscheme (Cassimatis, 2006; Kurup, Bignoli, Scally, & Cassimatis, 2011), and others (see Duch, Oentaryo, & Pasquire, 2008; Langley et al., 2009). However, while the current state of research can explain some questions about the scope of problems the human brain can solve, we lack some form of explanations what makes solving (novel) problems so fast, i.e., effective. We note that there have been proposed models or algorithms for general problem solving with special focus on the provable effectiveness (Fink, 2004; Hutter, 2002; Hutter, 2005; Schmidhuber, 2004; Solomonoff, 1986), but these models are not designed to mimic human problem solving process, and as such offer little explanation of this feat. Thus, the question why humans are still more effective problems solvers than computers is still left open (Poole & Mackworth, 2010).

In this paper, we present some ideas on this problem. The core of our arguments revolves around an optimal betting strategy for the following scenario. You are in the gambling house making bets. All bets win the same prize but they have different probability p_i of winning and come at different cost d_i. If you can make each bet only once, what strategy will give you the greatest win probability per dollar? According to Solomonoff (1986), the best strategy is to sort the bets by the ratio p_i/d_i and take them one by one starting from the top. We argue how this strategy relates to the human problem solving process, and what does it mean for its effectiveness.

The paper is organized as follows. First, we outline what is an optimal problem solving strategy in the sense of Solomonoff betting strategy. In the subsequent six sections, we argue how particular six cognitive mechanisms play role in driving human problem solving by the same manner. Finally, we close the paper with some remarks on the applicability of those six cognitive mechanisms in problem solving.

The effective problem solving strategy

In the following text we will use the term *solution candidate* as any sequence of steps the solver can consciously take during the problem solving process. Examples being a particular rotation of Rubik cube, Google search for an existing solution, or drawing a visual representation of a problem and then rubbing out some parts of it. Intuitively, the notion of solution candidate represents a process, method, or idea how to proceed in problem solving, which also includes

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how the solver generates (or derives, or constructs) and selects the information used in this process. Thus, we have that the same process, method, or idea coupled with different approach to generation or selection of the used information represent different solution candidates. Moreover, we do not require the solver to know how to perform these steps (that can be a different problem on its own), but they should be clear enough to articulate or at least to understand. One can observe that in machine problem solving, a solution candidate is an analogue to a formal string of characters that can be fed to a Turing machine to check as a problem solution.

We realize that this definition of the solution candidates is still a little bit vague but this is probably as concrete as it gets in cognitive psychology. Our defense is that too much formalism can lead to deviation from the actual human problem solving towards machine problem solving. In this sense, let us call by *Blind search* a method of solving problems by checking all potential solution candidates in no particular order. By potential solution candidates we mean all the solution candidates the solver can think of at some point in the problem solving process. In machine problem solving, this method can solve any problem (provided the problem has a finite solution), although the time required can be huge. The same holds for human problem solving where the solver can, in principle, write down each combination of words, and check if they put together a valid solution. On the other hand, the following Solomonoff strategy presents a probabilistically optimal, i.e., effective, approach with a high chance of finding a solution in a reasonably short time.

Theorem 1 (*Solomonoff, 1986*). *Let $m_1, m_2, m_3, \ldots$ be candidates that can be used to solve a problem. Let p_i be probability that the candidate m_i will solve the problem, and t_i the time required to test this candidate. Then, testing the candidates in the decreasing order p_i/t_i gives the minimal expected time before a solution is found.*

Remark 2. To set things right, this strategy was probably known before Solomonoff used it in his general problem solving system. However, as he did not mention any references regarding this strategy (Theorem I) in his paper (Solomonoff, 1986), or, for that matter, a proof, which can now be found in (Duris, 2016), and we were not able to trace this strategy to any other source, we settled for the term Solomonoff (optimal) problem solving strategy.

It follows that the effectiveness of problem solving depends on

(i) the database of solution candidates, i.e., knowledge and experience of the solver,
(ii) the ability to generate in the effective order (Theorem 1) and in a short time the appropriate solution candidates.

Thus, there are differences between human solvers based on their knowledge (Voss, Greene, Post, & Penner, 1983) as well as their cognitive skills (Bassok, 2003). For this reason, we will talk about the problem solving effectiveness from the solver's perspective rather than the objective effectiveness of the found solution. Therefore, both novice and expert can solve a given problem effectively even though the objective effectiveness of their solutions might be (vastly) different.

The problem solving process is a recursive one, i.e., solving one problem can create new (sub) problems which have their own sets of solution candidates, and the probabilistically fastest way to solve them is again by Solomonoff strategy. We note that Theorem 1 assumes that the solver knows the values of p_i and t_i exactly what is rarely the case in real life. Instead, the solver may only know approximations of these values. For example, he may only know that a particular method is not very reliable, i.e., it has low value p_i, or that it is very time consuming, i.e., large value t_i. However, this is not necessarily a problem in our theory because the solver usually has, at some point during the problem solving process, only a handful of methods (solution candidates), and this approximate knowledge about such methods can still help him to apply them in the effective order according to Theorem 1. Moreover, in the following sections we will argue that human brain has several subconscious abilities to help the solver to generate solution candidates in the effective order even without the explicit knowledge of the values p_i and t_i.

However, we do not wish to argue that human problem solving is as mathematically optimal as Solomonoff strategy. It is most likely not. Rather, we wish to simply point out that there are several cognitive mechanisms that, on average, seem to drive human problem solving process in the direction similar to that of Theorem 1, and, because of this, they are most likely (part of) the source of the effectiveness of human problem solving. For this reason, these mechanisms should be considered for implementation in cognitive architectures aiming at human-like intelligent agents.

Hypothesis 3. The following mechanisms play a key part in the effectiveness of human problem solving:

1. Discovering similarities,
2. Discovering relations or associations,
3. Generalization,
4. Abstraction,
5. Intuition,
6. Context sensitivity.

In the following six sections we present arguments for each item on the list that it participates in the effectiveness of human problem solving with respect to Theorem 1.

Discovering similarities

Fact 4. *Similar problems often have similar solutions.*

A process of solving problems based on the solutions of the similar problems solved in the past is also called Case-based reasoning (Slade, 1991). The Fact 4 is used by everyone on a daily basis to quickly solve many situations in life, work, etc. It is not hard to see that it also fits perfectly with the Solomonoff strategy. More particularly, the solver identifies a set of problem concepts (properties, features, structure etc.) based on which he can quickly access similar concepts stored in his memory that are associated with an idea how to solve a known problem. In such a case the new problem and the known one are similar via this set of concepts. According to the Fact 4, this process provides the solver with highly relevant solution candidates (i.e., with relatively high values p_i/t_i), and, vice versa, the solution candidates that are not similar with the current problem are not recalled in this way. Moreover, it was observed that humans have cognitive abilities that support effective search for similarities and patterns (Bejar, Chaffin, & Embretso, 1991; Gentner, Rattermann, & Forbus, 1993; Robertson, 2003). Thus, this process is relatively quick and often successful, which is in accord with (ii) above.

Discovering relations or associations

Fact 5. *Related facts, problems or situations (i.e., relevant information) often hold the clues for the solution of the problem.*

A problem involving a right triangle can fire up an association with the Pythagorean theorem which can be used in search of a solution (the right triangle and the Pythagorean theorem are closely related but not really similar). Altshuller (1994) developed TRIZ, a general strategy for creative problem solving, that exploits already solved problems to suggest new solution candidates, and other authors also rely on finding related problems and situations in their problem solving strategies (Polya, 1957; Woods, 2000).

Clearly, related facts, problems, situations, experiences etc. (i.e., relevant information) often hold crucial clues for the solution of the current problem without which the solver would get stuck.