A Literature Review of Expert Problem Solving using Analogy

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We consider software project cost estimation from a problem solving perspective. Taking a cognitive psychological approach, we argue that the algorithmic basis for CBR tools is not representative of human problem solving and this mismatch could account for inconsistent results. We describe the fundamentals of problem solving, focusing on experts solving ill-defined problems. This is supplemented by a systematic literature review of empirical studies of expert problem solving of non-trivial problems. We identified twelve studies. These studies suggest that analogical reasoning plays an important role in problem solving, but that CBR tools do not model this in a biologically plausible way. For example, the ability to induce structure and therefore find deeper analogies is widely seen as the hallmark of an expert. However, CBR tools fail to provide support for this type of reasoning for prediction. We conclude this mismatch between experts' cognitive processes and software tools contributes to the erratic performance of analogy-based prediction.

Keywords: expert, problem solving, ill-defined, well-defined, analogy, case based reasoning, CBR, personality

1. INTRODUCTION

In this paper we consider software project cost estimation from a problem solving perspective. In cognitive psychology, problem solving has an extensive empirical basis. However, much software engineering research has tended to emphasize algorithmic aspects and treat humans as something of a "black box". We consider the specific problem solving situation of software experts making project predictions using analogical techniques. In its automated, algorithmic form, this is case-based reasoning (CBR). CBR tools are often used by project managers and other experts when attempting to solve ill-defined problems, but results are inconsistent (Mair & Shepperd 2006). This inconsistency may be a result of many factors. For example, while it is commonly understood that analogical reasoning is based on how directly the given problem corresponds to the problem solver's schemata (Akin 2001), CBR tools are based on algorithmic approaches. If the problem is ill-defined, the problem solver continuously restructures the problem in order to search for an appropriate solution. These changes in representation affect the use of analogical reasoning and demand the use of other strategies. Hence, if CBR tools are based on algorithmic processes, and humans use a range of strategies to solve the problem at hand, there is a potential mismatch between the nature of the CBR tool, the task, and the cognitive processes.

This paper contains a description of the fundamentals of problem solving from a cognitive psychology perspective. Then we narrow our focus to identify what is known empirically about analogical reasoning by professionals for solving ill-defined problems. To do this we use a systematic literature review (SLR), which is an increasingly used research instrument in software engineering. For background information on reviews see Petticrew (2001) and for a review of recent SLRs in software engineering see Kitchenham, Brereton, Budgen, Turner, Bailey & Linkman (2009). Finally we discuss how this insight may enrich our understanding of cognitive processes involved in problem solving and how this might impact a future research agenda.

2. BACKGROUND ON PROBLEM SOLVING PROCESSES

Problem solving involves memory, attention and perception. These higher cognitive processes are used to search for a solution to a given problem or reach a goal. They differ according to the problem solver's knowledge, experience and skills (Wang & Chiew in press). Generally, the problem is: (i) identified (the initial state), (ii) represented (actions to reach the goal state), and (iii) the course of actions to reach the solution (the goal state). Hayes (1978) proposed that the distinction between well-defined and ill-defined problems was the space of possible move sequences given the context in which the problem is set and the information-processing limitations of the problem-solver. In a well-defined problem (e.g. the Tower of Hanoi) the start-state, goal-state, and available operators and constraints are known in advance and heuristics, such as hill-climbing and means-ends analysis, are central to human performance (Simon & Reed 1976). On the other hand, in ill-defined problems, one or more states and operators may be ill-structured, or not known. Such characteristics define problems faced by project cost estimators in software engineering. Hence in this paper, we focus on ill-defined problem solving. Additionally, we consider expert problem solvers because typically software project cost estimators are experts.

In contrast to novices, experts have greater domain knowledge (Reiter-Palmon & Illies 2004), larger search space (Bonnardel, Marmeche 2004), advanced ability to recognise familiar patterns (Chase & Simon 1973), and represent problems at a deeper level (Day & Lord 1992), they are able to flexibly structure knowledge into meaningful chunks (Glaser 1989), encoding (Chase & Simon 1973) and organising (e.g. Chi, Feltovich & Glaser 1981) knowledge structures differently. Experts use a range of strategies including algorithms, heuristics (such as hill climbing and means-end analysis) and analogy to solve problems (Newell & Simon 1972).

The phenomenon of analogical reasoning has been used as the basis for the design of knowledge management tools, including those which use analogical or case-based reasoning (CBR). Using the concept that history repeats itself, but not exactly, CBR has been used to address many software engineering problems including cost or effort prediction. However, the variability of results when using CBR for prediction is difficult to interpret. Recent research interest in CBR as a knowledge management tool has emphasised algorithmic approaches. These are not typically used for solving ill-defined problems. This type of problem demands the application of complex higher-order cognitive strategies that differ from the application of algorithms.

Analogical problem solving or reasoning is a process of comparison using prior knowledge and applying it to the current situation (Gick & Holyoak 1980). The process depends on (i) noticing that an analogical connection exists between the source and the target problem, (ii) mapping corresponding parts of the problems onto each other, and (iii) finally applying the mapping to generate a solution to the target problem (Kolodner 1992, Schank 1990, 1999). In the automated, CBR cycle, the used or adapted solution is committed to memory. This allows a new problem to prompt the retrieval of similar cases. If the retrieved case is not useful, revisions take place until a satisfactory solution is found. This case is retained for later use. Thus solutions are derived from applying the lessons learned from previous problem solving experiences to the solution of the problem at hand (Aamodt & Plaza 1996). In humans, analogical reasoning can be spontaneous or subconscious (Blanchette & Dunbar 2002), but it is not necessarily so (Gick & Holyoak 1980). Gick and Holyoak (1980) found that students using analogical reasoning in problem solving enhanced their performance. However, it was not an automatic or spontaneous process. Rather, they found that prompting to use the analogue increased successful performance from 20% to 75%. This suggests the main problem lies in retrieval and is supported by Keane (1987) who found that domain similarity between the source and target facilitated retrieval. As domain knowledge is a characteristic of an expert, Keane's findings could suggest why experts are likely to use analogical reasoning. In fact, independent evidence for spontaneous and intuitive analogical problem solving leading to better solutions has been found in a range of domains including design (Dahl & Moreau 2002), investment banking (Olsen 2002), medicine (Weber et al. 1993), human computer interaction (Wijekumar & Jonassen 2007) and software engineering (Jorgensen & Gruschke 2008).

Despite its clear value to problem solving, analogical thinking is constrained by many factors: context (Tulving & Wiseman 1976), consolidation (Wixted 2004), categorisation and source encoding (e.g. Craik & Lockhart 1972, Tulving 1974). Encoding constitutes a form of categorisation (Runco & Pritzker 1999) and creative individuals (divergent thinkers) have the ability to categorise in both conventional and unconventional ways which facilitates efficient retrieval by means of analogies and unpredictable associations (Necka, 1999, cited in Runco & Pritzker 1999). Such associative processes enhance creative thinking and problem solving (e.g. Mednick 1962) and have a positive effect on generating new ideas (Bonnardel & Marmeche 2004, Dahl & Moreau 2002, Bonnardel 2000). Sweller (1988) found that when experts interact with automated (e.g. CBR) tools to facilitate the handling of familiar aspects of a problem, cognitive capacity is available to deal with novel aspects of the problem at hand this allows creative thinking. Dahl and Moreau (2002) found that participants, exposed to an analogy, solved a problem more creatively than those exposed to other information.

Analogical reasoning has been recognised as a potentially important problem solving strategy in software engineering for more than 25 years (e.g. Maiden 1991, Myrtveit & Stensrud 1999, Shepperd, Schofield & Kitchenham 1996). Computational models of analogy, such as LISA (Hummel & Holyoak 1997, 2003) have attempted to understand the neural correlates of analogy, but have failed to include perception as well as linguistic representations (Barsalou 1999). In addition, Holyoak (2005) reports that early (e.g. Anderson 1990, Holyoak & Thagard 1989b) later models have not been well integrated. Hence the challenge of understanding human ill-defined problem solving using analogical reasoning remains.

3. SOFTWARE PROJECT COST ESTIMATION BY ANALOGY

We have set out to understand problem solving from its underlying cognitive processes including the application of analogy. Furthermore, we aim to understand the benefits and limitations of analogy as a problem solving strategy in terms of cognitive processing and also in its application to a CBR tool. The following section briefly considers analogy from the software engineering perspective.

Analogical reasoning has been recognized as a potentially important problem solving strategy in software engineering for more than 25 years. For example, Boehm's seminal book on software engineering economics (Boehm 1981) proposes that analogy is one basis for effort prediction problems. These ideas have been subsequently formalised by ourselves (Shepperd, Schofield & Kitchenham 1996) and other research groups, for instance (Myrtveit & Stensrud 1999). The approaches became formalized as CBR tools with quite explicit notions of how similarity between different cases, in this situation software projects, might be measured for example by standardised Euclidean distance. By retrieving similar projects to the target project one can construct a history-based prediction. Challenges include choosing an effective set of features to represent a project and appropriately populating the case-base.

Other applications of analogical reasoning in software engineering are described in (Maiden 1991) on analogy to support requirements engineering, using CBR to support the discovery and reuse of software components (Tessem & Bjørnestad 1997) and for process modelling (Zhuge, Ma & Shi 1997).

However, despite considerable research activity into analogical reasoning as a basis for prediction within software engineering, we find quite mixed experiences. These are best summarized by our SLR that sought to compare empirical results of effort prediction based upon analogy compared with the benchmark method of regression analysis (Mair & Shepperd 2005). Here we found that about 25% of studies were internally inconclusive. We also found that there is approximately equal evidence in favour of, and against, analogy-based methods. Our conjecture is that data analysis based upon historical data sets fails to address real-world issues concerning the interaction between expert problem solver (the person producing the estimate) and the mathematics behind the CBR tool.

4. SYSTEMATIC LITERATURE REVIEW

Having considered the background to analogical problem solving research, we now turn to a more focused question of what is known empirically about the analogical problem solving behaviour of experts when confronted with non-trivial or ill-defined problems such as are encountered in project effort prediction. Note however, we do not constrain our search to the domain of effort prediction and so make an underlying assumption that lessons from more general studies may be relevant to our specific problem domain.

Our goal therefore is to conduct a systematic literature review (SLR) of the empirical literature on cognitive aspects of expert problem solving using analogies for ill-defined problems. The aim is to identify all relevant studies and synthesize the results into a coherent picture that is unbiased and repeatable.

Prior to the review, a protocol was defined which contained an unambiguous description of the inclusion and exclusion criteria that an article had to satisfy in order to be entered into the review. The main objective for our search was to discover which empirical studies examined expert problem solving using analogy. Details are contained in Table 1. Note that we did not use an explicit quality instrument since the empirical methods employed by the different articles were extremely diverse. Instead we merely required articles to be demonstrably refereed. Articles contained a mixture of qualitative and quantitative data.

Since different databases have varying syntactic niceties we present the logical search:

- (cognitive) AND
- (analogy OR "case-based reasoning" OR CBR) AND
- ("problem solving", OR "decision making", OR "cognitive processes", OR predict OR estimate) AND
- (expert OR professional OR experience) AND
- (empirical OR participant OR subject)

Research question	What do we know empirically about expert problem solving using analogies for ill-defined problems?
Search method	Database search plus hand search plus previously known articles
Databases used	ACM, PsychINFO, Science Direct and Web of Science
Population	Experts or professionals
Setting	Open or ill-defined problems
Studies	Empirical research including interviews/surveys, action research, case studies, observational studies, ethnography.
Date of searches	February 2009
Inclusion criteria	Refereed research articles Non-trivial description of an empirical study of expert problem solving Cognitive perspective Includes analogical reasoning
Exclusion criteria	Same empirical study reported more than once[1] Review article Only student / child participants Unrealistic problem Article describes tools, systems or models rather than original empirical research Unable to obtain a copy of the article
Language	English language only
Article dates	Unconstrained

TABLE 1: Systematic Literature Review Summary

Note that each database provides some basic stemming to deal with plurals and other close variants. The initial searches yielded more than 5000 articles from four databases. Duplicate articles were then removed. First titles and then abstracts from all articles were checked against the inclusion and exclusion criteria. Full-text articles were obtained if it was unclear from the abstract whether the study met our criteria. This search was augmented by a hand search of authors known to be active in the area of software project estimation by analogy and articles drawn from one researcher's personal bibliographic database. The final short list of identified articles was then checked by two researchers. In all cases reasons for rejecting these articles were recorded. Citations to relevant articles were then analysed using Google Scholar to attempt to find other articles as the study progressed. Again this procedure used a hand search.

Whilst there is a very large problem solving literature and also a good deal of interest in analogical reasoning, only twelve articles (organised chronologically in Table 2) were found to satisfy all our criteria. Other articles were typically rejected because they:

- were not relevant to problem solving/analogical problem solving
- did not adopt a cognitive perspective
- dealt only with well-defined rather than ill-defined problems
- were focused on a child or student population i.e. not expert or professionals
- were reviews
- did not describe original empirical research

Note that although there is a good deal of activity in the area of software project effort prediction by analogy almost all this work was excluded due to the fact that the perspective is algorithmic rather than cognitive. A total of four papers were related to the software engineering domain (and a further paper partly). Of these, only two (R10 and R12) addressed effort prediction directly. There is some tendency for an increase in activity since 2000.

[1] Where there are multiple articles describing a single study we select the most recent account.

Ref	Authors	Year	Title	Source
R1	Guindon, R. & Curtis, B.	1988	Control of Cognitive Processes during Design: What tools would support software designers?	Proceedings CHI '88:
R2	Sutcliffe, A. & Maiden, N.	1991	Analogical software reuse: Empirical investigations of analogy-based reuse and software engineering practices	Acta Psychologica
R3	Weber, E., Böckenholt, U., Hilton, D., & Wallace, B.	1993	Determinants of diagnostic hypothesis generation: Effects of information, base rates, and experience	J. of Experimental Psychology: Learning, Memory, & Cognition
R4	Visser, W.	1996	Two functions of analogical reasoning in design: a cognitive-psychology approach	Design Studies
R5	Gregan-Paxton, J., & Cote, J.	2000	How do investors make predictions?	J. of Behavioral Decision Making
R6	Olsen, Robert A.	2002	Professional Investors as Naturalistic Decision Makers: Evidence and Market Implications	Journal of Behavioral Finance
R7	Ball, L., Ormerod, T. & Morley, N.	2004	Spontaneous analogising in engineering design: a comparative analysis of experts and novices	Design Studies
R8	Casakin, H.	2004	Visual Analogy as a Cognitive Strategy in the Design: Process: Expert Versus Novice Performance	J. of Design Research
R9	Crespo, K., Torres, J. & Recio, M.	2004	Reasoning process characteristics in the diagnostic skills of beginner, competent, and expert dentists	J. of Dental Education
R10	Jørgensen, M.	2004	Top-down and bottom-up expert estimation of software development effort	Info. & Softw. Technol.
R11	Casakin, H.	2005	Design aided by visual displays: A cognitive approach	J. of Architectural & Planning Research
R12	Gruschke, T., & Jørgensen, M.	2008	The role of outcome feedback in improving the uncertainty assessment of software development effort.	ACM Trans. on Softw. Eng. Methodology

TABLE 2: Included Articles

Table 3 summarises the detailed findings of each of the 12 papers included in our SLR. Some of the headings require a little explanation. 'Natural analogies' indicates whether the study, in some sense, artificially contrived the source analogies, or whether it utilised 'natural' analogies. Of course, the latter implies a good deal more realism.

A variety of problem domains and populations were studied, ranging from architecture to dentistry. In addition, various empirical research techniques were employed. In general, qualitative methods were used, e.g. observation and think-aloud protocols where there were fewer participants. Most studies considered only ill-defined problems. However, study R11 explicitly contrasted problem solving for ill and well-defined problems. Another common theme was to contrast expert with novice behaviour. Here the general expectation was to find that experts are more effective at identifying and utilising analogies, particularly across domains, although study R8 actually contradicted this expectation.

Another aspect of analogical problem solving that has received a good deal of attention is its relationship with creativity. This was particularly noteworthy for the design (including architecture) domain characterised by the use of 'deep' or inter-domain analogies as opposed to surface analogies.

Ref	Population	Type of study	Task	Expert versus novice	Natural analogies	Analogies and Creativity	1. Encoding the target	2. Retrieval from the case base	3. Mapping the target and case base represent-ations	4. Adapt-ation and side effects
R1	software designers	experiment / think aloud	software design	N	Y	Y	N	N	N	N
R2	software engineers	experiment / think aloud	requirements specification	Y	N	N	N	N	Y	Y
R3	doctors	questionnaire	generate diagnostic hypotheses	Y	Y	N	N	N	N	N
R4	industrial designers	observation and think aloud	two design and one software problem	N	Y	Y	N	Y	N	Y
R5	expert investors	experiment	predict business success	N	N	N	Y	Y	Y	Y
R6	financial analysts	survey	investment decisions	N	N	N	N	N	N	N
R7	designers	experiment / observation / think aloud protocols	design an automated car-rental facility	Y	Y	Y	Y	Y	Y	N
R8	architects	experiment / observation / think aloud protocols"	solve design problems	Y	Y	Y	Y	Y	Y	Y
R9	dentists years)"	experiment/ think aloud /interview	generate diagnostic hypotheses	Y	Y	N	Y	Y	Y	Y
R10	project managers + software developers	experiment	estimate project effort	N	Y	N	N	Y	N	N
R11	architects	Experiment / observation / think aloud protocols	solve design problems (	Y	Y	Y	Y	Y	Y	Y
R12	software professiona ls	experiment + interview	estimate the most likely effort of programming tasks	N	Y	N	N	N	N	N

Table 3: Included Study Findings

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1. Encoding the target: this concerns the way the target problem is represented. In CBR this typically takes the form of a vector of features
2. Retrieval from the case base: the way that source cases or analogies are retrieved from memory or in CBR terms the case base.
3. Mapping the target and case base representations: how the source representations are mapped to the target problem, which may involve decomposition, in order to suggest solutions.
4. Adaptation and side effects: how the suggested solutions may be modified and any learning side effects particularly in the form of meta-cognitive lessons.

A typical study is R5 by Gregan-Paxton and Cote (2000). Here results show that financial investors rely on analogical reasoning to generate input to the decision-making. Investors engaged in two distinct forms of analogical reasoning, one driven primarily by structural correspondence (the base and target overlap in terms of the relations linking the individual elements of a representation together) and one driven by surface correspondence (the base and target overlap in terms of the individual features making up their representations). Many investors induced an abstract representation of the structural correspondence of the base companies and used it to predict the outcome in the target company situation (i.e. they engaged in relational reasoning). Thus, findings from this study suggest that investors engage in relational reasoning, a process driven by the structural correspondence of a company to an existing schema. However, the results also indicate that investors engage in literal similarity reasoning, a process driven by surface correspondence on one company to another. This finding implies that literal similarity and relational reasoning may serve as complementary strategies in many decision-making contexts. Despite our expectations, informed from the more theoretical literature, no study we were able to locate considered the role of personality and its interplay with problem solving behaviour.

The other general observation is that the majority of studies, particularly outside the effort prediction domain, adopted a far broader view of analogical reasoning than that encapsulated by CBR. Most notably this features in the view that analogies may be construed as deep (structural) or surface level, that is, feature similarity. This would imply that CBR, and in particular for project effort prediction, is solely operating with surface level analogies. Another difference is the far richer view of how an analogy might be represented. For example, R8 and R11 considered the use of visual analogies and how these might help novices to expand their explorations in the 'problem space' (Casakin 2004).

A summary of the findings of our systematic review follows:

- We found total of 12 studies that empirically examined analogical problem solving of experts from a cognitive perspective. However, none of the studies that we were able to locate considered software engineering as a problem domain.
- Clear empirical evidence that analogical reasoning plays an important role in expert and professional problem solving in a wide range of problem domains.
- The types of analogy (within and cross-domain, textural and visual, detailed and imprecise) varied considerably and likewise the ways that they contributed to problem solving. This seemed to depend upon a number of factors including setting, nature of problem and experience of the problem-solver).
- The majority of studies differentiated between surface analogies (where the target and the solution analogies share similar values for their characterising features) and structural analogies (where deeper analogies are to be found in terms of induced structure rather than feature values). The ability to induce structure is frequently seen as the hallmark of an expert.
- Schema representation is an important determinant of problem solving particularly in terms of locating and using structural analogies.
- Analogies were seen to enhance creative thinking.
- We found no study that investigated personality and analogical problem solving in a natural setting. Thus, there seems to be a gap in the research literature.

Finally, we are aware that the SLR is in many senses preliminary and it is very possible that there are other relevant studies that we have not yet located. This is because of (i) the lack of defined terminology for many of the concepts we are interested in (ii) the lack of a single well-defined 'host' research community and (iii) the rather open-ended nature of our research question.

5. SUMMARY

This research was motivated by the question of why software project managers when using CBR tools to predict project costs has led to rather inconsistent results (see Section 3). By adopting a cognitive psychology perspective we are able to take a broader perspective on problem solving rather than conceiving it as principally algorithmic.

By means of a review of the discipline, and a systematic literature review of empirical studies of analogical problem solving by experts for ill-defined problems, we conclude that the CBR approach adopts a restricted view of analogical problem solving. Essentially CBR seeks to exploit surface-level rather than structural similarity. Certainly this is so for CBR prediction tools that explicitly aim to minimise standardised Euclidean distance between feature sets. The assumption behind such a world-view must be either proportionality or at least some regularity between the problem domain and the solution domain. This is termed proportional or predictive analogies.

We might explore moving into the world of transference or deep analogies. This will require the problem solver (project manager in our case) to induce structure from surface features. Presently such cognitive processes are unsupported by CBR tools such as ANGEL (Shepperd, Schofield & Kitchenham, 1996) and moreover, are potentially hindered due to the representation of features as vectors. Many studies claim that experts can find and use structural or deep analogies unlike novices, and furthermore, that structural analogies are more likely to lead to successful results.

To summarise, tools based solely on algorithmic approaches to problem solving are deficient in many aspects. This could go some way towards explaining the variability of results reported when utilizing these tools for project prediction. Finally, the SLR generated no study that investigated personality and analogical problem solving in a natural setting. We aim to address this gap in the research literature. A deeper understanding of the cognitive processes and approaches involved in human problem solving, combined with knowledge of the impact of the problem solver's personality, will help us design better prediction tools for the future.

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