J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*

IDEA PROCESSORS

Idea processors represent computerized endeavors to generate and organize ideas, thus enhancing (or amplifying) human creativity. The term *idea* means an understanding, insight, or some primitive form of solution to a problem (1). In a looser sense, the term idea processor also covers various creativity support systems. Idea processors are used to support work in early, emergent, and usually creative stages of human intellectual activities such as research planning, conceptual design, software requirement analysis, knowledge acquisition, decision making, counseling, motivation, as well as others (1). In the last two decades, idea processors have gained increasing popularity in various applications (particularly in those related to business and engineering) and have made some impact on people's daily lives.

The topic of idea processors is an interesting one for several reasons. The literature of idea processors consists of many product reports, thanks to the proliferation of commercial tools. Scholarly papers do exist, but usually they deal with individual experimental systems, and comprehensive studies are hard to find. As a highly interdisciplinary area which involves many fields within computer science (such as human-computer interface and information retrieval), idea processors have a close relationship with artificial intelligence (*AI*; see also Artificial Intelligence). However, the study of idea processors is usually not considered as a part of AI proper, partly due to the fact that the force is actually rooted in management science. Although there is some overlap with the study of creativity in AI, idea processors have many features of their own. All of this has put idea processors in a unique situation.

The aim of this article is to discuss important features of idea processors, summarize the state of the art of idea processors, provide comments on various (sometimes conflicting) viewpoints, and point out future directions of related studies. We do not intend to provide a complete survey, although we do incorporate several products to illustrate various aspects of idea processors.

This article consists of three parts. The first part is an overview. It consists of two sections: basics of idea processors and how idea processors work. The second part provides some technical details of idea processors; this part consists of the following five sections: the nature of idea processors, architecture of idea processors, theoretical work on idea processors, evaluation methods, and creativity enhancement in group decision support systems. The third part provides a sketch for future research. This part includes two sections: theoretical studies of computational creativity, and some issues for future research.

Basics of Idea Processors

Since some key ideas of idea processors can be found in product reports, in this section, we will summarize some important features of idea processors using commercial products. A more detailed analysis will be given later in this article.

Computer Support for Human Creativity. The purpose of an idea processor is to assist human intelligence, namely, to provide computer support for ordinary people. We are interested in human creative potential—not just with analyzing it, but with seeing how people can become more creative (2). An individual's natural creative potential is biologically determined and established early in life, and is not expected to vary significantly over time. However, through training, an individual's creative performance can be amplified or inhibited. Creativity training represents the individual's past knowledge and developmental history concerning his or her creative behavior (3,4). Idea processors have been developed for this purpose; they influence an individual's performance by providing the necessary suggestions and cures to produce a creative response (5).

Various commercial products have been made available in the last two decades, including some software which can be viewed as predecessors of idea processors. In fact, many word processors already have outliners built in. A computer-based outliner combines the organizational power of the traditional outline with the flexibility and fluidity of electronic text. Computer outliners can provide the form or template of the outline and prompt the writer to supply ideas. The act of filling out this form may help writers sort out their initial, random ideas and build relationships among them. Deciding where to put each idea as it comes may require the writer to examine how the idea relates to all the other ideas that have come before. Word processors with outliners still co-exist with idea processors. Word processors may also be equipped with graphic idea organizers.

In some sense, early idea processors may be viewed as an extension of word processors and spreadsheets. However, the word-oriented, rather than number-oriented, feature has led idea processors to take a more symbolic direction as employed by artificial intelligence.

Idea processors can be examined from the computerized problem solving perspective. Since their main tasks are idea generation and organization, idea processors fall in the scope of knowledge-support systems (6) and can be viewed as a partner for human beings in problem solving. However, unlike some other partner machines, idea processors usually are not participants of the whole problem solving process; instead, they are only used for idea generation and organizations in some specific stages of problem solving.

Three levels have been defined for supporting idea processing systems using metaphoric thinking (7,8): at the secretarial level (the computer is used essentially as a dynamic electronic blackboard), the framework-paradigm level (the computer can provide frameworks to organize the user's thoughts and to provide examples to serve as both thought stimuli and guides to the user), and the generative level (the computer can automatically synthesize and display new ideas). The three support levels are hierarchical and cumulative; thus, the generative level includes the prior two levels. Idea processors are tools at the generative level.

Issues Related to Electronic Brainstorming. Creative thinking is usually considered as relating things or ideas which were previously unrelated. For many idea processors, the most important technique is to generate ideas through electronic brainstorming. Brainstorming, first proposed by Alex Osborne in the 1930s for management, is a method of getting a large number of ideas from a group of people in a short time (9). Idea processors use electronic means to achieve effect similar to conventional brainstorming for idea generation, but they do not necessarily rely on a group effort.

Several guidelines for brainstorming are noted, such as suspension of judgment, free-wheeling, quantity, and cross-fertilizing. Brainstorming can be conducted through several stages including (1) state the problem and discuss, (2) restate the problem in the form of "How to . . .," (3) select a basic restatement and write it down, "In how many ways can we . . .," (4) a warm-up session, (5) brainstorming, and (6) identifying the wildest idea. Some evaluation method should be used to identify a few good ideas for implementation (10). An implicit assumption used here is the quantitative measure: if a large quantity of ideas has been generated, then the idea pool very likely would contain high-quality ideas. An important note here must be that despite the controversial (sometimes poor) laboratory performance of techniques such as brainstorming (based largely on quantitative measures), the business world continues to rely on them. Brainstorming has also been used in the engineering design processes to offer strategic support because it separates the production of ideas or plans from any criticism of them (11).

Related to brainstorming is brainwriting, which is characterized by silent, hand-written communication. Brainwriting can be categorized as either interactive or nominal (which is non face-to-face idea generation). Electronic brainstorming is actually electronic brainwriting.

A special form of brainstorming is *PMI* (12). The difference is that in PMI, the participants are deliberately directed to brainstorm the good, bad, and interesting points. PMI is an attention-directing tool. Participants first direct their attention toward the plus points (the P of PMI), then toward the minus points (the M of PMI), and finally toward the interesting points (the I of PMI).

Two related issues that must be addressed in brainstorming are convergence and divergence of ideas. Convergence refers to analytical thinking where the process converges to a single answer, while divergence refers to creative thinking where the process diverges to a large number of ideas and ranges far and wide over the problem. Creative thought has both divergent and convergent aspects, as will be further explained in the next section. The process of brainstorming is divergent, with participants ranging far and wide in their endeavor to find possible solutions. Evaluation is convergent, seeking to convert the many ideas into few solutions.

Electronic brainstorming tools are frequently used as components of group decision systems to brainstorm ideas. These thoughts are then organized into categories using the categorizer or idea organization tools. A ranking/ordering/voting process is carried out to prioritize the final categories and achieve consensus. An alternative sequence may consist of stages of divergence (brainstorm or collect ideas), convergence (consolidate, or make some sense of the ideas), evaluation (typically vote in some fashion), debate or lobbying (to gain a better understanding), and finally organization of the results (to develop presentable output) (13).

Traditionally, idea generation has been seen as a group task. Techniques have been designed to facilitate the sharing of ideas and the refinement of ideas generated by other individuals, although techniques which helped the individual problem solver come up with more or better alternatives have also been studied (4,14). This article will focus on idea processors for individuals, but since many idea processors employ brainstorming techniques, and since brainstorming is a group activity, from time to time, our discussion will be intertwined with group decision support systems.

How Idea Processors Work

In order to have a concrete idea about idea processors, we now have a brief discussion of some sample programs (many are commercial products) of idea processors, as well as some applications. The purpose is not to provide complete or up-to-date information of these products; rather, we use them to provide some working examples to show how idea processors actually work. Behind these idea processors are various heuristics which stimulate human thinking.

Destructuring and Restructuring Processes. As mentioned earlier, many idea processors rely on brainstorming techniques. Directly related to this is the rearrangement heuristic: ideas and thoughts are solicited from the user(s), followed by a possible randomization, and then rearranged into topics later. Gestalt psychologists suggest that creative thinking proceeds neither by piecemeal logical operations nor by disconnected associations, but by more a determinate restructuring of the whole situation. Creativity lies in the ability to redirect a line of thought taken in solving a problem (15). We can gain useful insights into problems by making use of computer programs that help us to destructure our thinking and then to restructure it in a different way (16,17). For example, in Idea Generator Plus (17,18), users go through a step-by-step problem analysis and solution finding process. Seven techniques are provided to the user: examine similar situations, examine metaphors, examine other perspectives, focus on goals one by one, reverse the goals, focus on the people involved, and make the most of the ideas (including rephrasing some ideas, weeding out others, and grouping of similar ideas).

Generative and Exploratory Systems. Categorically, creative thought can be viewed as responses from two types of mental processes: generative and exploratory (3). Within the generative mode, divergent ways of thinking, including remote association and pattern switching, produce novel, unique concepts. In the exploratory mode, convergent thought, such as elaboration or successive refinement, reformulates a unique concept into a meaningful and valuable response. The nature of the decision task defines which mode is likely to dominate response formation (3). IdeaFisher is an example of an idea processor with a generative focus (5).

A. Koestler (19) used the term *bisociative thinking* to show the linking of two unrelated planes or matrices in the creative act. Two or more quite unrelated concepts can be combined to give a totally new concept. In IdeaFisher (an idea processor using hypertext databases from Fisher Idea Systems Inc.), all entries in the IdeaBank (the database) are cross-referenced by concept and association. One can engage in free association, jumping from one related word or phrase to the next, and IdeaFisher automatically records the findings on the Idea Notepad. When idea-hopping is done, the user can export the contents of his Idea Notepad as a text file. The program also allows the user to generate new ideas based on combinations of words. Whenever a user types in any two words, IdeaFisher creates a list of people, animals, verbs, adjectives, and phrases that are all somehow associated with the combination of the two words. Although IdeaBank may not always work, in general, the rich supply of interconnected ideas are effective in stimulating new ideas. The user can also turn to IdeaFisher's QBank—a collection of more than 5000 questions that help the user probe and evaluate ideas and flush them out. IdeaFisher extracts the key ideas from the user's responses to the QBank's questions by collecting a list of all the words with which the user repeatedly answered the questions. IdeaFisher Systems also offers three plug-in QBank modules, one for creating a mission statement and producing long-range plans, one for preparing grant proposals, and one to assist in creating speeches, lectures, and other presentations (20).

Ideatree is an idea processor with an exploratory focus. Rather than asking open-ended questions or offering lists of generic ideas, it provides a means for users to embellish, emphasize, and polish ideas. The user has a chance to type concepts into the idea boxes, which can then be linked laterally or hierarchically (21). Ideatree does not actively inhibit generative thought; it focuses on detailing, arranging, and coordinating ideas to make them more meaningful and valuable.

Thinking with Visual Aid. Visualization has been frequently used in idea processors. Inspiration (from Inspiration, Inc.) provides a blank canvas on which the user can quickly record and arrange ideas as they occur to him. Inspiration's diagram mode allows a user to take a visual approach to organizing his thoughts. Each idea typed by the user gets inserted into its own symbol box. One can change the relationship between ideas by simply dragging the symbols on the screen, and one can connect related ideas by dragging links between them to create a graphical map of the user's ideas. Visually clustering the idea symbols on screen allows the user to see emerging relationships, thought patterns, and terms. The program also has a strong outline mode for translating the user's idea map into a traditional hierarchical outline. At any time, the user can jump back to the diagram view, where one can use a palette of standard drawing tools to enhance one's idea map before printing it. The reader can also consult Ref. 20, where discussion of some other products can be found.

Experimental Idea Support Systems. In addition to commercial products, some experimental systems have also been developed. They are developed either for practical applications or to serve as research prototypes. A system called *GENI* will be examined later. The following are two examples of applications.

An interactive computer system called the Emergent Media Environment (*EME*) has been developed to support creative work in the emergent stage (or upper stream) of human intellectual activities. The system is intended to integrate facilities for supporting the generation, collection, organization, and presentation of ideas and advising about the divergence and convergence of the ideas (1).

Another idea support system has been developed to support corporate competitive positioning. Among its features are the supporting of the planning of corporate competitive strategy corresponding to the positioning and the supporting of knowledge acquisition and the expedition of organizing the knowledge. One feature of this method is that these tasks are executed integratedly and simultaneously (22).

The Nature of Idea Processors

Having briefly examined some existing idea processors, we now take a closer look at the nature of idea processors. Particularly, we are interested in questions like: Where do they stand in relation to computer science? What is their general relationship with AI?

Idea processors are developed to assist human thinking, including idea generation and organization. This task is a very special kind of symbolic problem solving and is of an open-ended nature. In order to assist, enhance, and amplify human intelligence, studies in psychology (some are from folk-psychology), management science, as well as artificial intelligence, have served as useful sources and have made important contributions.

Analysis of Idea Processors from An Artificial Intelligence Perspective. We first examine some features of idea processors by providing a sketch of their relationship to artificial intelligence.

Relationship Between Creative Problem Solving and General Problem Solving. AI employs symbolic approaches for general problem solving, with creative problem solving as a special form of problem solving. Creative problem solving has been commonly viewed as a multistage process. At the core of Wallas' widely cited creativity model (23), the following stages are involved: preparation, incubation (a part conscious, a part unconscious deliberation and idea finding phase), illumination (the moment of recognition when an idea has been found), and verification.

Ideally, one might like to see a programmed or programmable idea generation procedure, although such a procedure may seem antithetical to the very concept of creativity. Nevertheless, there are a number of heuristics to facilitate problem structuring and idea generation. For example, several heuristics focus on asking the right questions, such as the Schank question categories; other heuristics involve linking the present problem with a remote context (14).

AI Techniques Used by Idea Processors. According to a modern viewpoint, the task of artificial intelligence is to build rational agents (24) (see also Artificial intelligence). Typical concerns in AI include heuristics, search, weak methods, knowledge representation and reasoning, as well as others. Techniques for brainstorming can be viewed as various kinds of heuristics to stimulate human thinking. In the following, we summarize some other aspects of idea processors from an AI perspective.

First of all, AI deals with symbolic problem solving. Some idea processors intend to help users take a fresh look at problems by guiding what may be a user's otherwise undisciplined intuition through a series of problem-solving exercises. Some of these programs deliberately force people to think in nonlinear, nonlogical, playful ways. The idea behind them is to divert one's thinking from the channels that day-to-day work has forced it into, sparking new ideas and new ways of thinking. Others focus one's attention on the psychological aspects of overwork, such as motivation, stress, and depression. Guided problem-solving supplies frameworks into which a person can plug his ideas. The main advantage of computerized, guided problem solving is that the programs will prompt a user for his ideas in a thorough manner (25).

Problem solving in AI is conducted as a state-space search. It has been noted that for a given set of variables and processes operating within a bounded context or focus, any computational model will construct a bounded state-space. Creative design can be represented in such a state-space by a change in the state-space (26). Recent development in AI has also emphasized knowledge-based approaches. Frequently, new ideas are sparked by reviewing old ones. In order to achieve the goal of assisting human thinking, idea processors usually perform extensive search in memories, including large databases, knowledge bases, or text bases. New ideas may be produced by summarizing or reorganizing unorganized chunks in such memories. For example, IdeaFisher is a giant cross-referenced text base of words and phrases representing concepts and images enhanced by a series of questions. IdeaFisher is perhaps the purest rendition of a hypertext database. IdeaFisher is built around a sprawling database called the IdeaBank, which contains more than 60,000 words organized by major categories (such as Animals, the Senses, and Emotions) and topical categories (groups of related concepts). It provides more than 705,000 direct associations and a huge number of secondary (linked) associations. It also has QBank—a collection of more than 5000 questions that help the user to probe and evaluate ideas and flush them out (5,20).

The system for assisting creative research activities (27) has a large scale database consisting of 1,100 journal and conference papers on scientific research. In a narrative generation system (28), narratives are generated by executing appropriate narrative techniques under the control of narrative strategies based on a set of events and narrative parameters given by the user. The system consists of about 50 narrative techniques, about 100 narrative strategies based on about 15 narrative parameters, about 500 frames and instances in knowledge bases, and other procedures.

More advanced AI techniques have also been used by idea processors to be discussed later in this article.

Some Differences from Traditional AI. The above discussion clearly indicates some common concerns shared by idea processors and traditional interest of AI, because both deal with solving nonquantified, unstructured problems. However, there are also some important differences between them. A study of these differences will be important for us to understand the nature of idea processors.

In large degree, AI is about knowledge representation and reasoning. In contrast, idea processors usually emphasize the broader sense of *thinking* instead of reasoning. As defined in dictionaries, the most basic meaning of thinking is to have as a thought; to formulate in the mind.

The task of AI is to build intelligent, rational, and autonomous agents. This task is rather ambitious. In contrast, idea processors have a much humble goal, namely, to assist human intelligence, rather than carry out discoveries by themselves. Although both AI and idea processors are concerned with using computers to achieve creativity, the role of idea processors in creative thinking is quite limited; they can only assist in generating ideas which are the starting point of a lot of work, which needs to be done by human beings.

Due to these different aspects and different emphases, idea processors and AI may employ quite different methods. For example, instead of developing efficient searching algorithms for reasoning, idea processors may rely on much less sophisticated methods (e.g., random combination or permutation) to generate ideas, although AI algorithms (such as genetic algorithms) may also be used.

Nevertheless, some overlap exists between the study of AI and the practice of idea processors. It is noted that in the AI research community, "efforts at modelling discovery processes have sometimes been aimed at developing a theory of human discovery, sometimes at constructing systems that can, in collaboration with scientists autonomously, engage in discovery work (29)." Some interactive software and database search strategies have been developed to facilitate the discover of previously unknown cross specialty information of scientific interest. The software can help to find complementary literature and reveal new useful information that cannot be inferred from either set alone. These studies from the AI research community echo efforts related to idea processors, particularly the emphasis of connections between concepts (30).

Some Other Aspects Related to Computer Science. In order to understand the nature of idea processors, we should also take a look at the general standing of idea processors in computer science. Since idea processors have wide connections with various branches of computer science, we can only examine some of the key aspects of these connections.

Computer-Human Symbiosis. The intensive interaction between idea processors and their human users promotes a kind of computer-human symbiosis, which goes beyond the traditional human-computer interaction (*HCI*). For example, an idea processor can provide bullet chart slides, boxes with double or triple lines, as well as multiple windows side by side for easy cutting and pasting between documents or portions of documents.

Furthermore, the future for human-computer interaction lies in the symbiosis of human and artifact (31), which implies a comprehensive understanding between computers and human users; they are more than just techniques for enhancing interaction, but rather, authentic symbiosis. This echoes similar proposals from the HCI community where computational models on information flow and control between humans and computers have been developed; in such models, computers will have an impact on human thinking (32).

The idea of the computer as an assistant which takes an active and positive role promotes the notion of the computer as a cooperative partner and opens up new possible modes of interaction (6). According to this viewpoint, idea processors may play the role of intelligent agents (33). Agents represent a fundamental shift in the human-computer interaction paradigm because an agent is a program that performs unique tasks without direct human supervision. As such, it transforms the user from a worker into a manager who delegates tasks to that agent.

Natural Language Processing and Generation. For idea processors for idea generation, it is necessary to communicate with users. To avoid any potential barricade in this process, a smooth communication between the user and the machine is an essential requirement. Natural language processing and generation thus becomes an important aspect of idea processors. For example, a narrative generation system has been developed as a creative interface tool (28). This approach is based on the assumption that narrative has some useful characteristics (or functions) for supporting human creative tasks, and that we can utilize the narrative generation system as a kind of creative interface tool by building a system which provides such functions. These functions include a meaning generation function (which integrates fragmentary materials into a story), an aesthetic representation function, a virtual reality function, and a knowledge integration function. The main objective of the narrative generation is to stimulate human imagination and human creativity. The system can flexibly generate a variety of narratives from one input. It reorganizes each story into some plots. For example, if it uses a plot generation technique with viewpoints, different plots are generated from the same story based on each actor's viewpoint. The system can integrate a variety of theories or knowledge representations, and that extends the system, itself.

Information Retrieval. Searching techniques are assisted by traditional information techniques, for example, there is the use of thesaurus and hypertext. IdeaFisher has topical categories such as

jump/spring/bounce/deflect/reflect
wild/fierce/uncivilized/tame/domesticated

which resembles a hierarchical thesaurus. As we will see in a later section, information retrieval techniques have been used for analog retrieval in a system for automated generation of suggestions (34). In addition, just like the case of information retrieval, precision and recall are used for evaluation (27,33).

The close relationship between idea processors and information retrieval has also made idea processors ready to lend themselves for assisting information retrieval, as exemplified in (27).

Architecture of Idea Processors

In the computer science literature, the use of the term *processor* is usually related to computer hardware; but it can also be used in a broader sense, such as in *word processor*.

Examples of computer architecture for symbolic problem solving include implementation of *LISP* or Prolog and expert system architecture. Artificial neural networks can also be viewed as special purpose hardware for AI problem solving. The history of special purpose machines for AI, such as implementations of machines for list processing (*LISP*) or Prolog, can be found in Ref. 35. Some other related discussions can be found in Ref. 36.

In contrast, idea processors are normally software packages developed for personal computers or workstations; hardware and equipment issues may need to be addressed to deal with some particular concerns of idea processors (for example, to take advantage of the underlying hardware, or how to deal with network communications as needed in some idea processors).

Common Components in Idea Processors. Two types of programs can be developed to elicit or facilitate human creativity: the creativity acquisition programs (somewhat similar to knowledge acquisition in knowledge-based systems) and the creativity facilitation programs (15). Although the structure of idea processors highly vary, some common components can be found. A typical idea processor usually consists of the following:

An idea generator
An idea organizer
An idea base
An idea presentor
A computer network and
Supporting components

In the following, we provide a brief description for each of them.

Idea Generator. In an integration of idea creation tools, or Emergent Media Environment (*EME*) (1), a component called the keyword associator facilitates idea divergence through association retrieval. An associative dictionary consists of a set of keywords and three types of similarity nets (between keywords and groups, between keywords, and between groups). The user enters words and/or articles to the keyword associator and relevant words and/or articles will be retrieved.

Idea Organizer. In contrast to an idea generator, the task of an idea organizer is to provide convergent advising. Diagrams can be used to represent and organize personal ideas and to share ideas among people in the group work. In EME, values concerning relationships among keywords of ideas (such as similarities) are calculated, and idea segments related to the idea creation process are organized into an integrated conceptual diagram (1).

Idea Base. The place for idea storage is usually referred to as the idea base. For example, a model for organization innovation system (37) consists of a large set of ideas, an idea base, which functions as the organizational unconscious. These ideas are collected from all organizational members over time and are stored electronically to facilitate searches using a database management system or a hypertext system. A frame-based representational scheme can be used for the idea base. When an idea is generated, the slots must be filled to completely describe the product. Frame-based systems have the virtue of slot inheritance as discussed in object-oriented literature. The idea base acts like a bulletin board through which organizational members can browse and to which new ideas can be continually added.

Idea Presentor. The last basic component of a typical idea processor is the idea presentor. For example, it may convert the net-structured diagram for idea organization to linear-structured documents for display purposes, as in EME (1).

Supporting Components. In addition to the basic components described above, some supporting components may be needed to enhance various functionalities (such as idea generation or organization). For example, in an organization innovation system of (37), an expert system is used to aid the decision maker to select a small set of most useful ideas from the idea base. This process is akin to the mental activity of the creative subconscious. The process of convergent thinking is applied to the large set of possibilities by accessing the domain-specific expert system that contains rules for evaluating ideas in a specific domain. The knowledge base of the expert system would contain heuristics obtained from experienced members of the organization who are considered experts in the domain interest. The evaluative component is based on the consensual technique for creativity assessment.

Computer Networks. A hypermedia-based architecture can be used to mimic the function of a human brain to store and retrieve information by associates. A typical hypermedia system is equipped with a text editor, a graphics editor, and a database management system to support data manipulations of objects where a distributed database can be used. In addition, cause-effect analysis (also known as Fishbone Analysis) can be used as an architecture for the design of the creativity facilitation programs. The branches and the layers in the network are not fixed or predetermined. The hypermedia technology aides the user to create the nodes and helps keep track of the paths. The user can navigate through any layer and any node (15).

A network architecture is also used in a generic protocol developed for asynchronous group idea generation, which is described using open systems interconnection (*OSI*) protocol description methodology (38). A two-layer architecture is used. The group message layer is concerned with the reliable transfer of messages between entities and provides a group-oriented structure to the message transfer service. The task of this layer is carried out by a group communication agent. The group activity layer provides services specific to group idea generation and supplies an activity-oriented structure over the group message layer.

Special Equipments for Applications.

Idea Abstraction for Software Library Support. In some applications, it would be ideal to incorporate idea processors into the system for some particular environments. For example, a library-supporting editor with idea processor has been proposed for software development. The particular problem considered here is to deal with the limited program size in single-chip microcomputers. The idea processors supports human thinking processes such as creating a hierarchy of grouped ideas and an abstracting group and a hierarchy of ideas. Abstracted contents are treated as one idea (or its intermediate) and lead to further abstracted contents (39).

Equipment Requirements for KJ Method. All the idea processors examined so far have been developed for English-speaking users. Special architectural concerns must be addressed for idea processors developed for Japanese-speaking users. When documents are written in English (or other languages using similar alphabets), a large number of documents in linear text form may be easily created by using typewriters. A hierarchical structure consisting of chapters, sections, subsections (and the like) can be used to organize the text. Outline processors are the programs which support the process of building this kind of structure. In contrast, Japanese typewriters are very inefficient. This is why J. Kawakita ("*KJ*") invented the chart forming method for Japanese text processing. This method has been widely accepted in Japanese business society.

The KJ method, developed by J. Kawakita (40), claims to establish an orderly system from chaos through its proper usage. The first step is to write down on a card what has come to mind on the subject under discussion. The second step is to associate the cards into groups. The third step is to arrange the card groups on a large piece of paper and to enclose each group by an outline to make clear the mutual relationships between the cards and groups. The result is called an A-type diagram. The fourth step is to write an essay on the subject according to the A-type diagram just completed, called B-type writing (41). According to an implementation of the KJ editor (41), a video terminal display is used as a desk-top on which cards are arranged. One problem with card manipulation simulation on a computer is the size of the screen (a big screen cannot be as large as a desk). To deal with this problem, two screens are superimposed on a video terminal. One is a bitmap screen (the universal screen) that provides only the arrangement of cards, and the other (the local screen) is a character screen that provides a close-up view of the card arrangement on the bitmap screen and written characters on individual cards that are visible and readable. This implementation exemplifies the special architectural concerns of idea processors.

Research Work on Idea Processors

Although the major driving force of idea processors is from industry, there are also academic studies devoted to idea processors. Several dimensions can be identified. One dimension of work seeks to establish a theoretical foundation to stimulate human thinking through computerized mechanisms. Another dimension of study is concerned with creativity modes or styles. In the following, we examine some existing work along these dimensions. There are some research programs devoted or closely related to techniques used by idea processors.

Theoretical Foundation for Stimulating Human Thinking.

An Outsider Model for Breaking Fixed Idea. A system has been constructed to stimulate the divergent thinking process by making an artificial outsider attend a brainstorming session in a teleconferencing system with realistic sensations. Based on a study on what kinds of information can break human fixed ideas and how an outsider can extract such information, an outsider model was proposed for obtaining such information, and a prototype system was developed. Moreover, by classifying the whole information space into four regions from objective and subjective viewpoints, the specific region which stimulates the human imagination is identified, and an evaluation method was proposed to determine whether a piece of information can effectively stimulate the human imagination. The results show that the prototype system can extract information that is capable of stimulating human imagination (42).

Automatically Constructed Word Space for New Concept Formation. From the viewpoint of concept formation, one main process of creation is divergent thinking in which broad alternatives are searched, and another process is convergent thinking in which a unique solution is sought. A mechanism can be developed to reflect the fragments of concepts that are not articulated yet and thereby stimulate the formation of new concepts. A computer system called AA1 has as its main feature a strategy for building a two-dimensional space from the words the user provides and for presenting this space to the user. The system is as nonprescriptive as possible, but it provides stimulation for the user to form concepts. Experiments show that the most prominent effect is that empty regions in the space automatically configured by the system often lead to new concepts (43).

Generating Alternatives as Making Connections. A central task of management is decision making, and a crucial aspect of decision making is having good alternatives from which to choose. Based on a conceptual framework considering creative processes, environments, outputs, and individuals, generating alternatives is viewed as a process of making connections—internal connections among problem elements and external connections between a problem and its environment (14).

Making connections refers to the creation of new ideas through associations among existing ideas. Such connections (associations) can come in many forms. A central distinction is between internal connections and external ones. Internal connections are those between elements of the focal problem itself. External connections are those between the focal problem and external factors. Internal connections may focus either on the form of the problem or on the purpose; external connections may be local or distinct.

An experimental system called GENI (standing for GENerating Ideas) (14) incorporates a variety of techniques to assist in making these different types of connections. A computer environment for individual problem solvers is characterized, in part, by problem structuring techniques, techniques that provide stimuli otherwise found only in an outside environment, as well as idea recording and evaluation techniques. The heart of the GENI program is the idea generation module which supports the connection process. Specific procedures represent all four types of connection processes.

(1) Relational combinations represent internal connections (form and function). It is a technique which combines problem elements (i.e., entities and processes) by means of randomly selected relational words such as “above,” “before,” or “over.”
(2) Ends-means chains, which represents internal connections (purpose), encourage the user to derive ideas from goals in a top-down manner.
(3) Idea transformations, which represent external connections (local), is a programmed technique used to create variations on a theme and to refine existing ideas.
(4) Metaphoric connections, which represents external connections (distant), force the user to connect the problem and a remote context.

The GENI program consists of three main modules: a problem structure model, an idea generation model, and an idea evaluation module. The above four methods, along with brainstorming, form five options for the user.

Discovering Latent Relationships Using Genetic Algorithms. Connections can also be established by incorporating machine learning algorithms (such as genetic algorithms), as shown in the work in an experimental system (44), where a methodology for stimulating analysts (the users) is proposed to formulate new ideas. This methodology is able to stimulate analysts and expand their perspectives on some commonly interested issues. Analysts try to formulate new ideas by discovering previously unknown combinations of ideas. The methodology works in two stages. Stage 1 is an analytical process for characterizing idea fragments, including the establishment of analytical viewpoints, characterization, and classification of ideas. Stage 2 consists of an iterative process for stimulating new ideas using genetic algorithms, and a genetic learning mechanism is used. The system can suggest latent relationships among ideas, provide suggestions within the analysts' focus, provide suggestions outside the analysts' focus, and support multiple viewpoints. On the basis of the results obtained in the first stage, the system generates two kinds of genes: idea genes (which correspond to particular ideas) and relationship genes (which are used for evaluating the closeness of the idea genes). Evaluating previously unknown combinations of existing ideas stimulates analysts to come up with new ideas.

Modes or Styles in Idea Generation. Earlier we mentioned that there are two thinking modes: generative or explorative, and the actual mode of thinking in creative response is largely task-oriented (4). A somewhat different but related notion is creativity style, which is defined as a preferred and stable manner of bringing about change. A framework for group decision support systems has been developed based on the dimensions of quantity and style (45). Two principal preferred creativity styles have been identified, namely, adaptation and innovation. Corresponding to these two styles are two kinds of creative products, paradigm-preserving (*PP*) and paradigm-modifying (*PM*). It has been suggested that a variety of idea-generation techniques could promote the generation of PM ideas by requiring participants to artificially force relationships between unrelated concepts, one of which is called guided fantasy.

New ideas may be generated by introducing new elements into a problem context, by altering the relationships between the elements of a problem, or both—by introducing new elements as well as by altering the relationships between elements (45).

In addition, some heuristics related to creativity style have been observed:

Stimulus relatedness: The more related the stimulus, the more likely is the generation of PP ideas. The less related the stimulus, the more likely is the generation of PM ideas.

Free association: Free association is likely to generally result in PP ideas, while forced relationships are likely to result in PM ideas.

Simultaneity: Simultaneity can result in the generation of PP ideas. Conversely, turn-taking can potentially encourage the generation of PM ideas relative to simultaneous idea generation.

Structure Mapping for Suggestion-Generation. A kind of reasoning process closely related to PM is analogical reasoning. It has been mainly studied in the context of machine learning (46), but it has also been studied for idea generation. For example, in the creativity method called synetics, two principles were developed to facilitate imaginative speculation: to make the strange familiar and to make the familiar strange. The second is much more difficult to apply, but both principles are closely tied to analogy (47).

Research work has been conducted to support analogical problem solving or achieve creativity support systems through computerized metaphor generation. In the following, we use a model as well as an experimental system [both will be referred to as a cognitive model for information retrieval (*COGMIR*)] (34) as a concrete example. This will illustrate some concrete considerations behind idea generation using Gentner's structure mapping theory (48) for analogical reasoning. Note that COGMIR is not an idea processor by itself, but it reveals the internal process in idea generation that usually cannot be found elsewhere. In COGMIR, the specific form of idea generated is called a suggestion. COGMIR is also a representative example for examining many other aspects of computer science, including the role of information retrieval and database management techniques in idea generation.

This model for intelligent information retrieval deals with storage and retrieval of short scientific documents written in restricted English defined by simple grammar. The model consists of the following components. There is a document space (or document base) D, which is the conceptual place to store the documents. There is also a knowledge space (or knowledge base) K (consisting of nodes connected by links) which is the actual place to store the knowledge converted from the documents. Each acquired document is assigned a unique sequential identifier, is converted to its internal form (called document stem), and then is stored in a global knowledge base. Each document stem occupies a certain area in the knowledge base; each area is bound by its own boundary. A system component called document description list (or keyword list) L identifies the boundaries of the document stems. The system also consists of a conceptual memory, which is a hierarchically structured thesaurus used for indexing documents. Finally, the system consists of a set of mapping functions M between various system components.

This computational model provides dual modes for dealing with queries. If information is available to answer the user's request (in terms of keywords), a document (or a fact consisting of portions of several documents) is reconstructed from its internal form in the knowledge base (called the document stem) and presented in the text format to the user. This is the regular mode. In case the requested information is not available, the user may use the analogy mode to ask the system to generate a document using analogical reasoning. This generated document may serve as a suggestion or an advice to the user. One option that could be considered here is to map the keywords in the query list submitted by the user to another list. Since both the document description list and the query description list consist of objects, if a suggestion is to be generated using analogy reasoning, it has to be done by mapping of objects only. A pseudo-fact is a document-like unit containing a portion which is generated through structure mapping. This model thus provides a detailed solution for analog retrieval for generating suggestions. For example, the system may have no knowledge about how to detect an enemy plane. But if it has knowledge (in one document or several documents) about bats' behavior, it is able to use this analogy to construct a pseudo fact for the user and suggest producing *sound-like* thing for people to detect an enemy plane.

The components of the system, as well as an overview on the general pseudo-fact generation process in our computational model (as well as in the experimental system), are depicted in Fig. 1.

The COGMIR model (and the system) shares many features with conventional idea processors, such as the use of search in knowledge base or knowledge base, the use of hierarchically structured conceptual memory (which resembles IdeaFisher's topical categories), the use of connection (between entities and between documents), as well as others. However, some significant differences also exist. One may note that the system does not randomly generate a large number of wild ideas (as in conventional idea processors); rather, only a small number of suggestions directly related to the user's current interest are generated, and they are generated one by one. Such suggestions have a better quality than those ideas generated in conventional idea processors because the system includes a kind of evaluation process so that only the most promising ideas will be further explored.

Creativity Enhancement Through Group Decision Support Systems

The original brainstorming techniques are used among a group of people. Since idea processors employ electronic means to achieve brainstorming, the group environment is not necessary. So far, we have focused on creativity itself and have tried to avoid the group factor. However, since idea generation in a group environment has some features different from a nongroup environment, it deserves some special concern.

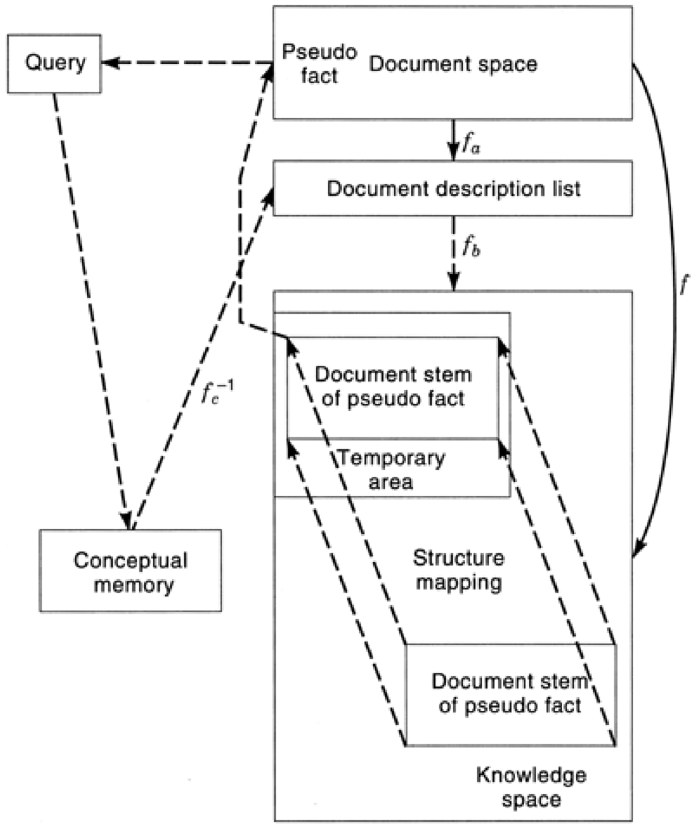

Fig. 1. Components of the COGMIR model.

Several frameworks for group decision making have been proposed, including one mentioned earlier (45). In the following, we present a sketch for three other approaches for idea processors in group environment.

(1) Generic protocols for group idea generation. Group idea generation is one of many classes of *CSCW* (computer-supported cooperative work) systems. Most group idea generation systems to date have been synchronous systems. Researchers have examined the extension of group idea generation systems to non-real-time situations, such as when people are working in different countries and time zones. A range of group idea generation techniques are examined to identify a core group of components from which they can all be constructed and form the basis for a set of generic protocols. Key components identified are roles, phases, and workspaces (38).

(2) Intelligent meeting agents. Groupware has produced measurable productivity gains for major corporations in recent years. Agent software enhances productivity even more by helping groupware perform convergent tasks, thus freeing users for more creative work. An experiment with an Al-based software agent shows that it can help users organize and consolidate ideas from electronic brainstorming. The agent recalled concepts as effectively as experienced human meeting facilitators (33). In addition, research work has been carried out which uses Kohonen neural nets to organize the brainstorming as a result of the use of groupware (49).

(3) Unconventional approaches. Some unconventional approaches also exist which can be viewed as extending group decision support systems. For example, an approach proposed to deal with the problem of improving the acceptability of decisions affecting the work of numbers of people by a form of democratization, that is by bringing them into the process of decision, so that it takes on the character of agreement from within rather than of a dictator from without (50).

Evaluation Methods

Evaluation of idea processors has been carried out in different ways or at different stages.

Overall Process. For evaluation, one typical approach in management science is to start with hypotheses formation (4,14). Human rators or judges are usually used. Experiments in comparative studies have employed evaluations of the following factors: creative ability, judges' reliability, idea fluency (which refers to an individual's ability to generate a number of different ideas in response to a specific decision task), creative performance, generative and exploratory support, and software satisfaction (4).

Problem Design in GENI Experiments. A well-designed problem set is essential for a fair evaluation. In the case of GENI, problems are selected in a way that they can lend themselves to creative problem solving. A word processor was chosen as the control. Subjects were recruited from undergraduate business school classes. In total, each subject worked on five different problems: a pencil and paper problem, three main problems using a control treatment on one problem and GENI on the other two problems, and a contest problem using either GENI or the control treatment. An interesting finding is the result concerning the answer to the question of "whom does the program help the most." It has been observed that the program seems to have an amplification effect: the best subjects improved the most.

Comparison of Different Techniques. Another issue in evaluation is what should be evaluated. Evaluation can be carried out to compare different mechanisms or specific techniques used by idea processors; for example, an idea processor supporting generative thinking has been compared with an idea processor supporting exploratory thinking (4). Experiments have also been conducted to compare verbal versus electronic brainstorming, as well as the effects of different electronic techniques. For example, electronic individual poolwriting has been compared with electronic gallery writing methods (51).

Using Recall and Precision for Agent Evaluation. Most experimental studies in the evaluation of idea processors involve only human subjects. However, the agent perspective of idea processors suggests testing the idea processors versus human beings in a more direct manner. Such a process can be exemplified by an experiment to verify an intelligent meeting agent's performance against that of human meeting facilitators (33). Three subsets of ideas can be distinguished: *identified* represents the items on the original list; *target* represents the categories the facilitator felt should be on each list; and *relevant* represents the intersection of the identified and target sets and indicates the items on the identified list that were also on the target list. Two measures were adopted from document recall and precision measures popular in information science applications; concept recall (the number of relevant items divided by the target items) represents the percentage of relevant meeting ideas that were properly captured in the original list, and concept precision (the number of relevant items divided by the number of identified items) represents the percentage of concepts on the original list that the facilitators deemed relevant to the meeting topics (33).

Special Purpose Evaluation Methods. In certain cases, special methods are needed to evaluate techniques developed for some particular needs. Earlier, we briefly examined the popular KJ method for Japanese language idea processors. A thinking support system, D-ABDUCTOR, has been developed by Japanese scholars (52) as an interactive system to support dynamic thinking processes like the KJ method by using diagrams (or graphs). It is evaluated at three levels: the algorithm level (theoretical evaluation of each fundamental algorithm and performance evaluation of the programs of the algorithm), the operation level (evaluation of the total efficiency on a thinking process for operations, such as editing, reforming, redrawing, etc.) and thought level (evaluation of the effectiveness for thought on a thinking process). A method called the Labeled Construction-Rule Method has been used for evaluating experiments at the operational level.

Theoretical Studies of Computational Creativity

In order to understand future directions for idea processors, we should further examine existing work which provides a theoretical background for some existing studies of computational creativity which are not directly related to idea processors. There is a bulk of studies focusing on the nature of creativity and related computational aspects. Note that although they may not necessarily serve as the foundation of idea processors, many results can be incorporated into idea processors.

We should also point out that many aspects in AI may not necessarily shed light on idea processors. For example, rich literature exists in machine learning (46), including various algorithms for inductive learning. However, as Schank has pointed out (53), inductive learning usually is not equal to creativity. Knowledge discovery in databases (*KDD*) and data mining (54), techniques have been used to discover knowledge patterns or rules, not to generate ideas.

Computational Aspects of Creativity.

Creativity as Representation Redescription. Most researchers have agreed that creativity is generally defined as the production of something (e.g., a scientific theory, a work of art, a poem, a novel) which is both novel and valuable according to consensual judgment (55).

There are different viewpoints within the AI research community about the nature of intelligence. One influential viewpoint (59) is to view creativity as representation redescription. Problem solving is a search over a given search space defined by a set of constraints, operators, and representations. Creative problem solving involves finding important solutions that other searchers miss. The extra search power comes from an ability to transform the search space. That is, creative search involves changing or extending the constraints, operators, or representation, using an additional set of operators whose job is to modify the first set. Therefore, ordinary thought is a search over an ordinary search space, while creative thought is a metasearch using a separate set of operators.

Creativity often has an emotional surprise or *aha!* aspect (which implies something which violates our expectations has happened). Boden likens intelligence to a generative system (59). Creativity results from changing one's conceptual system to produce new thoughts which were impossible under the old conceptual system. Creative thought is distinguished from ordinary problem solving by conceptual restructuring.

Computational Models for Creativity. The following are two examples of computational models for creativity.

Achieve Computational Creativity Through Transformation. The engineering aspects of AI have encouraged many researchers to develop exploratory programs to achieve computational creativity. According to an approach for computational creativity (56), problem solving is seen as the search of an explicit knowledge space for known solutions and creativity as the search of a vast, implicit knowledge space for new solutions. Creativity is distinguished from problem solving not by a single distinguished mechanism (i.e., representational redescription) but by the types of solutions it discovers: solutions incorporating knowledge not found by ordinary problems solving. New problem solutions can be created by transforming a problem into a new problem, solving the new problem, and then adapting the solution back to the original problem. This model also provides an explicit mechanism by which a problem solver can perform the kinds of knowledge redescriptions needed to be creative.

Case-Based Reasoning Framework. In a framework revised from case-based reasoning, creative thought, like all thought, is treated as involving processes of problem interpretation and problem reformulation, case and model retrieval, elaboration and adaptation, and evaluation. Creativity arises from the confluence and complex interaction of inferences using multiple kinds of knowledge in the context of task or problem and in the context of a specific situation (57).

Scientific Discovery and Technical Invention. An aspect of idea processors is that they are more directly related to everyday thinking rather than scientific thinking. However, there are strong similarities between everyday thinking and scientific thinking.

Scientific discovery and technical invention have different emphases: the task for discovery is to reveal or uncover some existing features or relationships, while the task for invention is to generate new solutions (or possibly generating new problems as well). Nevertheless, they share some common concerns, as demonstrated in some famous landmark programs in AI history (58).

In AI, computational creativity has been studied along with both the directions of discovery and invention. In a discovery system, given an appropriate set of data or a database, a clever computer program can rediscover important scientific laws (54,58). In contrast, generative systems exemplify the study along the direction of invention (59).

Retrospective Analysis. Computerized discovery and invention systems have a much more sophisticated structure than idea processors. Although some techniques may be eventually incorporated into some idea processors, most will not. The real reason to study computational aspects in invention and discovery largely lies in the analysis of the thinking process behind invention and discovery. For this purpose, retrospective approaches are frequently used to trace the mental processes involved in invention and discovery. Such analysis may produce useful hindsight serving as heuristics. These heuristics can then be used in generating new ideas for idea generation, or meta-idea generation.

Creative studies are a way of cultural self-inquiry: Explaining creativity would mean for a culture to be able to transcend itself and look at itself from the outside (60). This can be carried out at a high, philosophical level, but more directly related to our interest, detailed studies in various concrete knowledge domains are important.

Two fundamental questions that need to be answered in technical invention are whether we can describe invention in a general way, and whether we can extract principles (heuristics) of invention from particular cases that have some generality across inventions (61). To illustrate, consider heuristics which are concerned with *join,* an activity which combines several things together if they share some common part. For example, a claw hammer is the join of a striker head and a claw that share a common handle. Observations like “what the striker part of the hammer will do, the claw will undo, and vice versa” may suggest the inverse join heuristic: “Combine only those tools or ideas that are inverses of one another” (62). Retrospective analysis may also help to identify some useful patterns involved in invention. For example, from the conceptual history of a chair, an evaluation-fix-produce cycle has been identified (63).

Heuristics obtained through retrospective analysis, such as the join heuristic and the invention cycle mentioned above, can be incorporated into knowledge bases of idea processors. A similar approach has been taken where an introduction to the theory of inventive problem solving (*TIPS*) is presented (64). TIPS is aimed at directing the search for solutions to engineering problems. It was developed by G. S. Altshuller and his school in the former USSR, based on an extensive study of the world patent database of over 400,000 inventions from different engineering fields. From these studies, it was recognized that the evolution of technical systems follow a series of laws or trends. These laws can be utilized in the development of engineering solutions as an alternative to trial-and-error or brainstorming techniques for problem solving. The theory consists of a set of the most commonly applied inventive principles, an algorithm for inventive problem solving, standard solutions, and a database containing hundreds of physical, chemical, and geometric effects.

Retrospective studies have also been carried out on specific domains. For example, in a study on oxide superconductivity research (65), over forty hypothesis formation heuristics have been identified, such as

If a physical effect E cancels another effect F, then hypothesize that there is another effect G related to E and F.

If the value of a property P changes with the value of another property Q, then hypothesize that P and Q are related.

A related issue is experience-based creativity (66). Some researchers believe that there must be some medium by which experience can be combined to create the new form of information so that it will be deemed as creative. The combination rule should be based on simple principles, and the creative act can be implemented and viewed as a largely domain-independent process.

Within computer science, Dasgupta (67) provides an explanation of Maurice Wilkes' invention of microprogramming; the approach used there is also retrospective.

Relationship with Idea Processors. Some aspects in computational creativity as summarized above can be incorporated into idea processors, but many of them will not. As engineers for exploratory studies of machine intelligence, AI reseachers typically take algorithmic approaches. For example, in the computational models provided by (57), several inferential mechanisms have been provided, which exemplify the inferential aspect of thought. These include reinterpretation of an idea in terms of a different but familiar idea; visualization, mental simulation, and thought experimentation; constraint relaxation and substitution, which is useful in problem reformulation and elaboration; relaxing constraints during memory search, which facilitates problem reformulation and retrieval: relevance assessment, which is useful in retrieval and evaluation; and explanation of anomalies, which is also useful in retrieval and evaluation.

In contrast to those vivid and colorful aspects which characterize idea processors, academic research work in AI is usually not involved in the study of divergence. However, AI research work may be complementary to idea processors and shed light on them. For example, although many researchers agree that the naive notion of creativity as random novelty is useless, some authors have tried to introduce chaos to deal with idea generation (68). A random search through an idea space will eventually reach sufficiently close to a desired point, but it may take a very long time. A mathematically chaotic function can supply a source of random numbers. In order to rapidly reach the desired point, we must mix deterministic rules with chaos, giving a *strange attractor*.

Neural networks were used to construct a neural map to perform the creative selection step, including partially activating those regions of the network relevant to the problem using the associative linkages between neurons. A two-level system was proposed: the main level is that of rule-based behavior (a theorem-proving system), and the metalevel is a neural network providing creativity.

Some Issues for Future Research

Some Gaps Observed. From the discussions in previous sections, we have noticed that in the area of idea processors, several kinds of gaps exist. A technical gap exists between manual and automation. Current idea-generation techniques are largely an automation of manual idea-generation techniques using information technology (e.g., electronic brainwriting). Automation, however, may introduce a qualitative difference in a technique so that its appropriation is different from the manual version (45).

Other gaps exist between academy and industry and between different research interests in management science and computer science. For the computer science community, an effort is needed to narrow an apparent gap between academia and industry (which is still the driving force of idea processors). The computer science community should also get more actively involved in application-oriented studies (so far, mainly generated in the management science community). Idea processors have not been well-integrated into the study of computer science. There may be some missed opportunities. For example, there are only few approaches for idea processors using object-orientation, a focus of current computer science study. In fact, as a complex knowledge representation scheme, objects may be more appropriate than productions rules in many situations. In addition, due to an anthropomorphical feature (69), object-oriented approaches seem to be excellent candidates for supporting creative thinking. Object-oriented approaches should also enhance the degree of software reuse for idea generation.

A somewhat related gap exists which is concerned with group versus individual creativity. Research work from a management science perspective traditionally emphasizes group activities, while research work in computer science usually focuses on individual creativity. Although both group and individual creativity are important and the two kinds of studies can complement to each other, a more balanced research from each discipline (namely, more group-oriented studies from computer science and more individual-oriented studies from management science) would be more beneficial for the future of idea processors.

Research Directions and Challenges. In the following, we briefly examine some issues that need to be investigated in the future, including some important aspects and applications not mentioned before (e.g., education related studies).

Better Theoretical Foundation. From our earlier discussions, we can see that idea processors have been dominated by methodologies adopted from management science or psychology (including folk-psychology). Idea processors should be integrated into the general AI task of building intelligent agents. Recent developments in creativity using AI approaches have made some change in this picture, but a better theoretical foundation for idea processors is still needed. Related tasks include finding a better theoretical foundation for idea processors and finding more applications for theoretical results.

In addition, formalisms have been used to describe advanced algorithms used by idea processors. For example, an invention grammar for creative design (70) and algebraic operators for creativity (71) have been proposed. Although it may not be necessary, formalisms could be useful in serving as common languages and guidelines for future research in idea processors.

Education-Related Studies. As mentioned earlier, idea processors have been used in many applications in business and engineering. Another important area of application is education.

For example, the use of idea processors has been suggested to enhance classroom writing instruction. More recently, several creative techniques developed by professionals that promote innovative, original, and alternative solutions to problems have been examined from an educational prospective. These techniques include mind mapping, symbolic analogy, forced connections, manipulative verbs, and bionics (72). However, more studies are needed for education-related applications, including experimental studies for students' classroom performance.

Creativity and Connectionism. With a better understanding of connectionist models (i.e., artificial neural networks) (59), some researchers feel that there are expectations for connectionist models to shed new light on creativity. In a neural network, the structure of the space is represented in such a way that transition from problem to solution can sometimes be made solely on the basis of random (chaotic) stimulations. The system effectively traces a path through the transition network making appropriate random choices (given the fixed probabilities) at each chosen point. Viewed from this perspective, the model is suggesting that creativity is like a search or a guided walk (68).

As noted earlier, some idea processors have already incorporated the concept of guided problem solving. However in general, much more work is still needed in applying connectionist techniques. For idea processors, the hope is that connectionism may provide an effective way to explore the notion of creativity as a combination of existing ideas, so that new ideas can be generated.

Parallel Processing. An important research direction which has not been mentioned so far is the role of parallel processing in idea generation and organization. This is not to say that no work has been done in this direction. It has been noticed that a major advantage of electronic meetings is that members can brainstorm in parallel (33). As another example, a computational model using a parallel distributed processing architecture has been presented (73) which incorporates the role of memory retrieval and analogical reasoning in creativity. The model can simulate the transfer of relations from one domain to another, as occurs in the creativity use of analogy. In the methodology proposed in (44), by using multiple affinity diagrams, analysts can simultaneously analyze various central ideas from analytical viewpoints. Nevertheless, the state of the art of using parallel processing for creativity support is relatively low, and much work is still needed.

Combining Creativity with Expertise. Combination of creativity and expertise has been addressed by some authors. We have already mentioned experience-based creativity (66). Another direction might also be explored, namely, how to combine creative knowledge with domain knowledge (71).

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READING LIST

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Books on invention in everyday life: H. Petroski *The Evolution of Useful Things*, New York: Vintage Books, 1994.

R. J. Weber *Forks, Phonographs, and Hot Air Balloons.* New York: Oxford University Press, 1992.

For products of idea processors, there are also several Web sites to visit, including the following: http://ideaprocessor.citi.doc.ca

http://www.maxthink.com

http://www.ozemail.com.au

http://www.inspiration.com

http://web.singnet.com.sg/∼axon2000

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