Creating Creativity: User Interfaces for Supporting Innovation

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A challenge for human-computer interaction researchers and user interface designers is to construct information technologies that support creativity. This ambitious goal can be attained by building on an adequate understanding of creative processes. This article offers a four-phase framework for creativity that might assist designers in providing effective tools for users: (1) *Collect:* learn from previous works stored in libraries, the Web, etc.; (2) *Relate:* consult with peers and mentors at early, middle, and late stages; (3) *Create:* explore, compose, evaluate possible solutions; and (4) *Donate:* disseminate the results and contribute to the libraries. Within this integrated framework, this article proposes eight activities that require human-computer interaction research and advanced user interface design. A scenario about an architect illustrates the process of creative work within such an environment.

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1. INTRODUCTION

People have long relied on technology for information preservation and dissemination. Ancient traders recorded contracts on clay tablets; religious scribes hand copied illuminated manuscripts on parchments; and Gutenberg applied his printing press to reproducing bibles. Print media led to dramatic changes in society, and then modern broadcast media shook the world further with even more rapid and widespread dissemination. Today,

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even in remote locales, most people have seen television and heard radio. The World Wide Web is dramatically transforming society by providing greater user control and initiative.

But information preservation and dissemination are only the first two uses of information technologies. A third application is rapid two-way communication among people at ever greater speed and lower cost. Writing letters was a rare process among the literate members of ancient societies, but making phone calls is now widespread, and sending email is becoming common.

A fourth use for information technologies is to support the creation of knowledge and art. Even into the 20th Century, scientists, inventors, novelists, and painters were seen as specially gifted citizens whose rare creative productions were treasured. Photography shook the art world because it enabled the majority to produce striking images rapidly at low cost. Similarly, information technologies could be harnessed to make creativity more common. Not every artwork, novel, photo, or digital product is creative, but facilitating broad access to powerful tools expands the potential.

Information technologies that allow more people to be more creative more of the time are likely to have profound effects on every institution [Johnson 1997]. Education could expand from acquiring facts, studying existing knowledge, and developing critical thinking, to include more emphasis on creating novel artifacts, insights, or performances. Medicine's shift from applying standard treatments to tailoring treatments for each patient, reflects the trend to personalization that is already ascendant in marketing and media. Expectations of teachers, lawyers, and designers are likely to rise as creativity is expected on more occasions from more people. These changes will be welcomed by some, but resisted by others. The challenge to leaders and participants will be to preserve appropriate elements of existing knowledge work while shaping new technologies and then integrating them into the workplace. Standards for creative work will continue to evolve; computing logarithms by John Napier was a great breakthrough in 1614, but is now seen as merely a mechanical operation that is embedded in calculators.

This article begins with three perspectives on creativity: inspirationalist, structuralist, and situationalist. Section 3 focuses on evolutionary creativity, rather than revolutionary or impromptu creativity. Section 4 reviews and refines the genex (generator of excellence) proposal, a four-phase integrated framework to support creativity [Shneiderman 1998c]. Designers who follow the genex framework can create powerful tools that enable users to be more creative more of the time. This article's main contribution is the identification of eight activities that support creativity. This list of activities implies a research agenda for human-computer interaction theoreticians, designers, software engineers, and evaluators.

2. THREE PERSPECTIVES ON CREATIVITY

The large literature on creativity offers diverse perspectives [Boden 1990; Couger 1996; Gardner 1994].[1] Some writers, I will call them inspirationalists, emphasize the remarkable "Aha!" moments in which a dramatic breakthrough magically appears. Stories of Archimedes (3rd Century B.C.) jumping from his bath screaming "Eureka!" as he discovered hydrostatics or Freidrich August Kekule's (1829–1869) dream-given insight about benzene's ring structure emphasize the intuitive aspects of creativity. Most inspirationalists are also quick to point out that "luck favors the prepared mind," thereby turning to the study of how preparation and incubation lead to moments of illumination. The inspirationalists also recognize that creative work starts with problem formulation and ends with evaluation plus refinement. They acknowledge the balance of 1% inspiration and 99% perspiration—a flash of insight followed by much hard work to produce a practical result.

Those who emphasize this inspirational model promote techniques for brainstorming, free association, lateral thinking [DeBono 1973], and divergence. They advocate strategies to break an innovator's existing mind set and somehow perceive the problem with fresh eyes. Since they want innovators to break from familiar solutions, their recommendations include travel to exotic destinations with towering mountains or peaceful waterfalls. Inspirationalists talk about gifted individuals, but usually stress that creativity-inducing thought processes can be taught.

The playful nature of creativity means that software support for inspirationalists emphasizes free association using textual or graphical prompts to elicit novel ideas. Inspirationalists are often oriented to visual techniques for presenting relationships and for perceiving solutions. They would be sympathetic to information and scientific visualization strategies that helped users understand previous work and explore potential solutions. Many writers and software developers of tools such as IdeaFisher or MindMapper encourage two-dimensional layouts of loosely connected concept nodes to avoid a linear or hierarchical structure. The casual style and freedom from judgment that are implicit in sketching are encouraged. Inspirationalists would also appreciate templates as starting points for a creative leap, as long as powerful tools enable them to explore fresh combinations.

A second group of writers on creativity, the structuralists, emphasizes more orderly approaches [Mayer 1992]. They stress the importance of studying previous work and using methodical techniques to explore the possible solutions exhaustively. When a promising solution is found, the innovator evaluates strengths and weaknesses, compares it to existing solutions, and refines the promising solution to make it implementable. Structuralists teach orderly methods of problem solving such as Polya's four steps in Polya [1957]:

[1]See also Charles Cave's "Creativity Web" at http://www.ozemail.com.au/˜caveman/Creative/.

(1) Understanding the problem

(2) Devising a plan

(3) Carrying out the plan

(4) Looking back

For structuralists, libraries and Web sites of previous work are important, but the key software support comes in the form of spreadsheets, programmable simulations, and domain-specific scientific/engineering/analytical/mathematical models. These software tools support "what-if" processes of trying out assumptions to assess their impact on the outcomes. They often show processes with visual animations. Structuralists are usually visual thinkers but their preferred tools are for drawing flow charts, decision trees, and structured diagrams. Since they favor methodical techniques, they are likely to appreciate software support for step-by-step exploration, with the chance to go back, make changes, and try again.

A third group, the situationalists, emphasizes the social and intellectual context as a key part of the creative process. They see creativity as embedded in a community of practice with changing standards, requiring a social process for approval from scientific journal editors, museum curators, or literary prize juries. For example, Csikszentmihalyi [1993] sees three components to creativity:

(1) domain, such as mathematics or biology, "consists of a set of symbols, rules, and procedures."

(2) field which "includes all the individuals who act as gatekeepers to the domain. It is their job to decide whether a new idea, performance, or product should be included in the domain."

(3) individual person whose creativity is manifest "when a person using the symbols of a given domain such as music, engineering, business, or mathematics has a new idea or sees a new pattern, and when this novelty is selected by the appropriate field for inclusion in the relevant domain."

Situationalists are most likely to talk about the influence of family, teachers, peers, and mentors. They consider the influence of challenges from memorable teachers, the strong desire to create, and the pursuit of recognition. For situationalists, vital user interfaces are those that support access to previous work in the domain, consultation with members of the field, and dissemination of results to interested members of the field.

These three perspectives on creativity—inspirationalism, structuralism, and situationalism—are all useful in shaping user interfaces to support creative work. With careful design, these perspectives can sometimes be combined. User interface designers can develop tools that stimulate inspiration based on previous work, link to associated ideas, and provide templates for action. Designers can build structured tools for exhaustive exploration, which is already a common strategy in computing. Designers can also facilitate consultation by email and more refined methods, to support the social strategies of the situationalists. Section 4 expands on these possibilities.

3. LEVELS OF CREATIVITY

Only some knowledge work or art products are creative. Much work is merely repetitive application of rules or copying, but could be competent original work or could rise to the level of creative work. A professor's speech may occasionally include rote memorized phrases, but usually it contains original sentences. However, inspired lectures and creative rhetoric—such as Martin Luther King's "I Have a Dream" speech—are rare. Similarly, redrawing a travel map to your home is copying; doodling on an envelope may be original, but Picasso's drawings in the Vollard Suite reach the level of creative work. The proposals in this article are intended to support creative, not merely original, work.

The large literature on creativity considers diverse levels of aspiration [Boden 1990]. A restricted definition would focus on great breakthroughs and paradigm-shifting innovations [Kuhn 1996]. Einstein's relativity theory, Watson and Crick's discovery of DNA's double-helix, or Stravinsky's "Rite of Spring" are often cited as major creative events. Such a definition confines discussion to rare revolutionary events and a small number of Nobel Prize candidates. A looser definition would include what Kuhn referred to as normal science, useful evolutionary contributions that refine and apply existing paradigms [Basalla 1988]. Evolutionary acts of creativity include doctors making cancer diagnoses, lawyers preparing briefs, or photo editors producing magazine stories. Their work is important in changing someone's life by medical care, legal practice, or journalist reporting and is made public so that it can be assessed by others. Evolutionary creativity is the focus of this article, in part because it is most likely to be helped by software tools. There is a chance that software tools that support evolutionary creativity may also help produce revolutionary breakthroughs. On the other hand, it is possible that software tools that support evolutionary creativity restrict thinking or even discourage paradigm shifts.

A third, still broader, definition of creativity is conceivable—impromptu or personal creativity. Can lively conversation or attentive parenting be considered as parts of the creativity spectrum? These more spontaneous and private activities may be creative in a broad sense, but since they seem harder to support and evaluate, they are not considered in this analysis. They are assessed on a personal basis and are less likely to have enduring impact on a wide range of people.

The focus of this article is not on revolutionary or impromptu creativity, but on evolutionary creativity. This still covers a wide range of possibilities. Developing software support tools for evolutionary creativity according to the three perspectives identified in this article—inspirationalism, structuralism, and situationalism—is a sufficient challenge.

It seems necessary to address in advance the hubris or arrogance of proposing technology to aid human creativity. A critic might scowl that creativity is inherently human and no computer could or should be brought into the process. But technology has always been part of the creative process, whether in Leonardo's paint and canvas or Pasteur's microscopes and beakers. Supportive technologies can become the potter's wheel and mandolin of creativity—opening new media of expression and enabling compelling performances. Creative people often benefit from advanced technology to raise their potential and explore new domains.

My expectations are largely positive, but there are many problems, costs, and dangers in anything as ambitious as a tool and framework to support creativity. An obvious concern is that many people may not want to be more creative. Many cultures encourage respect for the past and discourage disruptive innovations. Promoting widespread creativity raises expectations that may change employment patterns, educational systems, and community norms. Introducing computer supports for creativity may produce greater social inequality as it raises the costs for those who wish to participate. Finally, these tools may be used equally by those who have positive and noble goals as well as by dictators or criminals who seek to dominate, destroy, or plunder.

These fears are appropriate, and reasonable cautions must be taken; but support for innovation could lead to positive changes to our world. However, the moral dilemma of a technology innovator remains troublesome: how can I ensure that the systems I envision will bring greater benefits than the negative side effects that I dread and those that I fail to anticipate? Widespread access to effective user interfaces for creativity support could help with major problems such as environmental destruction, overpopulation, poor medical care, oppression, and illiteracy. It could contribute to improvements in agriculture, transportation, housing, communication, and other human endeavors. The path from high expectations to practical action is not easy, but examples of how information technologies helped identify ozone depletion by remote sensing, improve medical diagnosis with computer-aided tomography, and enable bans on nuclear tests are encouraging. Ensuring more frequent positive outcomes and minimizing negative side effects remain challenges, but a framework that provides for substantial consultation and broad dissemination may help. Participatory design methods and Social Impact Statements may be effective because they promote discussion and expand the range of options for decision makers [Greenbaum and Kyng 1991; Muller et al. 1993; Shneiderman and Rose 1997].

4. GENEX: A FOUR-PHASE FRAMEWORK FOR GENERATING EXCELLENCE

This article combines and extends two previous efforts. The genex framework [Shneiderman 1998c] was a first attempt to build on Csikszentmihalyi's approach, by supporting access to the domain and consultation with the field. The name genex (generator of excellence) was chosen to echo Vannevar Bush's memex (memory extender) [Bush 1945]. The original genex framework had four phases: collect, create, consult, and disseminate. This article refines the genex framework by expanding its scope and being more precise about what user interface tools are needed. The second source for this article is the educational philosophy, relate-create-donate [Shneiderman 1998b], that emphasized collaborative teams working together to produce something ambitious for use by someone outside the classroom. This service-oriented approach, using Web-based technologies, leads to innovative artifacts or performances. It emphasizes creativity to support learning, and learning to support creativity.

The foundational beliefs that led to genex's four phases were

(1) New knowledge is built on previous knowledge

(2) Powerful tools can support creativity

(3) Refinement is a social process

(4) Creative work is not complete until it is disseminated

However, the social processes that were characterized narrowly as a support for refinement can also be helpful at early, middle and late stages of the creative process. This article more clearly defines the powerful tools that can facilitate creative acts. Furthermore, the close relationship of learning and creativity is more apparent now. Combining the strategies in Shneiderman [1998b; 1998c] leads to a revised four-phase genex framework:

—*Collect:* learn from previous works stored in libraries, the Web, etc.

—*Relate:* consult with peers and mentors at early, middle, and late stages

—*Create:* explore, compose, and evaluate possible solutions

—*Donate:* disseminate the results and contribute to the libraries

These four phases are not a linear path. Creative work may require returning to earlier phases and much iteration. For example, libraries, the Web, and other resources may be useful at every phase. Similarly, discussion with peers and mentors may take place repeatedly during the development of an idea. The phases are also meant to be cyclical, in that the dissemination of results should support future users who seek to learn from previous work.

This four-phase genex framework has much in common with previous characterizations and methodologies, but there are important distinctions. Couger [1996] reviews 22 "creative problem solving methodologies" with simple plans such as

—Preparation

—Incubation

—Illumination

—Verification

and this, even more basic, three-phase plan:

—*Intelligence:* recognize and analyze the problem

—*Design:* generate solutions

—*Choice:* select and implement.

Couger offers his own plan with five phases:

—Opportunity, delineation, problem definition

—Compiling relevant information

—Generating ideas

—Evaluating, prioritizing ideas

—Developing an implementation plan

It is striking that so many of the plans limit themselves to the narrow perspective of the inspirationalists and structuralists. Problem solving and creativity are portrayed as lonely experiences of wrestling with the problem, breaking through various blocks, and finding clever solutions. The descriptions of even early phases rarely suggest contacting previous workers on this problem or exploring libraries for previous work. Consultation with others and dissemination of the results is minimally mentioned. Some reconsideration of such methodologies is in order because of the presence of the World Wide Web [Berners-Lee et al. 1994]. It has already dramatically reduced the effort of finding previous work, contacting previous workers, consulting with peers and mentors, and disseminating solutions [Kiesler 1997].

Of course there are costs and dangers in reading previous work or consulting with others [Shneiderman 1998c]. The time might detract from exploration, and the knowledge might be misleading. There are satisfactions in solving a problem on your own, but when dealing with difficult problems the benefits of building on previous work and consulting with peers and mentors can be enormous. The genex framework builds on the situationalists' perspective by embracing the expanded opportunities offered by the World Wide Web.

However, the need for improvements to the current World Wide Web was revealed in a study of support for idea generation [Massetti et al. 1999]. Twenty-three MBA students were asked to generate as many ideas as they could on three topics (robotics, societal change, and business opportunities in Ireland). In this within-subjects design, each subject was asked to use the World Wide Web, categorical cues (five suggested categories), and no support. Subjects using the World Wide Web did no better in generating ideas and did not have higher satisfaction. Categorical cues seemed to provide the best assistance, supporting the inspirationalist approach to stimulating creative ideas by guiding free associations.

The goal of genex framework is to suggest improvements for Web-based services and personal computer software tools. By reducing the distraction caused by poorly designed user interfaces, inconsistencies across applications, and unpredictable behavior, users' attention can be devoted to the task. In an effective design for a genex, the boundaries between applications and the burdens of data conversions would disappear. Data representations and available functions would be in harmony with problem-solving strategies. Then users would be in control and have the sense of mastery that enables them to concentrate on genex's four phases of creativity: collect, relate, create, and donate.

My suggestion of a close link between supporting creativity and generating excellence is a hope, not a necessity. Creativity support tools may be used to pursue excellence, high quality, and positive contributions, but I am sadly aware that this will not always be the case. The genex framework could tighten the linkage because of its emphasis on consultation and dissemination. I repeat my belief (from the end of Section 3) that making creativity more open and social through participatory processes will increase positive outcomes while reducing negative and unanticipated side effects.

5. INTEGRATING CREATIVE ACTIVITIES

The revised genex framework calls for integrated creativity support tools. Some of these tools already exist, but could be enhanced to better support creativity. However, the main challenge for designers is to ensure smooth integration across these novel tools and with existing tools such as word processors, presentation graphics, email, databases, spreadsheets, and Web browsers [Shneiderman 1998a].

Smoother coordination across windows and better integration of tools seem possible. Just as word processors expanded to include images, tables, equations, and more, the next generation of software is likely to integrate additional features. Some aspects of the integration can be accomplished by creating compatible data types and file formats (possibly standardized objects). A second aspect of integration has to do with compatible actions and consistent terminology, such as cut-copy-paste or open-save-close. Higher levels of actions that are closer to the task domain might be candidates such as annotate-consult-revise or collect-explore-visualize. A third aspect of integration is the smooth coordination across windows [Derthick et al. 1997; Dey et al. 1997; North and Shneiderman 2000]. For example, if users see an unfamiliar term they should be able to click on it and get an English definition, a French translation, or a medical dictionary report, all in a predictable screen location. Similarly, if users find a personal name in a document they should be able to get a biography, email address, or contact information. Other coordinations include synchronized scrolling of related documents to facilitate comparisons and hierarchical

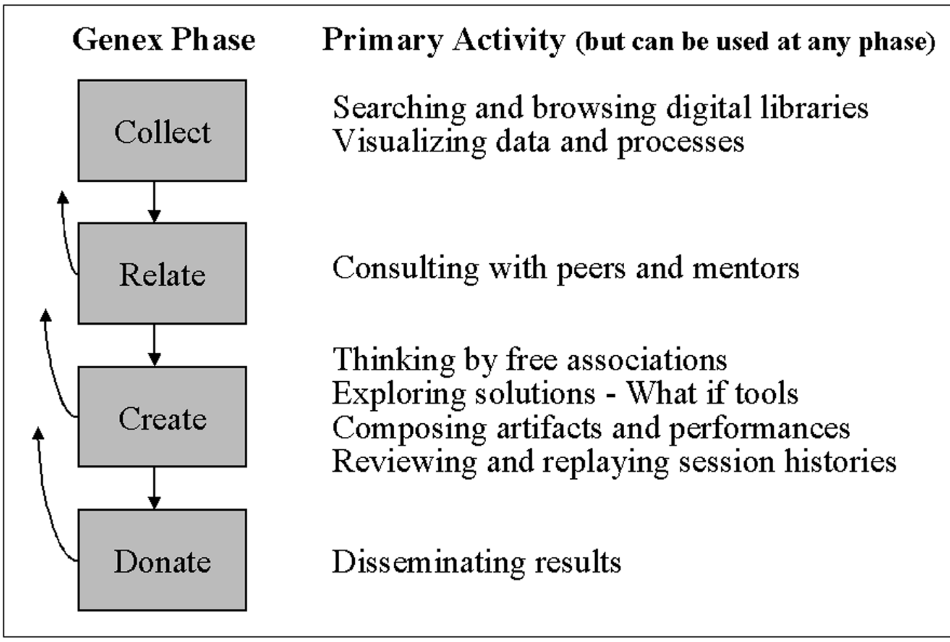

Fig. 1. Genex phases and their related primary activities.

browsing of a table of contents and a chapter to enable easy navigation of large resources.

These improved user interfaces will benefit many users for many tasks, but this article focuses on the genex framework as a means to support creativity. The three perspectives—inspirationalism, structuralism, and situationalism—each lead to useful suggestions for eight activities during the four genex phases:

—Searching and browsing digital libraries

—Consulting with peers and mentors

—Visualizing data and processes

—Thinking by free associations

—Exploring solutions—what-if tools

—Composing artifacts and performances

—Reviewing and replaying session histories

—Disseminating results

Genex's integrated creativity support tools should offer at least the eight activities in this list. Figure 1 indicates how these activities are primarily related to the genex phases, but these activities could take place during any phase. For example, searching of libraries, the Web, or other resources is primarily associated with the collect phase, but searching may occur in order to find consultants or to decide on candidates communities for presenting of results. Visualizing objects and processes is the activity that seems most pervasive and could appear in every genex phase.

5.1 Searching and Browsing Digital Libraries

Traditional libraries offer rich resources, but digital libraries provide dramatic capabilities that support searching, browsing, and filtering. Existing Web search engines and digital library interfaces could be much improved, and refinements to support creativity are possible. Situationalist users who want to steer the search to resources about previous work will want more control over the relevance ranking, range of sources, and over the presentation of the results [Koenemann and Belkin 1996; Marchionini 1995; Shneiderman et al. 1997]. For example, it should be easy for users to restrict a legal search to recent New York, New Jersey, or Connecticut court cases on tenants rights for heating. The result set should be grouped by claims (civil rights, contract violation, etc.) and ordered by date with green or red stars indicating the strength of the results for or against tenants. Extraction of plaintiff's or defendant's lawyers should also be convenient. This may sound like a tall order, but detailed search request specification while maintaining comprehensibility is possible. Since searching is part of a larger creative process the result set should be easy to save into a spreadsheet for further manipulation, include in an email note for consultation, or paste into a notebook for later referral.

In addition to searching, inspirationalists will want rapid browsing to more effectively support exploration, similar to what many people do in bookstores or physical libraries. Web sites with high branching factors (many links per page) support exploration by making what is available more visible. The more than 100 links on Yahoo's home page (http://www.yahoo.com) are helpful in getting an idea of what is available and what is not. Browsing textual menus supports exploration when specific terms or concepts are not known, but varying interpretations of category names still results in user confusion. Imagine the complex request implied by this question: which viral strains are causing recent flu symptoms for senior citizens in the Mid-Atlantic states? No specific search string could produce appropriate results, but browsing through search results may lead to exploration of viral infections, variant symptoms, other diseases, other locations, earlier epidemics, etc.

Information derived from searching digital libraries may provide the right results, but there are still many concerns about whether the information is accurate, complete, and up-to-date. Furthermore, online information may only be a fraction of the total information, and the search engines may search only a fraction of the online information.

5.2 Consulting with Peers and Mentors

Email, listservs, newsgroups, and threaded discussions are excellent asynchronous tools for situationalists' inquiries about previous work and for discussing new ideas. The capacity to find people who have a shared interest and are at work on similar problems is one of the greatest gifts of the Internet. Synchronous tools—such as phone calls, videoconferencing (e.g., CUSeeMe [Dorcey 1995]), and software sharing (e.g., Netmeeting)—enrich the possibilities for early-, middle-, and late-stage consultations [Olson and Olson 1997].

For early-stage consultations, innovators are likely to search widely, finding diverse information resources and broad communities. At this preparatory stage, innovators are forming questions, finding out about current workers who might be collaborators, and choosing directions. During middle-stage consultations, the tasks are to propose potential solution strategies and develop evaluation methods. As solutions are created and refined, late-stage consultations are directed at confirming the innovation, refining it to accommodate criticisms, and then disseminating it to appropriate parties [National Research Council 1993].

Consultations might involve continuing dialogs by email, phone calls, or personal visits. While these may often be collegial and friendly, some discussions might be tense, since other workers may be competitors who are pursuing similar goals. Either party might withhold some of their knowledge or ideas, or probe the other to gauge their intentions. Nondisclosure or noncompetitive agreements might be discussed or signed as part of a corporate consultation. University researchers are often more open, but the competition for solution of important problems and battles to promote reputations can suppress discussion.

These concerns greatly influence the design and use of technologies, since the appropriate balance of privacy protection and easy access to information is vital. Researcher's early notes and explorations need to be kept private, but claimed breakthroughs need rapid and broad dissemination. Appropriate credits for articles, patents, or software products are often the source of conflicts, so improved record keeping of the consultations that contribute to an innovation could resolve some questions and maybe encourage more cooperation.

5.3 Visualizing Data and Processes

While inspirationalists are likely to propose visual approaches, structuralists will also appreciate the thoroughness and rapidity with which alternatives can be reviewed using visualization. The field of pharmaceutical drug discovery involves review of thousands of compounds for their efficacy, shelf life, solubility, acidity, cost, allergic reactions, interactions with other medications, etc. Scrolling lists in spreadsheets are useful, but two-dimensional visual presentations with color and size coding are proving to be enormous benefits for this task. Early work on a FilmFinder [Ahlberg and Shneiderman 1994] led to a successful commercial product called Spotfire (http://www.spotfire.com) (Figure 2). A wide range of 1-, 2-, 3-, and multidimensional visualizations plus temporal, tree, and network presentations have been proposed [Card et al. 1999].

Visualization of digital library contents [Hearst 1999], financial information [Wright 1995], scientific data [Bryson et al. 1999], medical histories

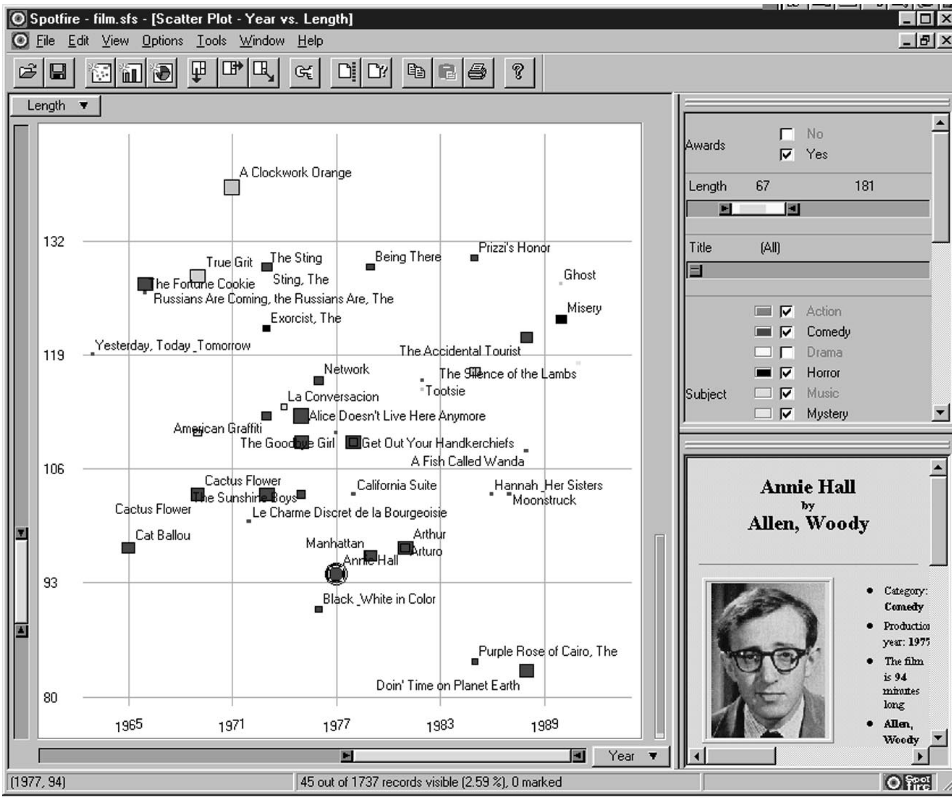

Fig. 2. Multidimensional film database viewed with a two-dimensional starfield display in Spotfire. The x-axis is the years, and the y-axis is the popularity of the film. Color coding is film type (action, drama, mystery, etc.), and larger-size dots indicate longer movies.

[Plaisant et al. 1996], etc. is growing, but to increase its benefits to creativity requires smooth integration. The results of a Web or database search should be easily imported (e.g., by cut and paste) into a visualization. Then users should be able to filter the data appropriately and adjust the visualization features, such as x,y-axes, color, size, or other codings. Then when an interesting group of items is found, users should be able to select them and paste them into a spreadsheet or statistics package for further processing. Then the visualization and processed items should be embeddable in a written report, slide presentation, or email note. Email recipients should be able to manipulate the visualization or report still further [Roth et al. 1996].

Situationalists should also find use for visualizations in exploring digital libraries, locating key people, and presenting their findings to others.

5.4 Thinking by Free Associations

Inspirationalists seek to liberate the mind by making free associations to related concepts. This Gestalt psychology approach [Mayer 1992] has led to innovative software that is meant to facilitate association of ideas by presenting related concepts. IdeaFisher (http://www.ideafisher.com) claims "to create a new method of generating ideas in a way similar to the workings of the human mind...by associations, or links....a thought like food leads to associations such as apple, cooking, cafe, washing dishes, and so on. When a creative new idea is born, it usually consists of associations linked together in a way that has not been thought of before. This is the heart of IdeaFisher technology—a dictionary of associations." Users apparently enjoy using IdeaFisher, but its benefits are still being assessed with empirical studies [Massetti 1996]. Support for the benefits of guiding associations with object names was found in a study of 10 designers who were asked to design an innovative stool for a Parisian cyber-café. Subjects in the guided condition produced many more concepts during their thinking-aloud session than those in the free condition [Bonnardel 1999].

Computerized thesauri may also be helpful textual exploration tools, since varied associations such as synonyms, antonyms, homonyms, rhymes, or even anagrams can be retrieved rapidly. Alternatively, random word presentations are also proposed as a method for stimulating fresh thoughts and breaking through creative blocks.

Other products enable users to produce thought-provoking visual representations of relationships among words or concepts. Examples include TheBrain (http://www.thebrain.com) which taps "the power of association" by "visualizing information flow" and MindManager (http://www.mindman.com) which allows users to "create relationships among information easily... identify relationships between items or branches." The Axon Idea Processor (http://www.singnet.com.sg/%7Eaxon2000/) is promoted as "a sketchpad for visualizing and organizing ideas" that "exploits visual attributes such as: color, shape, size, scale, position, depth, link, icon, etc. Visual cues facilitate recall, association, and discovery. Diagrams and pictures help you to represent and solve complex problems." Typical mindmaps show a main idea in a central node and then branches in all directions showing related ideas (Figure 3). As the diagram spreads out the nodes and font sizes decrease so that many small details are shown. A popular alternative is to have the main idea at the top or left, and then have a branching tree structure going down or to the right.

Mindmaps, concept maps, semantic networks, and other drawing strategies may be helpful to some people. Appropriate visual presentations, such as the periodic table of elements, help in problem solving because they compactly present substantial information and show important relationships. Geographic maps, architect's drawings, and electronic circuit diagrams are other examples of the great power of visual presentations for learning and problem solving. The gift of the computer is the capacity to quickly create and easily manipulate such diagrams. The same attributes are often celebrated in penciled diagrams and sketches which have a similar capacity to invite discussion, exploration, and revision.

The genex framework reminds us that such textual lists and diagrams should be easily shared with others, annotatable, linkable, and searchable.

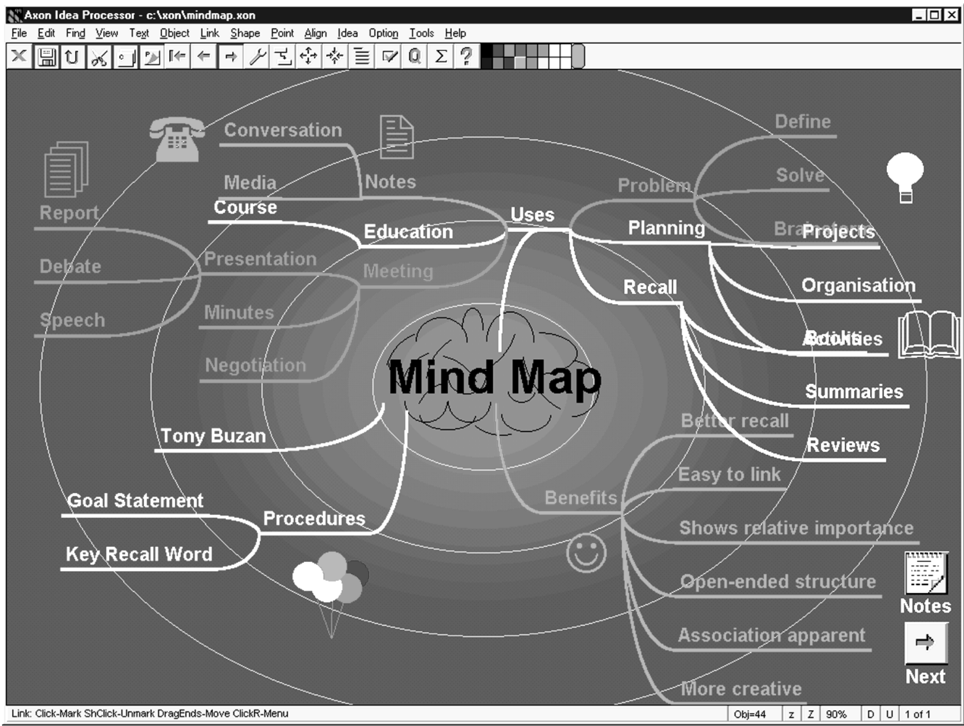

Fig. 3. MindMap produced with the Axon Idea Processor.

It should be possible to import and export from these programs so that related tools can be employed, for example, to translate terminology in a diagram into a foreign language or to link diagram nodes to Web sites.

5.5 Exploring Solutions: What-If Tools

A large family of software tools already support methodical exploration of solutions in the structuralist style [Elam and Melissa 1990]. Electronic spreadsheets are described as "what-if" tools that allow business planners and analysts to quickly try out a variety of scenarios. Such explorations are possible with paper and pencil, but they are far faster with electronic spreadsheets. However, there is still opportunity to support methodical exploration through macros that provide orderly tours of multidimensional attribute spaces. For example, stepping through business scenarios for ranges of expenditures on production, quality control, direct marketing, and advertising might identify creative solutions. These grand tour strategies are appealing, but difficult to carry out in high-dimensional spaces.

Similarly, flight simulators, traffic flow models, weather models, and thousands of scientific, engineering, economic, and other modeling tools allow users to explore alternatives safely, economically, and rapidly. Simulators have been largely custom built, but simulation-building software is growing from domain specific to broader coverage. These simulation models are also becoming more richly featured to support explanatory text, collaborative usage, history keeping, and more [Jones and Schneider 1996; Rose et al. 1998]. A popular class of home computer software includes simulation games, such as SimCity, which enables users to try out urban-planning scenarios. Also popular with personal computer users are flight, driving, and battle simulators that provide various levels of realistic experiences. These applications are enjoyable and educational; however, they are special-purpose and standalone applications that are not part of an integrated framework.

The genex framework and the situationalist perspective remind us of the importance of integration to support creativity. Having run a simulation, can users save the whole session and replay it later to study their performance or discuss it with a peer or mentor? Can they send the session to someone by email, annotate steps, or search for key events or actions? Can excellent sessions be stored in a digital library to allow future researchers or problem-solvers to build on the best work?

5.6 Composing Artifacts and Performances

Another large family of software tools already supports creation of artifacts and performances [Nakakoji et al. 1997]. The ubiquitous word processor is the premier example of a flexible tool that enables many users to create diverse high-quality printed documents using a relatively low-cost laser or inkjet printer. Only a few decades ago such high production quality required advanced typesetting skills that were available only to publishing professionals. The word processor enables business people to produce elegant newsletters and professional advertising. It allows individuals to produce high-quality resumes and elaborate full-length books. But word processors do more than facilitate quality appearance, they may also contribute to improved contents. The capacity to easily cut-and-paste, change terminology, or add references enables more people to create stronger scientific papers, legal briefs, or business proposals. It enables novelists, playwrights, and poets to easily accommodate suggestions from peers and mentors.

But even the word processor can be improved by thinking about creativity support in the genex framework. How might advanced visualization of a document help authors? How can consultation be facilitated? How can users locate appropriate previous work and build on it to suit their current needs? The basic notions of exemplars, templates, and processes have already begun to appear. Authors of business letters can purchase thousands of exemplars that they can adapt in their own word processor. Then some of these authors might be able to contribute or sell their improved or specialized exemplars through growing digital libraries, available through the World Wide Web.

A more flexible strategy is to prepare templates, as is done for business documents such as invoices or travel expense reports. These are supplied with many word processors. Templates differ from exemplars in that they

Fig. 4. The overview of steps in the process helps guide users in choosing the components of a slide presentation in Microsoft PowerPoint.

are somewhat more flexible, may include computational capabilities, and can have instructional guidance. Processes, such as Windows Wizards, extend the flexibility and allow richer variations.

Making a wider range of exemplars, templates, and processes available and a mechanism to create a market in new ones are still needed. Microsoft Office contains templates for word-processed newsletters, slide presentations sales reports, spreadsheet invoices, photo library databases, etc. (Figure 4). The structured processes of users' choices, embedded in the Microsoft Wizards, show overviews of the steps for generating an initial version of a personal resume or a legal pleading.

But effective composition tools go beyond the initial stages by providing transformations on documents and artifacts. Low-level changes like global word replacements or font changes are easy to implement, and mid-level changes such as reorganizing sections, figures, or style sheets are commonly available. However, there are few high-level tools that help in reorganizing presentations to give greater prominence to examples, shifting rhetorical style to question-answer expositions, or generating conclusions based on content. High-level revisions are more feasible if the domain is restricted such as a business letter or resume generator. An increased variety of low-, mid-, and high-level transformations should enrich the capacity of users to explore alternatives.

Adobe PhotoDeluxe provides an excellent example of the range of support tools for the complex transformations in getting, cropping, editing, annotating, and sending images. In addition, it offers impressive transformations for images to give them the appearance of Van Gogh's bold brush strokes, Seurat pointillism, or other styles. Music composition programs also provide transformations for a motif to generate New Orleans jazz or Rhythm and Blues pieces (http://www.pgmusic.com). Templates for fugues or sonatas and the strategies to recast motifs in the style of Beethoven or Joplin or other composers are realizable [Cope 1996].

Composition support tools should also provide evaluations. Modern word processors offer spelling and grammar checking, word counts, and sometimes reading-difficulty indexes. More advanced evaluation and critiquing tools are possible, especially if the domain of application is kept narrow. For example, tax preparation tools provide continuous feedback on the refund amounts as changes are made to the tax forms.

5.7 Reviewing and Replaying Session Histories

Reflecting on work is a central notion in quality improvement, creativity, and education methods. The metacognitive processes that promote self-awareness are learnable, but software support to capture the history of all user actions would seem to be a good foundation for many services. We have come to expect that Web browsers record the history of our site visits, so that we can return to them. One study of World Wide Web users showed that 58% of all URLs visited by users during a session were return visits [Tauscher and Greenberg 1997]. Even in this simple case controversies abound because the strategy for producing a compact, meaningful list (in a linear, tree, or network format) is not apparent. Another problem is that Web sites may change over time, so older histories may no longer produce the same results.

Producing histories of command lines in Unix or information retrieval programs is relatively easy, but understanding the meaning of each command may depend on the context (for example, the current directory). In richer graphical user interface environments such as simulators, image manipulators, legal information retrieval, or geographic information systems, recording each user step is feasible. However, success requires careful user interface and software design to ensure that the results are compact, comprehensible, and useful. Once these basics are accomplished, structuralists will especially like to manipulate session histories and replay the steps on another set of data or go back to change a step before replaying. Saving a sequence of steps for later use creates a basic macro, and by adding conditional and looping constructs quite ambitious programs could be built (Figure 5). For example, in a simulation of computer chip fabrication, it should be possible to rerun the simulation, changing the temperature by single degree increments from 100 to 200 degrees Centigrade. If histories are first-class objects then users should be able to send them to peers or mentors for comment or assistance with problems. Histories might also be searchable so that a set of hundreds of directories could be searched to see if any were done at a temperature above 200 degrees Centigrade. Users should be able to post or sell exemplars of excellence or processes that might be helpful to others.

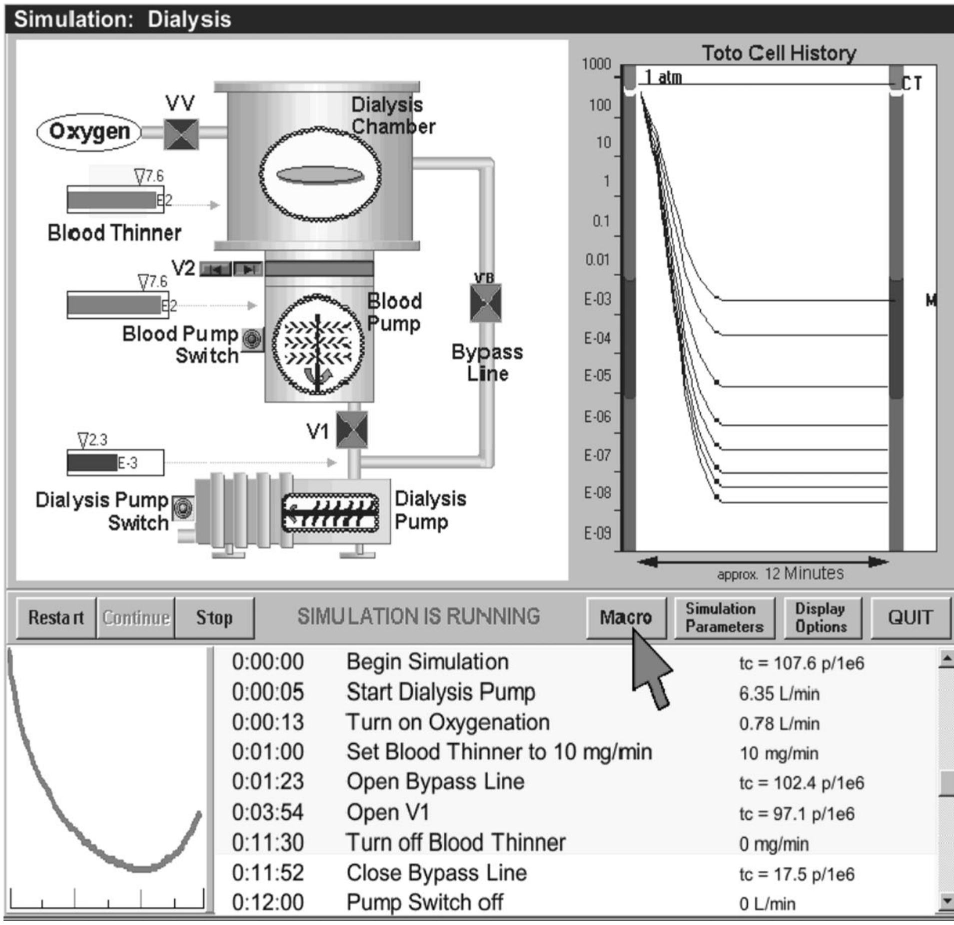

Fig. 5. History keeping in the SimPLE environment [Rose et al. 1998]. The user has run a simulation and produced a history, then rerun the history macro eight times to produce the eight outputs on the upper right.

5.8 Disseminating Results

Email, listservs, digital libraries, and the World Wide Web provide an excellent foundation for disseminating results, but these also could be improved by thinking of the genex framework. The first circle of people who should receive an announcement of an innovation include previous and current workers. While digital libraries and online resources may make previous work accessible, extracting email (or mailing) addresses and ensuring that they are current is tedious, at best. Finding current workers in a domain is sometimes possible by listservs, newsletters, or Web sites of relevant communities.

A second circle of interest might be readers of papers or viewers of Web sites with related materials. Finding the identity of Web site viewers is not usually possible, but registration strategies might be developed to enable visitors to request information about future developments. The commercial bookseller amazon.com offers a service that will send you email when books on a topic or by a given author appear. Obviously, such registration lists have great commercial value, but publicly available variants are likely to emerge and be appealing because of their narrow focus. These are modern versions of what information retrieval professionals call selective dissemination of information (SDI), a policy by which users are informed on a regular basis about new publications on topics they have selected.

Digital libraries are being reconceived of as digital library communities, by extensive use of online community software to turn every object into the focus of a discussion group [Brothers et al 1992]. Anyone retrieving a novel, scientific paper, legal precedent, or classical music score could register to participate in a discussion of that item. Such online discussion groups can stimulate creative work in many disciplines if appropriate usability design and sociability policies are developed [Preece 2000].

Additions to scientific journals, music libraries, or art galleries would require review by editors, collections managers, and curators. Modern technologies not only speed up the process, but also facilitate review from multiple sources. Maybe more importantly the complexity and cost of establishing online journals, libraries, and galleries is substantially less than physical institutions, thereby lowering the barrier. Having more diverse institutions that create digital libraries is also likely to stimulate creativity.

6. ARCHITECTURAL SCENARIO

The genex framework and the eight activities could reshape many forms of evolutionary creative work. Earlier genex examples included education, medicine, and legislation [Shneiderman 1998c]. The following scenario has some elements of wishful thinking, but it exemplifies how the genex phases (collect, relate, create, and donate) and the eight activities (search, consult, visualize, think, explore, compose, review, and disseminate) might be supported. This scenario assumes that genex tools would enable an architect to have a broader range of decision-making power. This reverses the decentralized and fragmented approach of contemporary practice by restoring control and responsibility in one individual. However, this is possible only if powerful consultation tools are available to coordinate and supervise tasks that are often delegated to many others.

Imagine an architect, named Susan, who is chosen to design a hotel at a national park because of her reputation for flexible designs. Her winning proposal was to break away from the uniform array of hotel rooms at many resorts, and allow flexible modules that can accommodate couples or be reconfigured for families and groups of up to 12. She searches an architectural library for exemplars of hotels from around the world, such as Swiss chalets, Austrian lodges, or Rocky Mountain log cabins (collect and search). She flips through 300 possibilities to open up her mind to a broad range of roof designs and sidings (collect and think). She visualizes the data on heating requirements, heat loss, and energy consumption patterns for these

300 possibilities to find strategies that are energy efficient (collect and visualize). Susan chooses a log cabin design and pays the creator a modest fee, then wrestles with the problems of adding more windows, movable modules, and solar heating panels. Her composition tools allow her to manipulate the underlying architectural model so that she can resize the building to accommodate the required number of rooms (create and explore). After choosing a cedar shingle roof and redwood siding, she superimposes the images on the backgrounds of two potential sites: on the hillside and at the base (create and compose).

The park managers and concessionaires who will run the hotel prefer the hillside site because of the wonderful views, rather than the base site. After consulting electronically with park commissioners and travel industry advisors, they accept the log cabin style, since it fits local and tourist tastes (relate and consult). A videoconference directly with the client using dual three-dimensional displays leads to immediate decisions about the reception desk, a commons area with a fireplace, and a gift shop (relate and consult). The distinctive plan for flexible modules to accommodate couples, families and groups of hikers meets resistance, but Susan perseveres. She adds further flexibility, allowing those who wish to cook their own meals to share a communal kitchen/dining area, and offering fine dining and maid service for those who want a more pampered experience. The steep incline of the hillside site presents a formidable challenge, but after an all-night session playing with the engineering models, Susan finds an innovative structural design that costs only 8% more than the base site (create and explore, compose). Susan reflects on how the traditional fragmented approach would have killed the flexibility theme because independent contractors would not risk novelty.

Susan collaborates with specialists who conference over her plans for the electric wiring, plumbing, phones, and Internet connections. The same groupware gets her rapid advice from other consultants, but preserves her control over wall decorations, flooring, and furniture styles (create and explore, compose). She does in hours what would have taken weeks when these tasks would have been sent out to consultants. After a virtual walk through, the client requests larger windows, which is handled by reviewing the design history and increasing the window sizes (relate and review). This change causes rerouting of wiring and stronger structural supports, but Susan's flexible design is preserved (create and compose).

At this point, consultations begin with potential builders (relate and consult). Susan reviews the capabilities of builders, and she receives bids electronically. She uses her software to generate bill-of-materials lists for suppliers and a construction schedule for discussion by all parties (relate, create and compose).

Susan decides to break with tradition and insists on supervising construction. She has to replace a slow-working subcontractor, but opening day is on schedule. There is already a waiting list of couples, families, and groups who are attracted to the beautiful setting and the flexible accommodations. Susan registers her design with the architectural society's digital library, and sends a description to interest managers of similar parks around the world (donate and disseminate). Her flexible approach is copied by others, for which she collects a fee, and she receives a resort industry award for architectural innovation. Susan appreciates how the software tools enabled creative designs and new business processes, but has a list of upgrades she wants before her next project.

7. CONCLUSIONS

Ambitious visions can be helpful in shaping more concrete research agendas. For example, Engelbart's goal of augmenting human intellect [Engelbart and English 1968] led to innovations such as the mouse and windows. Later, Brooks's belief in the importance of toolmaking [Brooks 1996] led to innovations such as haptic feedback in three-dimensional graphical environments. These inspirational visions were important catalysts for genex.

The ambition to support evolutionary creativity led to the four phases of genex:

—*Collect:* learn from previous works stored in libraries, the Web, etc.

—*Relate:* consult with peers and mentors at early, middle, and late stages

—*Create:* explore, compose, evaluate possible solutions

—*Donate:* disseminate the results and contribute to the libraries

These four phases and the eight activities described in this article

—Searching and browsing digital libraries

—Consulting with peers and mentors

—Visualizing data and processes

—Thinking by free associations

—Exploring solutions—what-if tools

—Composing artifacts and performances

—Reviewing and replaying session histories

—Disseminating results

are major challenges, but the integrated combination of them could produce an environment that greatly facilitates creativity. The eight activities and their integration form a research agenda for human-computer interaction and user interface design.

The goal of supporting more creativity by more people more of the time is attractive, but there is the danger that the genex framework might be ineffective or even limit creativity. By making easy access to previous work and current workers, there is a risk that more exotic ideas will be suppressed. Similarly, using creativity supports such as simulations and composition tools may restrict imagination to only what is possible with these tools. Consultations are time consuming, and discouraging advice for novel ideas is a possible outcome. Fear that others will plagiarize compositions or steal inventions is another legitimate concern. An understanding of the dangers is important in pursuing the positive possibilities.

Between the lofty ambitions and troubling fears, lies the practical path of careful research and detailed design for the eight activities described in this article. They need development, testing, and refinement to make them successful, find their flaws, and pursue alternatives. At every stage, widespread participation in design reviews increases the possibility that the resulting technologies will serve human needs in constructive and positive ways.

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