Informing the Design of Computer-Based Environments to Support Creativity

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Abstract

This paper addresses the problem of creating a human-centered computer-based support environment to facilitate innovation and creative work. It focuses on key factors to be considered in the design and development of any such user support environment regardless of the specific domain for which it may be implemented. The paper reviews psychological literature on how creativity, insight and innovation occur and how they can be fostered in working environments. Based on this discussion the paper then describes a generic set of user or functional requirements intended to apply to any domain specific computer-based working environment for support of creative activities. The paper proposes the conceptual model of a Virtual Workbench as a way of capturing some of these requirements and as a way of organizing thinking about the design of Creative Problem Solving Environments (CPSEs) in general. Finally, the paper proposes one possible translation of the Virtual Workbench and some of the functional requirements into a view of a generic model for CPSEs by describing three component sets of functions that would be a subset of those needed in almost any domain specific CPSE.

Keywords
creative work, user requirements, virtual workbench, insight, expertise

1.0 **Introduction**

This paper addresses the problem of creating a general view of human-centered computing support environments for innovation or creative work. The goal is to describe characteristics of such environments that would hold true regardless of whether the creative work in question takes place in design, in art, in science, or in engineering. After reviewing psychological literature on how creativity, insight and innovation occur and how they can be fostered in working environments, the paper describes a set of user requirements for a creativity support environment. This description is intended to be at a level that is general enough to be applied across several different domains of creative work.

In addition, the paper proposes the conceptual model of a Virtual Workbench as a way capturing some of these user requirements and as a way of thinking about the design, development and deployment of Creative Problem Solving Environments (CPSEs). In the Virtual Workbench model, any particular domain specific CPSE would be composed of a collection of different tools that can be configured and re-configured as needed. Some of these tools would be generally useful and therefore much the same across many different domains of creative endeavor. Clearly some of the tools would, by necessity, be domain specific (e.g., a synthesizer). However, it is expected that some tools that might, at first, appear to be domain specific would actually be conceptually similar or applicable in several domains with minor modifications (e.g., a mathematical equation solver which can be used to solve chemical equations). Similarly, some tools might appear to be domain specific but have the same functionality in several different domains. For example, it is possible to imagine that both an author and a composer might need the electronic equivalent of sticky notes. The notations used by a composer and a choreographer may differ, but the need to capture fragments of thoughts, ideas and relationships with minimal disruption of an ongoing activity would be the same.

Finally the paper goes on to propose one possible translation of the Virtual Workbench, and some of the embedded user requirements, into a view of a generic model for CPSEs. Specifically, the paper describes three major components of a Virtual Workbench that would be domain independent. These three components are: 1) a context sensitive hypertext help and knowledge-base module; 2) a notebook and event report module; and 3) a communication support and digital archive module containing collaborative communications, event logs, transition logs, auto-archived intermediate results of work in progress and any personal "notebook" logs, etc. While the detailed domain content and domain specific tools to be found in a particular CPSE will surely differ in some degree across domains of artistic and/or intellectual endeavor, it is claimed that the general structure and function of the sample CPSE components proposed here, e.g., context sensitive help, will be broadly applicable and will reduce or eliminate the barriers to doing creative work in domains where a creative product is a initial goal or emerges as a goal during ongoing work.

2.0 Is it possible to support creative activities effectively?

Before proposing conditions that need to be created in a computer-based environment to support creative activities, it is desirable to provide reasons to believe that providing such support is actually a reasonable goal. While it is clearly the case that we can not command creative insights or products, there are clear indications in the psychological literature that it is possible to create conditions that will improve the possibility of creative results, even if only by avoiding conditions that are known to disrupt or to work against creativity. Some of these conditions also illustrate the idea that many of the factors are necessary to the production of a creative result even though they are not sufficient to guarantee creative results. For example, in a book based in part on extended interview studies conducted with a number of creators of significant innovations, Csikszentmihalyi (1996) devotes an entire chapter to discussing the implications of his findings for potential enhancement of personal creativity. Among the factors he stresses that can enhance personal creativity is the notion of the individual taking and exercising control over his or her own working environment. "There should be room for immersion in concentrated activity and for stimulating novelty. The objects around you should help you become what you intend to be (p. 146)." However, simply having such control of the working environment is not sufficient to guarantee creative output.

Similarly, Shekerjian (1990) interviewed 40 MacArthur Foundation fellows, engaging them in a structured discussion about their own creative process. For those who may not be familiar with the MacArthur Foundation fellowship program, the awards are made on the basis of a judgment that the awardee has already made, and shows significant promise of continuing to make, creative contributions to his or her domain of artistic or intellectual endeavor. The MacArthur Foundation Fellowships have been dubbed "the Genius Awards" by the popular press in the United States. You do not apply for a MacArthur fellowship and nobody outside the Foundation knows who the nominating committee members are. The awards typically provide several thousand dollars a year support with no strings attached for a fixed number of years, but some awards have been for lifetime support. In either case, the recipients are not required to submit any kind of report to the foundation on how they use their time. In the view of the MacArthur Foundation nominating committee, creative contributions are defined quite broadly. For example, the recipients of MacArthur Fellowships represent a diverse set of domains, ranging from science and the arts to journalism, to law, to education, and to being a professional clown.

In her discussions with the MacArthur Fellows, Shekerjian found several messages that came through strongly. Some of these messages could be posed as recommendations for enhancing personal creativity from people with substantive credentials. The “recommendations” include such things as finding your talent, honing that talent, and being willing to take risks. One attitude common among the Fellows stressed that it is particularly important to "learn by doing." Another attitude of interest involved the idea of forcing one's self to look at the world in a new way or from a new perspective. For example, one of Shekerjian's interviewees was a Pulitzer prize winning journalist who made a practice of taking a periodic leave of absence to go and live in the most remote, isolated village he could get to in a country which he had never visited and where he did not speak the language.

In a recent literature review Nickerson (1999) suggests that there are reasons to believe that it is possible to teach some of the skills required to enhance creativity. While there are factors other than personal skills that clearly come into play in producing a creative outcome, several of the skills that Nickerson suggests are teachable can also be posed as recommendations for enhancement of personal creativity. All of these skills are consistent with a variety of research results, including study of the skills displayed by people with established records of creative work. For example, it is a necessary precursor to creativity that a person believe they can be creative given enough motivation and effort. In other words, enhancing creativity is somewhat akin to gambling--investing time and work in learning the game will not guarantee a winning streak, but, if you are not willing to put some effort and money into learning to play the game to win, the one thing that is certain is that you will not win in the long term.

Even after developing a belief that motivation and effort are necessary and might pay off, that belief is clearly not sufficient to guarantee creative results. As Nickerson points out, the individual must also have the goal of being creative and then proceed to engage in a deliberate program of building the basic skills that are fundamental to a basic education and to the acquisition of domain-specific knowledge. Being intrinsically motivated to do the necessary work for the sake of personal achievement rather than extrinsic reward appears to be important, as does having a willingness to take risks, to exercise curiosity and to engage in domain exploration. Furthermore, the willingness to take risks should be exercised in the context in which one is focused on domain mastery and self-competition rather than concerned about competition with others. Nickerson also suggests that developing and practicing self-management of one's own cognitive resources and putting into practice techniques and strategies for facilitating one's own performance may also be helpful. Regardless of whether one has the goal of producing creative results or not, this notion of deliberate practice focused on personal improvement appears to be essential to the development of high levels of domain expertise (Ericsson, 1996). Creativity in the absence of domain expertise just does not seem to happen (Gardiner, 1993).

Notice that the material reviewed thus far is quite consistent with the view that creative products may result from normal cognitive processes being pushed into dealing with a problem or situation which initially appears to be solvable, but where the answer or way to proceed turns out to be unknown or different than what was originally expected. In arguing for this point of view, Weisberg's (1986) major thesis is the idea that creativity basically emerges from a person's conscious work on a problem that does not solve easily. This impasse forces modifications of earlier attempts to develop a solution. The ongoing modifications make it clear that additional information or different strategies are required if a solution is to be found. Thus, for Weisberg, and others (e.g., John-Steiner, 1997), one key idea is that the unsuccessful application of past experience leads to an incremental evolution into a solution that is creative, i.e., one that is both novel and appropriate to the situation at hand. In this view, even though the product eventually created may be extraordinary, it is, nonetheless, the result of normal cognitive processes involving the use of an existing knowledge base and the extension of that knowledge into new areas of the problem domain.

In a later work, Weisberg (1993) discusses what he considers to be the three central questions in the study of creativity. Focusing on the individual, Weisberg explores the related issues of the origin of new ideas and whether it is possible to trace the antecedents of novel works (i.e., "the origin and development of creative works" p 242). Focusing on a comparison between individuals, Weisberg addresses the question of why novel works emerge from the work of one person rather than another who may seem to have similar characteristics and qualifications for producing creative work (i.e., what accounts for "the differences between creative individuals and others" (p. 242)). Focusing on the social aspects of creativity, Weisberg explores the question of why some works tend to be valued and others not.

In answer to the question of whether or not it is possible to trace the antecedents of creative work in an individual's thinking over time, Weisberg (1993) proposes that answer is a tentative "yes." He also notes that while not all creative works appear to begin with an analogy, enough do to support the hypothesis of analogical similarity as a source of creative insight. "The changes from initial idea to final work occur first because an individual can anticipate and respond to difficulties with a work before it is actually produced; and second, the work-in-progress can be judged inadequate, in which case attempts will be made to modify it." (p. 255) In addition, "Change in a work can also occur as the result of external events triggering a shift in direction." (p. 255) In his discussion Weisberg stresses the importance of the perception of identity relationships between two problems and the role of analogy and metaphor in creating a sense of similarity between two situations.

In summary then, there are several reasons to believe that there are techniques under the control of an individual that can be utilized to improve the likelihood of coming up with a creative result. Similarly it seems that many of these techniques may well be both teachable and learnable. These observations clearly justify the efforts to constrain the design and development of computer-based working environments for creativity support on the basis of user requirements that help to optimize working conditions for the individual and to support or those techniques or strategies that enhance creative work.

3.0 Does creative work differ across domains?

The issue of whether creative processes differ from one domain to another appears to rest upon whether one focuses on the work and processes or upon the product that results. The position taken in this paper is that while the products and domains of creative work may differ widely and in many ways, it is the domains, their associated constraints, and the resulting products, that differ. The fundamental processes and conditions required to make creative work possible, some of the most important parts of the development of creative products, are not domain specific.

The domains of creative work that have been studied all seem to require the mobilization of appropriate chunks and bits of knowledge and the other components of domain specific expertise such as motor skills, habits of thought, etc. All domains require that domain specific knowledge and skills be combined with the identification and/or clarification of the constraints operating in the situation. In all domains the knowledge, skills and constraints will shape the sorting through and identification of the appropriate building blocks that ultimately become part of a creative result. Finally all domains require the development of a vision--the pattern of relationships among building blocks--that becomes transformed into some sort of reality. The creative process must then consist in part of bringing all these things together at one time and place in an appropriate combination to produce a creative result.

One important mode of thinking in this process involves the formation and use of analogies with which to think about and to understand a domain based problem or challenge. Analogical thinking has been shown to play a critical role in producing at least some creative products in more than one domain (e.g., Bonnardel, 1999; Candy & Edmonds, 1995; Dominowsky & Dollub, 1995; Isaak & Just, 1995; Miller, 2000; Weisberg, 1993). It would clearly seem to be the case that, while the content of analogies might differ across domains, the process of analogical thinking remains basically the same regardless of the domain. To use an analogy, the memory contents of an expert in one domain will clearly differ from the memory contents of an expert in another domain, but the conditions influencing whether or not particular bits or chunks of that knowledge will be remembered are basically the same across individuals, regardless of their domain expertise. So, generally speaking, the salience and/or recency with which certain knowledge has been used both tend to influence ease of remembering that knowledge. Knowledge and skills employed yesterday or with great frequency are generally more accessible than knowledge and skills last used some years ago.

Another way to state the claim made here is that the difference between art and invention, between art and science, or between any two forms of creative endeavor, lies primarily in the domain and the constraints imposed by the domain or imported by the individual. For example, in the Ode to Joy movement of his 9th Symphony, Beethoven uses both the poetry of Schiller and his own music to communicate and mutually reinforce an emotional content that is communicated to some degree by each form of expression in the absence of the other. Musical composition has a somewhat different set of constraints than does the composition of poetry, but in this work Beethoven managed to produce an integrated whole which, for many listeners, has an impact that goes far beyond any effect achieved by either mode of artistic expression experienced separately.

Domain constraints may actually be similar across more than one domain but be weighted differently or given more importance in one domain than in another. For example, one obvious constraint imposed on the process of invention of a new artifact is that the end product must have utility or value on some grounds other than the communication of an aesthetic effect. Aesthetic concerns may be and often are present, but they may have to be subordinated to or be co-equal with functionality or other constraints. For example, the design of a vacuum cleaner which is pleasing to look at and comfortable to use can be considered a design failure if it can not be manufactured on the client's assembly line, packaged conveniently or shipped inexpensively to the point of sale location (Dreyfuss, 1955). Similarly, suspension bridges have a primary function which is quite utilitarian and which can only be ignored at tremendous cost, However, the need for functionality does not prevent bridges from being designed with certain aesthetic and financial considerations in mind as well (Petroski, 1996a).

In his exploration of design thinking, Rowe (1987) emphasizes two fundamental aspects of the design process. First, design thinking has a sequential step-by-step character. Second, design thinking is also well characterized as being a cyclical iterative process in which earlier steps may be repeated. In other words, while the designer may move through a sequence of steps it is clearly the case that the designer can and does cycle back to modify and repeat earlier steps as needed and then feed the new results forward into future steps. This is a description that seems to characterize many, if not all, domains in which people do creative work. For example, in an essay discussing the "evolving systems approach" to creative work, Gruber (1989) proposes that, "all examples of creative insights occur within protracted creative processes." Several illustrations of this phenomenon, and of a number of the other characteristics of creative work, appear in case study accounts in Wallace and Gruber (1989). Each case study author has focused on illuminating the creative product(s) and processes of a person notable for their contributions to some domain of art or science (e.g., Lavoisier, Wordsworth, Darwin). The common approach of each case study involves historical reconstruction of the individual's contribution and of the work leading up to their creative product through the use of notebooks, letters, etc. Also an integral part of each case study is a description of the multiple contexts in which the creator worked (e.g., work tasks, family, professional environment, etc.). One of the consistencies emerging from the historical records of multiple case studies is a pattern of activities much like that described by Rowe (1986) for the domain of design.

Similarly, Petroski (1996b) recounts the history of a number of engineered artifacts. In these cases one or more individuals have repeatedly engaged in working with an object or artifact (e.g., a paper clip or a pencil) to attempt to redesign it and reduce or eliminate its failings. This iterative interaction with artifacts has led to their incremental improvements over time, either by one person or by a series of people. One focus of Petroski's work is to look at how successful innovators in engineering must both devise new technology and also find a way of fitting it into the constraints imposed by the world in which they live. Using case histories of familiar and well documented items such as paper clips, aluminum cans, pencil points and zippers allows Petroski to explore the nature of invention, design and development in the context of the economics, aesthetics, and personal idiosyncrasies that play a part in the final result. As in the case studies in Wallace and Gruber (1989), one of the consistent patterns that emerges is a set of activities much like those described by Rowe (1986).

4.0 The importance and nature of insight

For a variety of reasons illustrated in some of the work already described and to be covered below, another explicit claim made here is that insight—a flash of recognition of a new relationship or new organization of knowledge--is very often a key ingredient in creative work of many kinds. Furthermore, an insight often emerges after intensive interaction with a domain related problem. Thus, understanding The Nature of Insight and the conditions under which insight occurs should inform the way in which we design, develop and deploy Creative Problem Solving Environments (CPSEs) in a wide variety of domains. A CPSE should not block or inhibit insight.

Although it would be rash to claim that all creative products result from an insight, the phenomenon of insight appears to be central enough to the process of creative work of many kinds that it should be explored. But first, an explicit reminder should be stated. As pointed out earlier, it is not possible to either command or predict in advance when an insight, an innovation, or a creative work will occur. However, as the discussion below points out, there are a number of conditions, which can be seen, as necessary to ensuring that novel insights are not blocked from occurring by the individual's working environment even though the presence of these conditions is not sufficient to cause insight.

As a non-trivial example of a necessary but not sufficient condition for insight, if an individual or group does not have a strong affective involvement with the problem to be solved and believe in the importance of the work (Gruber, 1995; cf. Csikszentmihalyi & Sawyer, 1995; Dunbar, 1995) innovation is very unlikely to occur. In other words, strong motivation will not guarantee results, but without it innovative results are not likely. Consequently, the claim made in this paper is that currently we do understand some of the necessary conditions under which insight and innovation can occur, but we do not yet have sufficient knowledge to guarantee that insight and innovation will occur just because some of the appropriate preconditions are present. Effectively, we do know some things, but the best that can be said at this stage of our knowledge is that it is possible to take steps to avoid getting in the way when we develop tools to support creative work. However, when working with computing systems, being able to stay out of the way would be a step forward.

Before reviewing some of the research on the conditions under which insight may occur, one question that must be addressed early on is whether insight is or is not a psychological real phenomenon. That is, when someone reports having had an insight, is this an accurate report of an actual mental event? Or, as some have argued, is the sense of having had an insight a side effect of some other process or event that has proceeded outside of conscious awareness? Historically, the debate over whether or not there is a mental event such as insight goes back to the 1930s and the Gestalt Psychologists' views of problem solving (Davidson, 2003). The Gestalt Psychologists argued strongly that the key to problem solution involves a restructuring of problem elements that may, or may not, lead to a sudden realization of a problem's solution. However, other theorists believe that problem solving involves an incremental process of getting closer and closer to a solution. This has led to a distinction being drawn between "insight problems" and "non-insight problems." The defining characteristic of a non-insight problem is that it involves analytical, step-by-step processing, e.g., problems in chess, arithmetic, logic, etc. The defining characteristic of insight problems is that the solution seems to appear suddenly, without any obvious connection to the immediately prior activities.

In a useful review of the different psychological theories that have been proposed to explore and to try to understand the phenomenon of insight, Davidson (2003) argues that certain commonalities have emerged from the various research traditions stimulated by these theories. Davidson notes that one commonality in the findings of all four research traditions is the important role played by old knowledge in helping individuals come up with new insights into the problem(s) with which they are dealing. In other words, the right bits of knowledge have to be available. The second major common theme Davidson finds running through the results of all four research threads is the importance of "restructuring of mental representation" of the problem. Also, Davidson goes on to point out that all four approaches to the study of insight have found, "…that prior knowledge and its match (or mismatch) with new information can lead to the restructuring of a non-routine problem" (p. 170).

Some work on people's understanding of their own problem solving processes suggests there is indeed a difference between insight and non-insight problems (Metcalfe, 1986a, b ; Metcalfe & Weibe, 1987). Participants who were asked to judge their degree of closeness to solution in working on both types of problems provided data that were consistent with there being a real difference between the two problem types. For non-insight problems, the study participants were better able to estimate their degree of closeness to a solution and were more accurate in evaluating the likelihood that they would in fact solve the problem than they were for insight problems.

As the technology for recording brain activities has become more sophisticated, it now appears that the debate over whether insight involves different kinds of mental processes than does routine problem solving is on its way to being resolved. Recent brain event recording experiments (e.g., Jung-Beeman et al., 2004) have demonstrated that there are significantly different patterns of neural activity for ordinary and for insightful problem solving. In effect the brain appears to marshal its resources differently for the two types of problems.

4.1 **Conditions required to foster insight and innovation**

An important first step in developing an understanding of conditions that facilitate the development of insight and innovation is to dispel an erroneous impression. For a variety of reasons, there is widespread belief in the efficacy of incubation, a period when the problem is simply set aside, in facilitating insightful thinking. This belief appears to stem from the work of Wallas (1926) who proposed a categorization of stages of problem solving, one of which was incubation. This categorization was post hoc in that it was based upon several anecdotal accounts provided by scientists, artists and writers. The difficulty with this type of analysis is that the analysis only looks at part of the data, the cases where there was a setting aside of the problem and an insight occurred. It does not tell us much about insights occurring without setting aside a problem or about the relative frequency of instances where a problem was set-aside without any insight resulting.

The more critical difficulty with the notion of incubation as a technique to enhance creativity, as it is usually presented, is that empirical research typically fails to provide convincing evidence that incubation works (Dominowsky & Jenrick, 1972; Eindhoven & Vinacke, 1952; Olton, 1979; Olton & Johnson, 1976; Patrick, 1937). Rather it appears that if anything resembling incubation effects occur at all they do so only under a very specific set of circumstances (Smith, 1995). These circumstances are that the problem must actually be doable and the solver is blocked in some way from the solution by active information or knowledge which currently interferes with seeing the solution but which becomes less salient over time (Smith & Blankenship, 1989).

In discussing the processes by which insights appear to arise, Csikszentmihalyi and Sawyer (1995) argue that insight is part of an extended mental process requiring total immersion in the problem. They suggest that the length of the innovation process also depends upon whether one is doing problem solving or problem finding. Furthermore, insights are characterized by a synthesis of information from more than one symbolic domain and that the before and after parts of the process appear to be heavily social in the sense that communication with others is important. In addition Csikszentmihalyi and Sawyer (1995) provide a list of conditions under which insight or creative innovations are **unlikely** to occur. For example, it seems clear that innovation will not occur without motivation and time for reflection, along with the opportunity (or inclination) to test possibilities. In addition innovation is unlikely to occur without a thorough grounding in one domain, without contact with others from another domain and without interaction with other domain experts.

Dunbar (1995) has explored some aspects of the importance and nature of contact and communication with others from the same or a related domain in the development of innovations in doing scientific research. His results suggest that the more successful research groups involve people with overlapping but non-identical backgrounds who have ample opportunity to interact and discuss research on overlapping but not identical projects. He also points out that successful research interactions appear to involve small groups working on similar projects and that the members of these groups tend to engage in analogical reasoning in working with each other and with people from other groups working on similar projects. In addition, Dunbar suggests that researchers who want to increase the likelihood of a creative insight should engage in a mixture of both low and high risk projects, that any surprising results should be especially noted, and that the researchers should create a library of problem analogs which can be modified and used in the future (cf. Dominowski & Dollub, 1995; Isaak &

Just, 1995).

As noted above, the environment in which one works can inhibit innovation or it can contribute to the opportunity for insight to occur by reducing known factors that work against the development of insight. For example, Mayer (1995) has observed that insight can arise in many different ways. He goes on to argue that this diversity implies that, in facilitating innovative problem solving, it is important to create systems and environments that are tailorable by the individual (cf. Csikszentmihalyi, 1996). One interpretation of what a tailorable environment might be like is offered by Ippolito and Tweney (1995) who suggest that a working environment to facilitate innovation should make possible both the perceptual aspects of problem representations (e.g., visual, auditory, tactile, etc.) as well as abstract and abstracted representations (e.g., numbers, figures, tables, etc.). Furthermore, Ippolito and Tweney propose that it should be possible for the individual to combine these representations and/or use them to construct mental models for test and evaluation.

The ability to combine and recombine different representations of problems and their elemental parts may very well facilitate the identification or elimination of constraints that inhibit innovative problem solving (Isaak & Just, 1995). For example, Finke (1995) reports on several studies, which suggest that to facilitate insight it is important to understand the basic elemental component pieces with which the person might work to create innovations. Thus it is necessary to provide tools and techniques for generating those basic pieces and for exploring their creative possibilities. Furthermore Finke suggests the idea of developing software to automate the generation of basic elemental components and all possible combinations so as to allow exploration and identification of promising creative paths.

Focusing on the role of problem constraints on problem solving, Isaak and Just (1995) propose that insight or innovative problem solving involves identification of the constraints and then working out a way to release, to relax, or to change those constraints. They go on to argue that invention requires iterative cycles of constraint release and imposition, with appropriate constraining operations being applied during each phase of invention. Isaak and Just also propose the creation of a problem analysis tool that asks for identification of the design space limitations in the form of precise well-elaborated statements of the goal of the invention. These statements constrain the design search space more effectively than vague statements of the problem (cf. Finke, 1995). Additional design space limitations that need to be identified are the technological feasibility of the innovation and any additional constraints (e.g., critical features and limitations) that can be identified from study of any existing earlier precursors of the invention or innovation (cf. Dominowski & Dallob, 1995). Turning their attention to generation of new designs, Isaak and Just (1995) propose that the initial constraints on a design are derived from implicit analogies and that one should engage in analogical and combinatorial play to facilitate the reformulation of invention constraints (cf., Finke, 1995). Finally, Isaak and Just propose that design analysis should involve analysis of any existing designs and/or analogs to the desired invention.

Further support for the importance of an archive of prior problems to serve as analogs to stimulate thinking for future problems appears in the work of Dominowski and Dallob (1995). These authors propose that one useful major component of an environment to facilitate insight or innovation is a library of practice problems that are similar to those that the person needs to solve. Their recommendations suggest that this library should include four major components. First the library should contain mechanisms and suggestions for re-representation of the practice problems (cf. Ippolito & Tweney, 1995). Second, the library should contain stories about the problem solving process engaged in by others as examples (i.e., "war" stories describing problems and solution procedures that worked and didn't work). Third, the library should contain examples that focus on identification and removal of constraints that inhibit innovative problem solving. For example, breaking up functional fixedness and problem solving set. Functional fixedness is the tendency to think of something as having only its intended function and failing to see that it can be used to serve other functions, such as using a small coin in place of a screwdriver to tighten a bolt. Problem solving set describes the tendency to solve problems that appear to be similar to each other using the same routine procedure, without realizing that there may be a simpler or more efficient procedure. Often this routine solution procedures can be just fine but sometimes the old "tried and true" procedures can inhibit the recognition that new ones may be better or even prevent one from recognizing that an entirely new strategy may be required.

Holyoak and Thagard (1995) also discuss some of the research literature on analogical thinking and creativity. They point out that analogical thinking can be a "two-edged sword" in that it appears in some cases to be the source of at least some creative insights and it appears in other cases to be a trap that can lead people astray. In their summary chapter they suggest that creative construction of a useful analogy with which to think about a problem can be facilitated by the use of multiple analogs. However, they point out that we have no good theory to tell us which source analog is the most appropriate one to use in constructing the target. Furthermore, it is not clear how to best combine multiple source analogs when they are potentially combinable rather than in competition with each other.

4.2 The importance of an "external" representation

As noted above, working with a mental image or with some sort of external representation of developing ideas is a common characteristic of many people who have produced creative products. Similarly, Miller (2000) stresses the important role that mental imagery has played in the history of physics. The importance of mental imagery is an emergent theme in many of the case study reports described in Wallace and Gruber (1989). However, the creation of a representation of a problem that is useful in thinking about that problem may take forms other than that of mental imagery.

Indeed, working with objects in the world is a natural part of what many creative people do. For example, the designer of the Lotus racing bicycle, Mike Burrows, is quoted in Candy and Edmonds (1996) as describing his own work in the following way, "I literally think with my hands...just pick pieces of metal out of the rack and drill holes...."

Or consider the following quotation:

> "Revell told me an interesting anecdote concerning how he and his partners came upon the idea of the Toronto Town Hall--two segments facing each other with a circular assembly building in the centre. It was getting near the date for the competition and they were working through the night without having a satisfactory solution. The overhead lampshade threw a strange shadow on the drawing board in front of them. Viljo was idly sketching in the outline of the shadow when it suddenly dawned on them. Here was the exact shape of the perfect solution!" (Mardall, 1968, p. 198)

In other words, working professionals use tools such as drawing, making models, taking pictures, producing or printing out intermediate results, etc. as a way of extending memory, a way of self-education and experiment and as a way of communication with others. For example, Robbins (1997) argues that architects use drawing as their design instrument since they need a tool that enables them to externalize and test their thinking and engage in communication with others. John-Steiner (1997) describes similar processes in several domains of artistic and/or intellectual endeavor. Furthermore, her discussion ranges broadly across different modes of external representation of thought in addition to the purely visual. John-Steiner stresses the importance of the idea that the creation of external representations with which to think is an important part of the process of internalization and integration of new information with existing knowledge structures and processes.

5.0 Mental processes, activities of creative work and functional requirements

Given that analogical thinking is important to the development of new insights in science, are there reasons to believe one can design CPSEs specifically to support and facilitate analogical thinking and other forms of creative activities? Some indicators can be found in the work of Candy and Edmonds (Candy & Edmonds, 1995, 1996; Edmonds & Candy, 1996) who have studied a variety of knowledge workers (e.g., a racing bicycle designer, a speech scientist, a concept vehicle designer, etc.). In their work they also have found analogical thinking to be important for creative work (Candy & Edmonds, 1995). For example, Candy and Edmonds (1996) worked closely with the designer of the Lotus Sport racing bicycle. (The introduction of this bicycle design into Olympic competition represented a successful major re-conceptualization of how racing bicycles should be designed.) Of particular importance to the work of this designer was being able to move his design ideas from one analogous domain to another.

Candy and Edmonds (1995) have proposed a process model for understanding how scientists, designers, and other knowledge workers interact with their subject matter. Resulting from work developing Knowledge Support Systems (Edmonds & Candy, 1993) and from observations conducted of experts at work (Candy & Edmonds, 1997; Candy, 1998; Edmonds & Candy, 1993, Candy et al., 1993), the Candy and Edmonds process model focuses on three modes of human activity. In one mode, Exploration and Evaluation, the critical activities consist of examining data, applying existing rules for analysis of data, and evaluating and refining rules for data analysis. In a second mode, Generation and Invention, the critical activities consist of examination of data and development of new insights, which can be applied to other aspects of the process, e.g., creating new rules for data analysis. The third activity mode, Consideration of the problem constraints and requirements, involves identifying, clarifying, and revising constraints and requirements that limit or shape the end product. Notice the degree to which this process model also consistent with the observations of many of the researchers described above.

Candy and Edmonds (1995) have also proposed software design criteria and extended their work to develop a criterion based approach to interactive system design (Candy & Edmonds, 1997). Several aspects of this work apply to the design of CPSEs. For example, some consistencies emerging from the work of Candy and Edmonds are that the user should, at any time, be able: 1) to take a holistic view, i.e., be able to "step back" and look at the whole picture; 2) to temporarily suspend judgment on any matter; 3) to make unplanned deviations; 4) to return to an old idea and goal; 5) to formulate problems as well as solve problems; and 6) to reformulate the problem space as the conception of the problem or the work in progress evolves over time.

Focusing on recommendations for software tool design, Shneiderman has proposed a conceptually similar analysis in some of his recent work (1999, 2000). Shneiderman introduces a taxonomy of the types of task related activities that seem to characterize various component processes involved with several aspects of human creative work. These activities involve: 1) searching and browsing digital libraries; 2) visualizing data and processes; 3) consulting with peers and mentors; 4) thinking by free associations; 5) exploring solutions using "what-if" tools; 6) composing artifacts and performances; 7) reviewing and replaying session histories; and 8) disseminating results. He suggests that these tasks are to a greater or lesser degree involved in one or more of four basic activities--Collect, Relate, Create, Donate--that he proposes as being characteristic of human creative work

Applying and extending the work of Candy & Edmonds (1995), Hewett and DePaul (2000) argued for a set of design requirements that should guide the design and development of human-centered problem solving environments (PSEs) intended for use in science and engineering. In addition, they argued that a PSE to support such complex innovative work should satisfy the following functional requirements (cf. the earlier discussion of factors which facilitate the possibility of insight and innovation):

The PSE should:

1) Provide a library of macros and analogs.

2) Make possible multiple alternative representations of domain-based problems.

3) Allow those multiple problem representations to be simultaneous so that they can be compared and tested and evaluated.

4) Allow for flexible and tailorable usage of the working environment.

5) Allow multiple configurations of the working environment and its tools that can be saved and restarted so that having to work on multiple projects does not require a shut down and reassembly every time the problem solver switches their attention from one problem to another.

6) Support a variety of multiple store and find operations.

7) Provide multiple access routes into archives and repositories or relevant data or other information.

8) Log processes and intermediate results to enable the user to easily recapture these results.

9) Make it possible for the user to re-configure or re-define the problem domain. Sometimes in working on a problem what one accomplishes first is development of an understanding of what the "real" problem is.

In the discussions of insight and of creative work above, there are clear rationale for claiming that this list of functional requirements is in fact applicable to the design of CPSEs in domains other than Science and Engineering. Much of the discussion of insight provides clear justification for the importance of providing a creative worker with access to a library of stored analogs of both end products and of component parts and processes. Multiple alternative representations of the domain content and/or structure plays a role allowing the creative worker to explore different visions or "what if?"courses of actions needed to add to existing knowledge. Having the ability to view alternate representations simultaneously allows the necessary instantiation of different possibilities that can then be compared or evaluated for how they fit with the emerging "solution."

The importance of tailorability of a working environment for creative work has been stressed in the work of several people reviewed earlier, as has the importance of allowing creative workers to shift work from one problem domain to another related domain with different constraints, etc. Similarly, taken as a group, these particular user requirements provide functionality that would enable the creative worker to do several important things. For example, all of the factors above would make possible the ability to engage in the type of domain exploration that is so much a part of the lives of creative people (Csikszentmihalyi, 1996; Wallace & Gruber, 1989; John-Steiner, 1997; Nickerson, 1999; Shekerjian, 1990). Any computer based working environment with these characteristics would provide multiple ways of externalizing thought and of testing one's own understanding and thinking about the solution or creative product being developed.

The type of flexibility provided by allowing multiple store and find operations and by providing multiple access routes into information archives or repositories seems to be clearly justified by the fact that in creative work one often does not know in advance exactly when a new piece of information or a new component will be needed. Similarly, auto logging of intermediate results and/or paths by which one got to a current state or situation in their thinking can greatly facilitate the process of recapturing what choices were being made at certain points and why they were being made. Finally, if an insight into the problem being worked on takes place and results in a reconfiguration of the creative worker's knowledge or understanding of what he or she is doing it can be essential to allow for the reconfiguration of the CPSE as well. Among other things, all of these user requirements would facilitate the process of domain constraint exploration described by Isaak & Just (1995).

Considering the work reviewed here, it seems reasonable to claim that the set of functional requirements listed above is actually a domain independent generic set of requirements to which any CPSE, regardless of the domain of activity, should be designed. While an actual CPSE, a "point solution" for one domain of creative work, will differ from another, the functionalities themselves are to be thought of as being general and domain independent. For example, a creative writer at work needs to be able to do things with a developing product, i.e., write, edit and revise. But this person also needs some mechanism for being able to capture ideas that occur during the writing process. The most useful solution is one that allows for an effortless, almost reflexive capture of the idea in a way that does not disrupt the work flow but which allows the writer to quickly capture the idea or insight, returning to it later for evaluation, etc. This same type of need exists for a composer developing a new work. The particular instantiation and form of the "ideas" will differ, but the need for easy capture that does not disrupt the workflow is there for both. Finally, it should be noted that the set of functional or user requirements proposed above is almost certainly a subset and that more thinking needs to go into the development and articulation of others.

Another point that needs to be about the design and development of CPSEs is the importance of making it possible for there to be **simultaneous** multiple problem representations which can be viewed or manipulated independently. In many types of intellectual endeavor it is important to be able to compare alternative possibilities or alternative scenarios. For example, in working with representations of data from an epidemiological investigation, the visible similarities and differences between two sets of data may only be detectable when the data representations are placed side-by-side or layered on top of each other. In discussing the domain of design thinking, Lawson (1993) has argued that one fundamental aspect of creative design thinking is the ability to work in parallel on more than one aspect of a design without having to make a final commitment to any one aspect. Clearly there is a need for simultaneous multiple alternative representations. While the question of whether representations need to be layered or side-by-side for comparisons may have to be answered in the context of a particular domain of effort, it is important that simultaneous representations be possible.

6.0 The workbench metaphor for a creativity support environment

As the discussion above demonstrates, an individual engaged in activities which have a creative result as a goal, or who winds up producing an innovation, even if that was not the original intent, will engage in a number of activities and bring several skills and processes to bear over time. Some of these activities, skills and processes can be anticipated in advance. The need for others may only emerge clearly from the individual's interaction with their domain and the constraints imposed by that domain. Clearly a broad range of user requirements need to be taken into account in thinking about the design, development and deployment of a working creativity support environment. For example, as Csikszentmihalyi (1996) and others whose work has been described here (e.g., Shekerjian, 1990; Mayer, 1995; etc.) have pointed out, one of the factors that appears to enhance creativity is the individual being able to take and exercise control over his or her own working environment. In addition this control must make possible the dynamic modification of that environment as the problem, the understanding of the problem, or the domain change over time.

The need for tailorability of working environments poses the question of how best to structure a working environment for the high degree of tailorability demanded by creative work. The approach to thinking about and organizing CPSEs suggested here is the notion of the Virtual Workbench. To explore the notion of a virtual workbench, consider a physical workbench. This working environment has a workspace in which activities take place. Connected to, or associated with this workbench, is a large set of basic components and a kit of tools, each of which has some special purpose use, e.g., nuts, bolts, nails, pliers, a hammer, different types of wrenches, saws and drills, etc. All of these artifacts are stored in locations that make them easily accessible. In some workshops one will find a large pegboard with hooks for storing the tools. Quite often the outline of each tool has been painted on the board to facilitate location of tools and replacement of each tool to its expected location. The individual using this literal workbench either assembles the subset of parts, subassemblies and tools to be used for a special task, e.g., repair of a broken toaster or a broken chair, or has each tool and part immediately ready to hand so that it can be called upon and used when or if the need arises.

Belief in the viability of a workbench metaphor as a generic way of thinking about the design, development and deployment of computer based working environments in general, is partially supported by recent work on development of Problem Solving Environments (PSEs) for scientists and engineers (Hewett & DePaul, 2000; Johnson, et al. 1998), and with a recent workshop on PSEs (Bramley et al. 2000). This workshop on PSEs drew together several of the leading researchers and developers of PSEs for a 3 day session to assess the current status and future directions for work in PSEs for science and engineering.

Among the results emerging from that workshop was the notion that a PSE for group of experts in science and/or engineering can be best conceived of and organized as a virtual workbench consisting of a collection of tools and components which can be selectively brought to bear on each of a series of problems, assembling and re-assembling different configurations of components and tools, depending upon the problem or task demands. This model for thinking about how a PSE should be designed represents a conceptual shift from the work on PSEs for science and engineering in the 1970s when it was thought that a PSE should be a single monolithic program that did everything. (E.g., An equation solver that would handle any ordinary or partial differential equation you might want to give it to solve.) The problems that emerged from this approach were that often such general-purpose packages became cumbersome for the user to be able to use, difficult for the software engineers to maintain, and difficult for either users or software engineers to modify because of the complexity of the PSE.

Conceptually, the domain expert engaged in creative work of any kind already occupies a virtual workspace and literal workspace in which domain knowledge use, knowledge representation and interactive modification of one or more domain related "artifacts" takes place. Connected to or associated with this workspace the domain expert should have a set of component parts, subassemblies and models, along with a range of conceptual and software tools which can be assembled and/or reassembled in different configurations as the understanding of the domain problem changes or when one problem has been completed and it is time to begin working on another. The appropriate virtual workbench configuration can then brought to bear as the need arises in working with a particular combination of domain problems and colleagues.

6.1 Major components for CPSEs

Consideration of the Virtual Workbench and many of the functional requirements described above suggests two things. First, by virtue of its very nature, the workbench metaphor actually incorporates in its basic design several of the functional requirements described earlier. Inherently, a workbench involves special purpose tools that can be used and reused in any of a variety of tasks. Those tools can be configured or brought into use in a way that suits the needs of the person using the workbench/tool set. Furthermore, any workbench to support complex problem solving and creative activities will have some tools that can be used in more than one domain or environment.

A second point to note is that any domain specific CPSE can be expected to have at least some major components which are common across several domains of creative work. The major concern in this section of the paper is to describe some of the support capabilities or components that any CPSE, regardless of its domain should offer. The focus is on three inter-related support facilities, some of the relationships among these support facilities and between these support facilities and the rest of a set of domain specific CPSE. For example, any working environment such as a computer-based CPSE will require an "owner's manual," i.e. a Help Library. In addition, to support the maintenance and improvement of the CPSE, online report and annotation functions should be provided. Finally, the support environment for any CPSE should take advantage of the power of hyper-linkages and make it possible for the user of a domain specific CPSE to access context specific help and other components of the CPSE.

In considering an overall vision for CPSEs, it is quite likely that almost any kit of tools for a domain specific virtual workbench will include tools that allow visualization of structures, visualization of processes, tracing of processes, pre-packaged routines or functions, and modifiable code/structures/processes. It is importance that hyper-linkages be used to make possible context sensitive access to help or to reminders of how something is used. Furthermore, access to this information should be possible from any place within the CPSE where it might be needed or applicable (Meadow, Hewett & Aversa, 1982a, 1982b). In effect, this functionality would make the entire CPSE working environment easily browsed from anywhere within that environment. For example, when utilizing one of the CPSE tools, it should be possible to simply click on a button and have access to a menu of information about the tool, help on the tool, exemplars of its use, the history of an existing "artifact," etc. Such functionality can reduce the burden on human memory considerably and help to eliminate or reduce the impact of distractions created by imperfect knowledge of all the complexities of the CPSE. Since human time is much more expensive than computer time it seems quite reasonable to ask that the computer bear the burden of support for human memory in ways that reduce cognitive load.

Similarly, the virtual workbench should have a user expandable library of re-usable "objects," either literally or metaphorically as appropriate. Depending upon the domain being supported, these objects should include, for example, components, subassemblies of components, models, and design patterns. Since it is intended that each of these objects can be "copied and pasted for re-use", it should also be possible to simply click on a button and have access to a menu of information about the object, including information about the object itself, help on the use of the object and exemplars of use. In addition, since the intent is that these objects are reusable, attached to each object there should be information about the allowable structural changes that can be made to the object and the list of values to be edited. In addition, the creative worker should be able to create a subset of components as needed for future use. The presence of hyper-linkages would make it possible for the CPSE user to access generic help, tool specific help, item specific help, information on use and reuse from virtually anywhere within the environment.

6.1.1 The CPSE "owner's manual."

Structured more or less along the lines of a standard user's manual, this segment of the CPSE user support capabilities should provide such things as a Table of Contents and an Index. Also included should be a basic review and description of the purpose, operation, and contents of the user manual. In addition, each of the artifacts referred to in the manual, be it tool, component, subassembly, model or design pattern, should have associated with it a general introduction to the object or artifact and a discussion of its use. Here hyper-links will also make it possible to: a) cross reference terms or other artifacts as needed; and b) pull up examples of one or more uses of the object or artifact. For example, a tool description would provide a description of the functionality of the tool. It would specify its input, output and use. Finally, the description would provide access to examples of use in practice and even enable the CPSE user try out the tool with a "training wheels" problem in the domain of interest. Research on the "training wheels" approach illustrates its support value in human-centered computing (e.g., Carroll & Carrithers, 1984; Meadow et al. 1982a, 1982b).

6.1.2 The CPSE notebook, online report and annotation form.

With every complex computer program or computer-based working environment comes the problem of bugs or software design choices which have unintended consequences that interfere with the user's ability to function most effectively. Consequently, ongoing improvement and maintenance of a CPSE is a set of activities that can and must be provided for in the most effective manner possible. At any time the user of a CPSE needs to be able to quickly and easily file a critical incident report without major disruption of their work. The user should not have to spend 5 minutes (or more) working out how to report a problem. If they do, they will not file the report. In this critical incident report, which would be stored in an online report file, the user would be able to file bug reports and comments about the usability, and re-usability, of any tool or component contained in the CPSE. Included automatically along with this report would be a record of the context in which the report was activated and filed, thereby eliminating the need for the CPSE user to try to describe that context and steps leading up to a problem. This would greatly facilitate a maintenance programmer's ability to diagnose and fix the problem. Being focused on what they were trying to accomplish, it is often difficult for active users to mentally recreate the sequence of events leading up to a problem in sufficient detail to be useful to the maintenance programmer.

In addition to the bug and usability reports, the CPSE online report form should make it possible for the user to provide commentary, observations and suggestions about any tool and re-usable object in the CPSE. It should also add to the user's ability to capture, quickly and easily, with minimal disruption of their ongoing activities, any suggestions that occur to them about new tools or objects needed in the CPSE, about improvements that need to be made in existing tools or objects, and about any novel uses for a tool or object. The goal is to have this online report form be so readily accessible that the users of the CPSE are in fact able to store annotations, notes to themselves, and, possibly, intermediate results of work in progress. The archive created by these critical incident reports would then make it possible to update the CPSE knowledge repository with new examples, principles, stories, etc. Furthermore, this archive could be a critical resource in using the CPSE as an environment to maintain, update, or upgrade existing works or artifacts that may need to be changed as the world changes. Finally, given the importance in several domains of creative work of keeping a journal or notebook (John-Steiner, 1997), this functionality could serve the dual purpose of storing the creative worker's thoughts about both the CPSE and about the work being done there. In addition to the possible memory benefits for the creative worker, such a notebook could considerably enhance considerably the ability of the technology support people to develop an understanding of the creative worker's needs and goals.

6.1.3 The user benefits of hyper-linkages.

Special notice needs to be taken of the importance of developing CPSEs with the capability for hyper-linkages. From the perspective of a user of a complex working environment, one of the difficulties with which they are faced is keeping track of all that they need to know, to remember, and to be able to use efficiently. The human memory works best when there are sufficient environmental cues available in the working environment to help serve as reminders and activate important detailed memories in long-term storage. The absence of these environmental cues can create significant memory difficulties for the user. What humans usually store in memory are broad general recollections of work and tasks, but not all of the requisite details of construction and/or operation of infrequently used tools, etc. Enabling the CPSE user to click on a link and have information brought up without seriously disrupting the flow of work can sometimes be all that will be needed to refresh the user's memory for prior use and/or context (Hewett & Adelson, 1998).

In addition to providing appropriate memory aids for the CPSE users, hyper-linkages offer other benefits for improving the ability of a domain expert to work more efficiently or with less disruption. When a system is designed from the ground up to accommodate the hyper-linkages it is relatively simple to provide for the requirement that the CPSE needs to be able to grow and be improved over time through the addition of new artifacts and links among locations and artifacts in the working environment. Furthermore, with hyper-linkage flexibility built in from the beginning it is also relatively easy to have the entire support system take on different characteristics depending upon which links are severed or enabled. For example, selectively turning off some of the links in the fully active CPSE support system would make it possible to create one or more self-contained training modules on the use of selected tools and/or components of the CPSE. Similarly, selective turning on and off of links makes it possible that the artifacts within CPSE can be grouped or re-grouped in various ways to create , for example, special purpose tutorials. Similarly, the CPSE could on one occasion be configured to facilitate development of new works and on another to facilitate modification of existing products or artifacts.

6.2 Communication support and auto-archiving in CPSEs

The importance and value of providing adequate communication support for individuals working together has created a whole new domain of work in computer science and human computer interaction--Computer Supported Collaborative Work (CSCW). The value of communication support, and of auto-archiving of meta-data about the support, has been demonstrated in recent work in the realm of engineering and manufacturing design. Regli, his students and his colleagues (e.g., Foster et al. 2001; Regli & Cicirella, 2000; Hayes et al. 2000; Zaychik & Regli, 2003; Sevy et al. 2000; Zaychik et al. 2001) have demonstrated both the feasibility and desirability of creating a working environment for engineering designers which enables easy, efficient, rapid communication between design teams and their members, and of having those communications auto-archived. Once the communications have been adequately archived, it is possible to do analyses of the communications to create design meta-data which can inform the work of future design engineers seeking solutions to new design problems or to addressing the problems of maintaining, updating and/or upgrading existing models.

Regli's work is at least partially motivated by the vision of what he has called a Collaborative Design Studio (CDS) in which an enhancement of the design engineering process is achieved through integration of computer-aided design (CAD) tools, communication tools, and archiving functions. "Design context is automatically extracted from CAD tools for inclusion in communications, and all design related communications are automatically archived in a searchable database" (Sevy et al., 2000). This archive then provides a repository of design information for other designers to examine. It makes possible the creation of tools that range over the database to extract design meta-data. It also creates a resource that can be utilized by researchers interested in the dynamics of work groups and how they do such things as negotiate design trade-offs.

Given that many of the basic research questions about the architecture of such a working environment for CAD/CAM have been addressed by Regli and his research group it is a quite reasonable to envision that a CPSE could be extended and articulated to provide the same type of functionalities for any creative work. Indeed, many functionalities investigated by Regli and his group are needed by people working in many domains. For example, it is not unusual for a designer to express the desire to be able to look at an object created by another designer and want to be able to recapture the reasons why that designer made some of the design choices that are imbedded in an existing design. (Indeed, it is not unheard of for a designer to return to piece of his or her own work months or years after completion and want to recapture the reasons why certain design choices were made.) Similarly, it is not unusual for people in the arts, architecture, design and many other domains to study the work of others in order to understand how certain results were accomplished.

Given the desirability of auto-logging of processes and intermediate results suggested above (Hewett & DePaul, 2000) as a generic feature for a working environment to support complex work where innovation is desirable, it is a quite natural extension to auto-archive all communications taking place between someone working an a CPSE and one or more other people. If both the event log and the communications log are searchable, any creative workers who need to recover their own thought processes during a given project, will be able to do so from the event log. For example, by examining the communications log associated with other projects a designer or a design engineer should be able to determine the design rationale that led to design decisions made in the artifacts designed by others. If those earlier designers are still available, the questions asked by others, and the replies, can become part of the history associated both with the earlier creative result and with the current ongoing project. In other words, a CPSE should be designed to provide the domain expert with an integrated environment containing not only domain specific tools, but also communication tools, and multiple archives in the form of searchable databases.

It is also feasible to propose and develop tools which can automate the extraction of useful communication meta-data. For example, Zaychik and Regli (2003) have reported on a tool called CodeLink that was designed to capture communication and its context in the software project lifecycle. Zaychik and Regli (2003) begin with the reasonable assumption that manual capture of Design Rationale (e.g., documentation of reasons for making certain choices rather than others) usually fails because designers and software developers do not like interruptions to the flow of their thinking and work. Consequently, they designed CodeLink to automatically and unobtrusively extract the software development context associated with email-based project communications. These emails, along with code snapshots, are then stored in an archive that can be searched in a variety of ways. After describing the CodeLink software architecture they discuss a proof of concept implementation and a user study that indicated that the tool was performing as intended. There appears to be no reason in principle why this type of meta-data extraction could not become a part of the operation of any CPSE involving communication with others.

7.0 Concluding remarks

To recap the arguments and discussion in this paper, there are reasons to believe that it is possible to provide effective support for creative work so long as certain necessary conditions exist. Even though creative products can show substantial differences across several domains of human endeavor, there are reasons to believe that there are key conditions and processes that are not domain specific and that are associated with successful creative work regardless of the domain in which that activity takes place. Prominent among these conditions are the ability to create and modify an external representation of one or more interim results that can be used in thinking about the domain problem and then to rethink and revise the situation if need be. Similarly, analogical thinking seems to be critical to the transfer of ideas between problems and domains of creative work. Also of considerable importance to creative work is the ability to work through different aspects of the problem or creative endeavor in order to use what one has learned in one or more intermediate steps as a guide for either moving forward or for backing up to an earlier place so that a different alternative or path can be explored. In fact, one could make a convincing argument that the ability to produce interim results, sometimes in parallel, without having to make a final commitment is absolutely essential to creative work (e.g., Lawson, 1993) and that that argument applies across a broad range of domains of creative endeavor.

The paper then discussed several user or functional requirements that seem, on the basis of considerations of the nature of creative work and The Nature of Insight, to be desirable in any working environment intended to support creative problem solving. The paper then proposed that fruitful way of thinking about designing creative problem solving environments is use the metaphor of the Virtual Workbench. This metaphor has two useful characteristics. First, the metaphor itself captures or has embedded in it several of the user requirements developed from thinking about the nature of creative work and insight. Second, there are empirical reasons to believe it is a workable approach.

Although no domain specific creativity support tools have been described in this paper the concluding section explores several aspects of what a domain specific CPSE might be like by discussing a subset of generic CPSE components. This discussion illustrates characteristics that could be built into these components that would satisfy many of the user requirements for capabilities that appear to be generally needed across many domains. Furthermore, the discussion of these components illustrated some of the types of relationships that can and should exist between these generic components and other more domain specific tools or capabilities.

It is quite possible to take exception to some of the individual arguments and interpretations presented above, but it is, nonetheless, the case that there are several user requirements for computer-based systems that could be put in place to enable or facilitate the capability and possibility for doing creative work. Most of the ideas identified here have been “proven” in that all are based in prior practice and/or solidly grounded in Cognitive Science research results. Probably the most significant major weaknesses of this paper are its failure to create an exhaustive list of user requirements for creative work and its failure to take account of the differences that exist between those people who currently are experts in their domain of creative work and those who are much earlier in the development of their expertise. A CPSE designed to support expert performance is not necessarily the best environment for a non-expert to learn or develop new knowledge and skills. However, it is reasonable to believe that if the user requirements described here were actually in place in a domain specific CPSE, the resulting archival resources could be organized or customized so as to suit the needs of both experts and non-experts. Novices as well as experts could have access to a whole new set of insights into community practice based on being able to recapture such things as design history as it actually happened, rather than as it is remembered (or not) months or years later. As Frederick Brooks once observed in a keynote speech at an Hypertext Conference, the problem in presenting knowledge in hypertext lies in knowing which links to sever (1987). Design of an information resource which accommodates both the needs of experienced and non-experienced users can be structured by providing multiple paths through the information resource which include clear pathways for the inexperienced and short-cuts and memory aids for the more experienced (e.g., Hewett, 1987a, 1987b, 1989a, 1989b).

Several of the features of the generic CPSE envisioned here would help to improve personal productivity in creative work, if only through provision of memory aids or retrieval cues helpful in recreating prior thinking. Some of the CPSE's features would provide a simple easy way for the expert to store intermediate results that cue and reactivate the thinking that went into creating those intermediate results. This history would enable the person to ramp more quickly back up to speed after significant time delays or after intervening work on other projects. Finally, storage of intermediate results, and access to the thinking that led to those results, would facilitate the ability to develop and test alternative possibilities under varying sets of constraints without fear of loss of context or results. All of these features would greatly facilitate an individual domain expert's ability to engage in exploration of risky alternatives. In other words it would enable the type of exploratory thinking necessary for insights and creative results to occur.

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References

Bonnardel, N., 1999. Creativity in design activities: The role of analogy in a constrained cognitive environment, in: Candy, L., Edmonds, E. (Eds.), Proc. 3rd Creat. and Cog. Conf., ACM Press, New York, pp. 158-165.

Bramley, R., Char, B., Gannon, D., Hewett, T. T., Johnson, C., Rice, J. R., 2000. Workshop on scientific knowledge, information, and computing, in: Houstis, E., Gallopolous, S., Rice, J. R., Bramley, R. (Eds.), Enabling Technologies for Computational Science: Frameworks, Middleware, and Environments, Kluwer, Boston, pp. 19-32.

Brooks, F., 1987. Keynote address. The ACM/IEEE Computer Society Hypertext '87 Workshop and Conf., 13-15 Nov., Chapel Hill, NC.

Candy, L. & Edmonds, E. A., 1994. Artifacts and the designer's process: Implications for computer support to design. J. Design Sci. and Tech. 3, 11-31.

Candy, L., & Edmonds, E. A., 1995. Creativity in knowledge work: A process model and requirements for support, in: Proc. OZCHI '95, pp. 242-248

Candy, L. & Edmonds, E. A., 1996. Creative design of the Lotus bicycle: Implications for knowledge support systems research. Design Studies, 17, 71-90.

Candy, L. & Edmonds, E. A., 1997. Supporting the creative user: A criteria based approach to interaction design. Design Studies, 18, 185-194

Candy, L., O'Brien, S. M., & Edmonds, E. A., 1993. End user manipulation of a knowledge based system: A study of an expert's practice. Int'l. J. Man-Machine Studies, 18, 129-145.

Carroll, J. M. & Carrithers, C., 1984. Training wheels in a user interface. Commun. ACM, 27(8), 800-806.

Csikszentmihalyi, M., 1996. Creativity. Harper-Collins, New York.

Csikszentmihalyi, M. & Sawyer, K., 1995. Creative insight: The social dimensions of a solitary moment, in: Sternberg, R. J., Davidson, J. E. (Eds.), The Nature of Insight. The MIT Press, Cambridge, pp. 329-364.

Davidson, J. E., 2003. Insights about insightful problem solving, in: Sternberg, R. J., Davidson, J. E. (Eds.), The Psychology of Problem Solving. Cambridge University Press, Cambridge, pp. 149-175.

Dominowski, R. L. & Dallob, P., 1995. Insight and problem solving, in: Sternberg, R. J., Davidson, J. E. (Eds.), The Nature of Insight. The MIT Press, Cambridge, pp. 33-61.

Dominowsky, R. L., & Jenrick, R., 1972. Effects of hints and interpolated activity on solution of an insight problem. Psychonom. Sci. 26, 335-338.

Dreyfuss, H., 1955. Designing for People. Simon and Schuster, New York.

Dunbar, K., 1995. How scientists really reason: Scientific reasoning in real-world laboratories, in: Sternberg, R. J., Davidson, J. E. (Eds.), The Nature of Insight. The MIT Press, Cambridge, pp. 365-396.

Edmonds, E. A. & Candy, L., 1993. Knowledge support for conceptual design: The amplification of creativity, in: Proc. HCI Int'l, pp. 350-355.

Edmonds, E. A. & Candy, L., 1996. Computer support for concept engineering design: Enabling interaction with design knowledge. J. Sys. Eng. and Elect. 7 (2), 55-71.

Eindhoven, J. E., & Vinacke, W. E., 1952. Creative process in painting. J. Gen. Psych. 47, 139-164.

Ericsson, K. A., 1996. The acquisition of expert performance. In K. A. Ericsson (Ed.) The Road to Excellence. Erlbaum, Mahwah, NJ, pp. 1-50.

Finke, R. A., 1995. Creative insight and preinventive forms, in: Sternberg, R. J., Davidson, J. E. (Eds.), The Nature of Insight. The MIT Press, Cambridge, pp. 255-280.

Foster, C., Hayes, E., McWherter, D., Peabody, M., Shapirsteyn, Y., Anthony, L. & Regli, W. C., 2001. Discovering knowledge in design and manufacturing repositories, in: Honavar, V. (Ed.) Int'l. Joint Conf. of AI Workshop on Knowledge Disc. from Dist., Heterogeneous, Dynamic, Autonomous Data Sources, 40-42.

Gardiner, H., 1993. Creating Minds. Basic Books, New York.

Gruber, H. E., 1989. The evolving systems approach to creative work, in: Wallace, D. B., Gruber, H. E. (Eds.), Creative People at Work. Oxford: Oxford University Press, pp. 3-24.

Gruber, H. E., 1995. Insight and affect in the history of science, in: Sternberg, R. J., Davidson, J. E. (Eds.), The Nature of Insight. The MIT Press, Cambridge, pp. 397-432.

Hayes, E. E. & Regli, W. C., 2001. Integrating design process knowledge with CAD models, in: ASME Design Eng. Tech. Conferences: Computers and Info. in Eng. (DETC2001/CIE-21247), Pittsburgh.

Hewett, T. T., 1987a. The Drexel Disk: an electronic guidebook, in: Diaper, D. Winder, R. (Eds.), People and Computers III. Cambridge University Press, Cambridge, pp. 115-129

Hewett, T. T., 1987b. The design of an electronic guidebook, in: Proc. ACM/Nat'l Bureau of Standards Tech. Symp. on Next Gen. Info. Systems: Tech. for the Future. Washington DC Chapter of the ACM, Washington, D. C., pp. 147-153

Hewett, T. T., 1989a. A Gentle Computer Slossary 1.0. Drexel University, Philadelphia, PA. (An hypertext document with over 350 definitions of computer terms. Distributed by Kinkos Courseware Exchange, 1989-1991, and by Intellimation and W. C. Brown & Co., 1991-1992.)

Hewett, T. T., 1989b. The Drexel Disk: Hypertext based instructional software as a tool for the exploration of a constrained knowledge space. Beh. Res. Meth., Inst. & Computers, 21, 316-325.

Hewett, T. T. & Adelson, B., 1998. Psychological science and analogical reminding in the design of artifacts. Beh. Res. Meth., Inst. & Computers, 30, 314-319.

Hewett, T. T. & DePaul, J. L., 2000. Toward a human centered scientific problem solving environment, in: Houstis, E., Gallopolous, S., Rice, J. R., Bramley, R. (Eds.), Enabling Technologies for Computational Science: Frameworks, Middleware, and Environments. Kluwer, Boston, pp. 79-90

Holyoak, K. J. & Thagard, P., 1995. Mental Leaps. The MIT Press, Cambridge.

Ippolito, M. F. & Tweney, R. D., 1995. The inception of insight, in: Sternberg, R. J., Davidson, J. E. (Eds.), The Nature of Insight. The MIT Press, Cambridge, pp. 433-462.

Isaak, M. I. & Just, M. A., 1995. Constraints on thinking in insight and invention, in: Sternberg, R. J., Davidson, J. E. (Eds.), The Nature of Insight. The MIT Press, Cambridge, pp. 281-326.

Johnson, J. , Lakshman, Y. N., Hewett, T. T., Souder, T. , Donegan, S., Fitzgerald, T., & Morgovsky, P., 1998. Virtual office hours using TechTalk, a web-based mathematical collaboration tool, in: Proc. 3rd Ann. Conf. on Integrating Tech. into Comp. Sci. Ed. ACM Press, New York, pp. 130-133.

John-Steiner, V., 1997. Notebooks of the Mind. Oxford University Press, Oxford.

Jung-Beeman, M., Bowden, E. M., Haberman, J., Frymiare, J., Arambel-Liu, S., Greenblatt, R., Reber, P. J., & Kounious, J., 2004. Neural activity when people solve verbal problems with insight. PLOS Biology, 2, 4, (http://www.plosbiology.org/plosonline/?request=get-document&doi=10.1371/journal.pbio.0020097), accessed 5 July, 2004

Lawson, B. R., 1993). Parallel lines of thought. Languages of Design, 1(4), 357-366.

McWherter, D., Zaychik, V., Hayes, E. E., Regli, W. C., & Sevy, J., 2000. Software architecture to facilitate automated message recording and context annotation, in: Proc. Int'l Society for Optical Eng., Network Intell: Internet Based Manufacturing, vol. 4208, Boston.

Mardall, C., 1968. Architecture, in: Kallas, H., Nickels, S. (Eds.), FINLAND Creation and Construction. Praeger, New York.

Mayer, R. E., 1995. The search for insight: Grappling with Gestalt Psychology's unanswered questions, in: Sternberg, R. J., Davidson, J. E. (Eds.), The Nature of Insight. The MIT Press, Cambridge, pp. 3-32.

Meadow, C. T., Hewett, T. T. & Aversa, E. A., 1982a. A computer intermediary for interactive database searching: Part I: Design. J. Am. Soc. for Info. Sci. 33, 357-364.

Meadow, C. T., Hewett, T. T. & Aversa, E. A., 1982b. A computer intermediary for interactive database searching: Part II: Evaluation. J. Am. Soc. for Info. Sci. 33, 357-364.

Metcalfe, J., 1986a. Feeling of knowing in memory and problem solving. J. Exp. Psych.: Learn., Mem., and Cog. 12, 288-294.

Metcalfe, J., 1986b. Premonitions of insight predict impending error. J. Exp. Psych.: Learn., Mem., and Cog. 12, 623-634.

Metcalfe, J., & Weibe, D., 1987. Metacognition in insight and noninsight problem solving. Mem. and Cog. 15, 238-246.

Miller, A. I., 2000. Insights of Genius. Cambridge: MIT Press.

Nickerson, R. S., 1999. Enhancing creativity, in: Sternberg, R. J. (Ed.) Handbook of Creativity. Cambridge University Press, Cambridge.

Ohlton, R. M., 1979. Experimental studies of incubation: Searching for the elusive. J. Creat. Beh. 13, 9-22.

Ohlton, R. M., & Johnson, D. M., 1976. Mechanisms of incubation in creative problem solving. Am. J. Psych. 89, 617-630.

Patrick, C., 1937. Creative thought in artists. J. Psych. 4, 35-73.

Petroski, H., 1996a. Engineers of Dreams. Vintage Books, New York.

Petroski, H., 1996b. Invention by Design. Harvard University Press, Cambridge.

Regli, W. C. & Cicirella, V. A., 2000. Managing digital libraries for computer-aided design. J. Comp. Aided Design, 33, 2, 119-132.

Robbins, E., 1997. Why Architects Draw. The MIT Press, Cambridge.

Rowe, P. G., 1987. Design Thinking. The MIT Press, Cambridge.

Sevy, J., Zaychik, V., Hewett, T. T., & Regli, W. C., 2000. Developing and evaluating collaborative engineering studios, in: IEEE 8th Int'l Workshop on Enabling Technologies: Infrastructure for Collab Enterprises Workshop on Eval. of Collab. Enterprises. Gaithersburg, MD, 118-124.

Shekerjian, D., 1990. Uncommon Genius. Penguin Books, New York.

Shneiderman, B., 1999. User interfaces for creativity support tools, in: Candy, L., Edmonds, E. (Eds.), Proc. 3rd Creat. and Cog. Conf. pp. 15-21.

Shneiderman, B., 2000. Creating creativity: User interfaces for supporting innovation. ACM Trans. on Comp.-Hum. Interaction. 7, 1 (Mar.), 114-138

Smith, S. M., 1995. Getting into and out of mental ruts: A theory of fixation, incubation, and insight, in: Sternberg, R. J., Davidson, J. E. (Eds.), The Nature of Insight. MIT Press, Cambridge, pp. 229-251.

Smith, S. M., & Blankenship, S. E., 1991. Incubation effects. Bull. Psychonom. Soc. 27, 311-314.

Smith, S. M., Ward, T. B., & Finke, R. A., 1994. The Creative Cognition Approach. The MIT Press, Cambridge.

Sternberg, R. J. & Davidson, J. E., 1995. The Nature of Insight. The MIT Press, Cambridge.

Wallace, D. B. & Gruber, H. E., 1989. Creative People at Work. Oxford University Press, Oxford.

Wallas, G., 1926). The Art of Thought. J. Cape, London.

Weisberg, R. W., 1986. Creativity: Genius and Other Myths. W. H. Freeman, New York.

Weisberg, R. W., 1993. Creativity: Beyond the Myth of Genius. W. H. Freeman, New York.

Zaychik, V. & Regli, W. C., 2003. Capturing communication and context in the software project lifecycle. Res. in Eng. Design, 14, 75-88.

Zaychik, V., Sevy, J., Hewett, T. T., & Regli, W. C., 2001. Issues in building and evaluating networked engineering environments, in: Cugini, U., Wozny, M. (Eds.), 4th IFIP WG 5.2 Workshop in Knowledge Intensive CAD, Parma, Italy.