Computer-enhanced Scientific Creativity

Bruce J. MacLennan
Department of Electrical Engineering & Computer Science
University of Tennessee, Knoxville TN, USA
`web.eecs.utk.edu/~mclennan/`

Abstract

This chapter proposes a computerized tool to enhance a specific, but very important, kind of scientific creativity. Significant scientific breakthroughs are often enabled by a reconceptualization of some problem or class of phenomena. This reconceptualization may involve novel metaphors and analogies, especially visual, which allow the problem to be seen in a new light, and may suggest alternative mathematical tools that may be applied to the problem. The most fruitful reconceptualizations engage our innate (and largely unconscious) mechanisms for understanding and interacting with the world, for these faculties ground intuitive insight and understanding. Therefore, such cognitive models facilitate a scientist's intuitive grasp of the phenomena, facilitating experimental design and verification, theoretical elaboration, mathematical formalization, and fruitful extension into new applications.

The creative process is often divided into four phases: preparation, incubation, inspiration, and verification/elaboration. We propose a computerized tool to enhance the incubation phase of scientific creativity, with the goal of inspiring fruitful reconceptualization of a problem. It accomplishes this by exposing the scientist-user to continuous sequences of images designed to engage these innate, unconscious cognitive structures. The sequence is not fixed, but may vary either randomly or under user direction. When this image flow seems relevant to the user, they can record their position in it and their own ideas with a variety of low-interference recording techniques. Several simple image flows are described, along with the computational engine for generating them. We discuss means assessing the usefulness of the prototype for stimulating scientific creativity and for empirically evaluating the efficacy of image flows for engaging innate cognitive structures.

Keywords: archetype, chaos, creativity, evolutionary psychology, hypnosis, inspiration, Jung, quaternity

Background

Scientific Creativity

There is no need to rehearse the importance of science in our society, both for the technological developments it has enabled and for the profound revision of our worldview that it has entailed. Although much of this scientific progress has been incremental, at its heart are conceptual revolutions, including quantum mechanics, special and general relativity, the structure and function of DNA, and the neo-Darwinian synthesis. These are among the germ cells from which contemporary science has developed. Further, as Kuhn (1970) argued, new paradigms generate new research programs, asking questions that were not asked — or could not be asked — from prior perspectives. Therefore conceptual revolutions in science reveal new worlds, previously unimagined, awaiting exploration. The goal of our research is to provide technological support for future conceptual revolutions (minor as well as major).

Big-C Creativity

Gardner (1993) distinguished little-C creativity and big-C creativity. *Little-C creativity* is the sort of creativity that scientists, artists, engineers, and most other productive people engage in on a regular basis: finding new, non-obvious solutions to relevant problems. Although little-C creativity is critical to the improvement of human well being, it is not our primary concern here. Rather, our focus is on *big-C* *creativity*, the sorts of creative accomplishments that loom large in history books, and in particular the sorts of scientific accomplishments that effect conceptual revolutions. More modestly, our focus is on scientific creativity that results in a new, more fruitful way of understanding some class of phenomena. This requires a different sort of technological support than "ordinary" (little-C) creativity.

Unfortunately, much of the research on creativity, especially research aimed at improving creativity, has focused on little-C creativity. Indeed, many of the problems used in these studies amount to puzzles in which objects in the environment must be used in innovative ways in order to solve some well-defined problem. Certainly, seeing things in new ways, and avoiding a kind of functional fixation, are important in big-C scientific creativity, but what the latter requires is often a new perspective on a scientific domain, rather than a clever redeployment of existing elements. Our goal here is to use technology to encourage new conceptualizations and perspectives on scientific problems, and thereby to enable scientific breakthroughs.

Boden (1991) draws a useful distinction between P-creativity and H-creativity. *P-creativity* (*psychological creativity*) refers to the production of something that is new and interesting to the creator, although many other people may have already created the same thing. In contrast, *H-creativity* (*historical creativity*) is the production of something new and interesting that has never been produced before (at least in the creator's culture). For well-prepared scientists (see below), the two notions largely coincide, because these scientists will be aware of what has been accomplished in their field, and so if an idea is P-creative it is also likely to be H-creative. That, at least, is the goal. As we know, it is not uncommon for a scientist to discover that a psychologically original idea has been anticipated by others, that is, that an apparently H-creative idea is only P-creative. The focus of our project is on ideas that are P-creative, but simultaneously, as a consequence of professional preparation, very probably H-creative.

Stages of the Creative Process

Graham Wallas (1926) provided the best-known presentation of the four stages of the creative process, although they had been enumerated by Poincaré (1908/1952) and the first three were already mentioned by Helmholtz (1896) (see also Whiting, 1958). They are (1) preparation, (2) incubation, (3) inspiration (or illumination), and (4) verification (or elaboration). Regardless of the domain of creativity, *preparation* involves conscious work on the problem, *incubation* entails a suspension of this conscious activity, *inspiration* refers to the relatively effortless appearance of an attractive solution, which must be followed by (perhaps extensive) *verification* and/or *elaboration* of this inspired solution. Thus, according to Reichenbach (1938), the first three stages occur in the context of *discovery*, whereas the last is in the context of *justification* (empirical test or mathematical proof). Kris (1953) added a final phase, *communication*, which is certainly essential in science (and other forms of public creativity). Thus Stein (1967), who emphasizes the social benefit inherent in genuine creativity, enumerates three major phases: hypothesis formation (preparation, incubation, inspiration), hypothesis testing (verification), and communication.

In the case of scientific creativity the process of preparation is well-understood, for it involves the scientist's formal education, their ongoing effort to remain current in the progress of science, and their comprehensive understanding of the state of the art in their particular specialty. Information technology has had, and will continue to have, an enormous impact on the preparation stage of scientific creativity, but that is not the focus of our research. Nor is our focus on verification, although scientific verification is also facilitated by information technology. Our topic is technological support for incubation and inspiration in scientific creativity.

The inspirations that are at the core of big-C scientific creativity are historically significant because they typically have implications beyond the solution of an isolated problem. Rather, they offer new perspectives, concepts, and cognitive structures with which to understand a scientific domain. They are especially *fruitful*, both in the questions they pose and in the means of solution that they afford. (We discuss the nature and source of such fruitful conceptualizations below.) Our goal is to provide technological aid to scientists seeking new ways to understand their research domains.

Sources of Inspiration

What is the source of innovative scientific ideas and, in particular, of scientific inspiration? Certainly, many innovative ideas are a result of conscious analysis, but that is not our concern here. Rather, we are interested in what happens when extensive conscious problem solving has failed to provide an adequate answer; this is when preparation may prepare the ground for incubation, leading to inspiration (if the scientist is fortunate). Usually incubation begins when conscious analysis and other cognitive resources have been exhausted, and it terminates with the conscious recognition of a new, attractive synthesis. The intervening incubation process is necessarily unconscious, as has been recognized by Poincaré (1908/1952, 1929) and many others (e.g., Dorfman, Shames & Kihlstrom, 1996; Fritz, 1980; Gedo, 1997; Hadamard, 1945; Kipling, 1937/1952; Kris, 1952; Neumann, 1971). Therefore, to stimulate scientific inspiration, our technological aids should focus on the unconscious origins of scientific ideas.

Associationism suggested that unconscious associative networks among concepts provide a source for new ideas (Stein, 1974, pp. 86–8, 231–2). It was observed that on association tests creative individuals produce broader but shallower association trees than do less creative, more methodical individuals (Mednick, 1962). Certainly, unconscious associative networks are one source of creative inspiration, but we must distinguish between idiosyncratic associations and more universal ones. Idiosyncratic associations are a result of a person's individual genetic makeup and ontogeny, and of the contingencies of their biography. Certainly, such particularities are part of the reason that one scientist may have a creative inspiration denied to his or her colleagues. On the other hand, while an idiosyncratic association may enable the solution of a problem, as a scientific conception it may be sterile if very few scientists have that association. Historically fruitful conceptions are more likely to arise from associations that are universal or at least widely shared (e.g., throughout a culture). [This was also a limitation of Freud's (1948, 1948a) theory of creativity (Arieti, 1980; Jung, 1934, ch. 8).]

Gestalt psychology provided an alternative explanation of creativity, supposedly universal because based in neurophysiology and therefore better able to account for historically significant creativity (e.g., Wertheimer, 1982). According to this theory, a creative person is able to feel the frustration and forces in a problem situation leading to a cognitive reorganization that satisfies the constraints of the problem and is satisfying (exhibits closure). Unfortunately, in addition to being dependent on subsequently invalidated theories of cortical processing, Gestalt psychology focused on perception and on dynamic processes leading to static Gestalts. While creative understandings of static structure are not irrelevant to scientific creativity (e.g., the DNA double helix), in many cases scientific creativity lies in a reconceptualization of a dynamic process (e.g., Newtonian mechanics, Darwinian evolution).

The foregoing suggests that the source of creative, fruitful scientific conceptions lies in unconscious dynamical processes that are phylogenetic or at least very widely shared among humans. What is the nature of these processes and how can we tap into them?

Archetypal Processes

Definition

It will be convenient to use Jung's term *archetype* for these phylogenetic unconscious psychodynamical processes. In so doing we intend no mystification, for the archetypes are no more than the unconscious psychological correlates of instinctual and neurophysiological processes common to all humans. Indeed, Jung (*CW* 8, ¶404) said, "To the extent that the archetypes intervene in the shaping of conscious contents by regulating, modifying, and motivating them, they act like the instincts." Indeed, at its deepest level, the archetypal structure, "the biological instinctual psyche, gradually passes over into the physiology of the organism and thus merges with its chemical and physical conditions." (*CW* 8, ¶420).

Most of the archetypes are unconscious processes, grounded in our neurophysiology, that regulate and govern our perception, motivation, affect, and behavior to achieve biological ends (reproduction, survival, defense, dominance, care-giving, cooperation, etc.). When an unconscious archetype is activated through its *innate releasing mechanism* (IRM) by means of a *releaser* or by a conditioned *sign stimulus*, it begins its regulatory process and affects consciousness by altering perception, motivation, affect, and behavior (Stevens, 2003, pp. 64–65). Therefore, since an archetype encompasses the psychological effects of unconscious neural and physiological processes, it is consciously experienced indirectly and incompletely, in the context of a specific activating situation. As Jung (*CW* 9, pt. 1, ¶155) remarked, "The existence of the instincts can no more be proved than the existence of the archetypes, so long as they do not manifest themselves concretely." They are known through their consequences in consciousness.

Many of our archetypal structures regulate our interactions with other humans and constitute the foundations on which cultures are built (Stevens, 1993, 2003). Our nonhuman relatives have homologous neuropsychological structures, as shown by evolutionary psychologists. However, there are other, deeper archetypal structures that correspond to general neurophysiological processes that are not associated with particular behavioral adaptations. These include basic perceptual and cognitive processes, such as those studied by the Gestalt psychologists. These archetypes operate more impersonally than the others, and may be experienced as abstract forms, including geometrical shapes, numerical relationships, and abstract processes (MacLennan, 2006, 2007; Stevens 2003, p. 65; von Franz, 1974). Jung is well known for his studies of mandala-like figures as indicators and even facilitators of psychological integration (e.g., Jung, *CW* 9, pt. 1). These impersonal, mathematical archetypes are especially important in science, because they condition our abstract understanding of many natural processes. Number "preconsciously orders both psychic thought processes and the manifestations of material reality" (von Franz, 1974, p. 53).

Advantages

Jungian psychology has been a useful, illuminating, and fruitful perspective from which to study the creative process. Indeed Dyer (1991, ch. 10) lists more than 90 books published before 1991 that apply Jungian psychology to creativity (more than half published in the decade of the 80s). It will be worthwhile to mention a few of the ways that the concept of an archetype can help us to understand big-C scientific creativity.

One advantage of looking to the archetypes as sources of scientific inspiration is that they are universal, that is, phylogenetic adaptations of *Homo sapiens*. In that sense they are *natural* ways of understanding the world, and therefore better able to afford an intuitive understanding graspable by all people. That is, they are objective (i.e., public) rather than subjective (i.e., personal).

Furthermore, archetypal structures are not simply abstractions. As phylogenetic adaptations, they govern perception, motivation, affect, and behavior for biological ends. Therefore, when they are activated and experienced consciously, they are felt to be inherently meaningful. Since we unconsciously grasp these structures emotionally as well as intellectually, they are satisfying and have "the ring of truth." They are felt to be elegant and beautiful. Arguably, the most fruitful scientific theories are built around such an archetypal core. Thus Heisenberg (1975, p. 175) observes that in science an aesthetic response to the whole often precedes intellectual exploration of the details. He asks (1975, p. 175), "How comes it that with this shining forth of the beautiful into exact science the great connection becomes recognizable, even before it is understood in detail and before it can be rationally demonstrated?" It is not a result of conscious analysis for, "Among all those who have pondered on this question, it seems to have been universally agreed that this immediate recognition is not a consequence of discursive (i.e., rational) thinking" (Heisenberg, 1975, p. 177). Indeed, thinkers as diverse as Kepler, Pauli, and Jung (Heisenberg, 1975, 177–80) have attributed the process "to innate archetypes that bring about the recognition of forms"

(Heisenberg, 1975, p. 178). Thus Pauli (1955, p. 153): "As ordering operators and image-formers in this world of symbolical images, the archetypes thus function as the sought-for bridge between the sense perceptions and the ideas and are, accordingly, a necessary presupposition even for evolving a scientific theory of nature."

As innate structures of perception, motivation, affect, and behavior, the archetypes are at a fundamental level comprehensible to us; they are the universal and invariable dynamical patterns in our lives, and therefore intuitively understandable. Therefore archetypal scientific models and theories allow scientists to use all of their cognitive-emotional faculties — their intuition — to guide them in the further elaboration and verification of their insights. As a consequence, archetypal models and theories are especially fruitful, for they engage the whole scientist and suggest further elaborations and developments consistent with their archetypal root. Just as archetypal themes stimulate creativity in literature and the other arts, so also they are a source of inspiration in the sciences.

The utility of archetypally grounded scientific inspirations is illustrated by historical examples, one of the most famous of which is Kekulé's discovery of the benzene ring (Kekulé, 1890, tr. in Benfey, 1958). He said that he had a vision in a reverie of a serpent biting its tail, which is a paradigmatic archetypal image, the *ouroboros* (e.g., Jung, *CW* 12, passim, *CW* 14, passim; Stevens, 1998, pp. 13–14, 142–3, 192, 197, 261). He remarked that his "mental eye" had been "rendered more acute by visions of this kind," and he advised, "Let us learn to dream, gentlemen, then perhaps we shall find the truth."

Objections

One obvious objection to focusing on archetypal structures in scientific creativity is that there is no *a priori* reason to suppose that natural phenomena conform to these patterns. Although the archetypes are the fundamental dynamical structures of human neuropsychology and have been adaptive in our evolution on earth, we cannot assume that they are the structures of other natural phenomena. While they constitute inherently human ways of grasping the universe, it can be argued that they need not correspond to the inherent structure of the universe.

These are valid concerns; nevertheless there are important reasons for focusing on archetypal sources for scientific creativity. First, there are, in general, several equally good ways for understanding a scientific phenomenon (e.g., the wave and matrix formulations of quantum mechanics). However, in the early, creative stages of the development of a scientific theory, when understanding is fragile, it is extremely valuable to have a model that affords multiple avenues of deep understanding. Development of the model will be facilitated if the scientist can bring to it multiple, intuitive modes of comprehension (somatic and affective as well as cognitive).

Moreover, if the archetypally-grounded model does not turn out to conform exactly to the phenomena under investigation, then it can be refined and brought into conformity during the elaboration and verification stages of the creative process. Even if an archetypal model is not entirely accurate, its fundamental embedding in human existence and understanding may grant it greater fruit than a more accurate, but less illuminating and inspiring model. Thus archetypal models and theories persist and continue to inspire, even after they have been superseded by empirically or theoretically superior models and theories (wave mechanics in quantum theory might be cited as an example).

Evolutionary Neuropsychology

One useful way to understand creativity is in terms of Freud's distinction between *primary-process* and *secondary-process* thinking, for Kris (1952) already showed the importance of the primary processes to creativity. For while the secondary processes serve the *reality principle* and include the faculties of logic, analysis, and rational inference, the primary processes are characterized by imagination, wide-ranging association, play, and wish fulfillment; they serve the *pleasure principle*. As a consequence the primary processes, which service *biological drives*, are more closely connected with the instincts;

their locus is the unconscious, whereas the locus of the secondary processes is the preconscious, according to Freud. Fromm (1978) identified the primary/secondary distinction as the principal axis of cognitive function. Creative people seem to be able to move along this axis more easily than other people, thus allowing fluid alternation between the free and uncritical production of imaginative ideas, and their systematic elaboration and critical evaluation (Martindale, 1999). Primary-process thought is closely related to defocused (high capacity) attention and to broad and flat (vs. deep, "steep gradient") associative trees, both of which are characteristic of creative people (Martindale, 1999; Mednick, 1962; Mendelsohn, 1976). Therefore computer support for creativity ought to facilitate primary-process ideation, wide (vs. focused) attention, and unfettered association.

Primary-process thought is commonly supposed to be more primitive and childlike than secondary-process cognition. Thus, when a scientist resorts to the primary processes it is a sort of regression, but it is an *adaptive regression*, or "regression in service of the ego" (Rosegrant, 1980, 1987; Stein, 1974, pp. 91–3; Wild, 1965), in that it is a conscious adoption of a less rational, more imaginative process for the sake of creativity. Therefore, computer support for creativity should facilitate an adaptive regression to playful, imaginative thinking.

Secondary-process cognition occurs with moderate levels of arousal ("alert wakefulness") as measured by EEG frequency and amplitude, heart rate, galvanic skin response, etc., whereas extremes of arousal ("emotional tension" vs. "sleep and reverie") are characterized by the primary processes and defocused attention (Martindale, 1999). A number of studies, by Martindale and others, have shown that creative people are in a low state of cortical arousal (compared to their resting level) during the inspiration phase of a consciously creative activity, but not during the elaboration phase or during activities not perceived to be creative. Thus, creativity seems to be enhanced by a low arousal state, but creative people do not seem to achieve this state by any sort of conscious control (creative people are below average at biofeedback tasks: Martindale, 1999). Incubation is not an exercise in willpower, and creative people describe the inspirational process as effortless and uncontrolled. Indeed, creative people have less than average cognitive inhibition, as reflected in lower levels of frontal-lobe activation (Eysenck, 1995; Martindale, 1989). In many cases big-C creative people have learned to place themselves in environments that decrease their level of arousal without significant conscious effort or intent; these environmental interventions operate on an unconscious, even physiological, level (Martindale, 1999; Stein, 1974, pp. 105–7, 194). Therefore, computer support for inspiration should facilitate disinhibition, defocused attention, and diminished arousal through control of the environment.

To some extent the functional specialization of the cortical hemispheres corresponds to the primary and secondary processes (Galin, 1974; Hoppe, 1977). Roughly speaking, the right hemisphere (RH) is better suited to the holistic, imagistic, and associative processes essential to inspiration, whereas the left is oriented to the verbal, critical, and analytic processes that serve preparation, elaboration, and verification. Normally the left hemisphere (LH) is dominant, and we expect it to be especially active during ordinary scientific work. However, there is evidence that during creative tasks the right hemisphere shows increased activity so that there is more balance between the two (Katz, 1997; Martindale, 1999). This suggests that computer support for scientific creativity should preferentially activate the right hemisphere through the use of images and music (but not loud white noise, which can increase arousal and interfere with creativity: Martindale & Greenough, 1973).

We may bring the discussion back to the archetypes, for Stevens (2003, esp. ch. 13), in his analysis of the archetypes in terms of evolutionary psychology and neuropsychology, has argued that the principal neural substrate for the archetypes is the right hemisphere and lower brain systems associated especially with instinctive (phylogenetically determined) behavioral programs. Associations in the right hemisphere are symbolic and diffuse, rather than literal and linear, as they are in the left. Under ordinary conditions the left hemisphere filters and represses ideational content coming from the right, which seems bizarre and inexplicable to the left, due to the right's nonverbal, non-logical, and imagistic nature. However, we may experience it during dreams, reveries, and other states of diminished arousal, when the vigilance of the left hemisphere is relaxed. Therefore, if we want to use computers to improve scientific inspiration we must, on the one hand, create an environment of low arousal, defocused attention, and diffuse association, and, on the other, preferentially stimulate the right hemisphere by images likely to activate the archetypal modules that underlie deep understanding (see also Rossi, 1977).

An Inspiration Engine

Goals

In a special issue of the *International Journal of Human-Computer Studies* devoted to computer support for creativity, Lubart (1995) distinguishes four different ways of providing this support: (1) as "nanny" to help manage the creative process, (2) as "pen-pal" to facilitate communication among collaborators, (3) as "coach" to enhance the creative process, and (4) as "colleague" to cooperate in the actual production of creative ideas. In terms of this taxonomy, our research falls in category (3) since it is intended to enhance the incubation process so that the scientist-user is more likely to be inspired by significant creative ideas.

Creativity is a consequence of both personality factors and the situation (Nickerson, 1999; Stein, 1974, pp. 19–29, 194–250). The personality factors, some of which are heritable and some learned, have been studied extensively (e.g., Feist, 1999), but that is not the focus of our research, which aims to use technology to create a situation in which scientific creativity is more likely to occur no matter what the scientist's personality may be. In particular, our work focuses on the incubation phase, in order to facilitate a creative scientific synthesis.

Consistent with our discussion of the role of archetypal structures in scientific thought, our approach is to present archetypal images to scientists in order to inspire them with potential reconceptualizations of their problem. However, since archetypes are not static structures, but dynamic processes, we provide dynamic, variable, and interactive visual experiences for the user. An additional reason for a dynamic approach is that many of the problems for which a scientist might be seeking a creative solution involve processes rather than structures. We call these dynamic, nondeterministic, and interactive visual experiences *image flows*.

More specifically, we present video experiences to the researcher that are intended to engage the innate releasing mechanisms of unconscious archetypal processes, which then proceed in parallel with the visual experience. The external (visual) and internal (psychological) dynamics become coupled. If the structure of the archetype is completely or partially consistent with the target problem, then the researcher will experience a feeling of deep understanding and intuitive insight into the problem, which may be elaborated more systematically and analytically in later stages of the creative activity. Our approach meets the requirements of a *creative problem solving environment* (Hewett, 2005), but its novelty lies in its orientation toward archetypal sources of inspiration.

Archetypes are neither static images nor purely sequential processes. Rather, they are more like control programs, which regulate an organism's interaction with its environment. As Jung (*CW* 18, ¶1228) said, *archetype* "is not meant to denote an inherited idea, but rather an inherited mode of functioning, … a 'pattern of behavior'." When a visual perception has activated an archetype, the perceiver projects archetypal structure onto the stimulus, and the two (perceiver and stimulus) can interact in a coherent manner so long as the two structures (internal and external) are congruent. Therefore our goal is to permit the researcher to interact with image flows, not directing them, but guiding them according to the possibilities they afford. In effect, the researcher should be able to actively explore the unfolding archetypal structure.

As the researcher explores the space of archetypal images, it is intended that he or she will be inspired with ideas relevant to the target problem. Therefore another goal is to have "low-interference capture techniques," that is, means of recording ideas and intuitions without interfering with the wide-focus, non-verbal, non-analytic incubation process. These captured inspirations are linked to the places in the image trajectory that stimulated them. Furthermore, since the researcher's trajectory through the image space is not predetermined, they may want to return to "branch points" (places where they influenced the process) so they can explore different possibilities. More generally, the researcher can "drop a marker" at any interesting place in the image sequence so that they can return to it later for further exploration

The essence of the incubation stage is that the mind is not consciously engaged with the target problem. Therefore an additional goal of our approach is, so far as possible, to decrease the role of conscious processing during this phase of the creative activity. In particular, we want to facilitate an *adaptive regression to primary processes* and to decrease conscious filtering and editing of content arising from the unconscious. As is well known, premature conscious judgment and criticism can interfere with creativity (Nickerson, 1999). Therefore, the experience should be such as to increase right-hemisphere activity relative to left-hemisphere, both by stimulating right-hemisphere processes and by decreasing left-hemisphere inhibition of the right, since this inhibition is more common in scientists than in artists (Martindale, 1999). This should be in a context of overall disinhibition, low cortical arousal, especially in the frontal lobes, and defocused attention (Martindale, 1999).

Image Flows

Definition

An archetype is an abstract structure that organizes conscious content, including perception, motivation, affect, and behavior, in order to facilitate some biological adaptation (Jung, *CW* 9, pt. 1, ¶155). A stimulus in the environment can activate an archetypal process, and subsequent stimuli can maintain its activation and channel it in directions permitted by its structure. Therefore the goal of our system is to generate *archetypal image flows*, that is, continuous sequences of images conformable to an archetypal structure, in order to stimulate and maintain the activation of that archetype in the scientist. The intent is that if the images or their evolving sequence seem to resonate with the target problem, then the scientist will note ("capture") these associations for later elaboration, verification, or additional computer-mediated incubation and inspiration.

To accomplish these purposes an image flow must be more than a simple sequence of images, for archetypes are behavioral control modules, analogous to programs. Therefore flows may have branch points, at which environmental conditions, including user inputs, can influence the direction of the flow. Image flows may also include a certain amount of nondeterminism, permitting them to wander randomly within bounds, but the capture mechanisms always permit an interesting flow to be reproduced.

Our system is intended to contain an open-ended and expanding library of image flows corresponding to various archetypal structures, any one of which could inspire a new scientific model or theory. In our preliminary investigation we are limiting ourselves to a few archetypal structures described in the literature and to informal tests of their efficacy in stimulating scientific creativity (described below). Subsequent research will develop more systematic methods for discovering, implementing, and validating image flows for inclusion in the system library.

Examples

In order to make our method clearer, it will be helpful to describe several simple image flows. The simplest (and least interesting) image flow is just a sequence of discrete images chosen for their archetypal content (many of these are documented in the depth psychology literature). In the most basic case this amounts to a slide show, with each image cross-fading into the next. A simple variant of the slide show is a cumulative flow, in which successive pictures are added to a display depicting the history of the flow; this makes the structure of the flow more salient. A slightly more sophisticated version of the slide show uses standard "morphing" software to transform each image into its successor. Even these simple image flows need not be purely linear and deterministic, but could incorporate cycles and branch points (subject to user choice or random selection).

The abstract sequence of small integers is an important archetypal structure (von Franz, 1974). Commenting on the deep correspondence between physical processes and unconscious psychological processes, Jung remarked, "I have a distinct feeling that number is a key to the mystery, since it is just as much discovered as it is invented. It is quantity as well as meaning" (letter quoted in von Franz, 1974, p. 9). Similarly, in an essay recently published for the first time, Pauli writes, "Mathematics … has not only a quantitative side but also a qualitative one, which comes to the fore, for example, in the theory of numbers and topology" (Pauli, 2001, p. 196).

Each of the small integers is associated with a rich field of archetypal ideas, for example, (1) unity, integrity, wholeness; (2) polarity and opposition; (3) mediation, conjunction, and process; (4) balance and stability. Each of these ideas, in turn, can be symbolized in innumerable ways, and in particular by concrete or abstract images. These various representations may be more or less inspiring to a scientist in the context of a particular target problem, and so it is essential that the *deep structure* of the number sequence be visualizable in a variety of *surface structures* (concrete image flows).

Other examples of abstract structures that might be especially inspiring for the purposes of scientific creativity include ubiquitous models of emergence, self-organization, and growth (e.g., L-systems, fractals, period doubling, diffusion-limited aggregation). These processes can be visualized in a variety of suggestive ways, and afford many means by which the investigator can intervene in the process and affect its evolution. These are just a few examples of how abstract archetypal structures can be used to generate images flows in order to inspire scientific creativity. (Several of these examples are explored in detail below.)

Deep Structure

As Jung stressed, the archetypes are unconscious abstract structures that can be filled with concrete conscious content in innumerable ways (e.g., *CW* 9, pt. 1, ¶155). That is, the *deep structure* of an activated archetype regulates the *surface structure* of the stream of consciousness (in interaction, of course, with the environment); the archetype is *projected* on the concrete situation. Since different concrete images may differently affect different scientists with different target problems, our approach similarly distinguishes between the deep and surface structures of image flows. At the deep level the system operates on abstract images, whereas the user views and interacts with concrete images corresponding to them.

Therefore at the heart of the system is an engine that computes abstract trajectories in conformity with the deep structures of image flows. Our goal is to permit image flows in spaces with a wide variety of topologies, both continuous and discrete, and so we have tentatively decided on the U-machine architecture (MacLennan, 2010). This machine exploits a theorem proved by Pavel Urysohn (1898–1924), which shows that any second-countable metric space is *homeomorphic* (topologically equivalent) to a subset of a Hilbert space. This is important because all the familiar discrete and continuous topological spaces, including spaces of images, are second-countable metric spaces. The U-machine implements general computation over Hilbert spaces by means of linear combinations of simple nonlinear basis functions, in accord with several universal approximation theorems (e.g., Haykin, 1999, pp. 208–9, 249–50, 264–5, 274–8, 290–4). In the following, we present these ideas in some detail because the proof of the theorem is illuminates the operation of the U-machine.

The significance of Urysohn's theorem is that it embeds an arbitrary second-countable metric space in a subset of E^∞, the Hilbert space of square-summable real sequences, that is, of sequences $u_1, u_2, \ldots$ for which $\sum_{k=1}^{\infty} u_k^2 < \infty$. Specifically, the metric space is embedded within the *fundamental parallelepiped* (Nemytskii & Stepanov, 1989, pp. 324–5):

Definition: The *fundamental parallelepiped* $Q^\infty \subset E^\infty$ is defined: $Q^\infty \equiv \{(u_1, u_2, \dots, u_k, \dots) \mid u_k \in \mathbb{R} \wedge |u_k| \leq 1/k\}$.

Suppose the second-countable metric space to be represented is (X, δ_X). If the metric δ_X is not bounded, $\delta_X(x, x') \leq 1$ for all $x, x' \in X$, then we replace it by a metric that is:

Definition (Bounded Metric): $\delta(x, x') \equiv \delta_X(x, x')/[1 + \delta_X(x, x')]$.

The second-countable metric space is embedded in Q^∞ by the *Urysohn embedding*:

Definition (Urysohn Embedding): Suppose that (X, δ_X) is a second-countable metric space. We define the embedding map $U: X \to Q^\infty$ as follows. Since (X, δ_X) is second-countable, it has a countable base (dense subset) $\{b_1, b_2, \dots, b_k, \dots\} \subseteq X$. Let $u_k \equiv \delta(x, b_k)/k$ and define $U(x) \equiv \mathbf{u} \equiv (u_1, u_2, \dots, u_k, \dots)$. Since $|u_k| \leq 1/k$, $U(x) \in Q^\infty$.

Lemma: The Urysohn embedding is a homeomorphism because it is continuous (indeed, uniformly continuous) and its inverse is continuous on its range (Nemytskii & Stepanov, 1989, p. 326).

Theorem (Urysohn): Any second-countable metric space is homeomorphic to a subset of Q^∞. This follows from the Urysohn embedding being a homeomorphism.

It will be helpful to pause and consider the significance of the Urysohn embedding. A second-countable metric space has a countable base, that is, a countable dense subset. A familiar example is the rational numbers, which form a countable dense subset of the real numbers; arbitrary reals can be approximated by sequences of rationals. In the context of abstract image spaces, a countable base is a countable set of basis images that can approximate any image arbitrarily closely. The basis images form a dense, but countable matrix that fills the space. For any *x* in the space, $U(x)$ is an infinite vector (sequence) of distances between *x* and the basis elements. The specifics of the mapping depend on the order in which the basis images are enumerated, a topic we now address, for it is reasonable to expect the components of the representation $u_1, u_2, \dots$ to approximate the target image *x* more and more closely.

Definition (ε-Net): For any $\varepsilon > 0$, a finite set $B = \{b_1, b_2, \dots, b_n\} \subseteq X$ is an ε-net in the metric space (X, δ) if for every $x \in X$ there is at least one $b_k \in B$ such that $\delta(x, b_k) < \varepsilon$.

Obviously, an ε-net provides a set of approximants for every element of the metric space (accurate to ε). In our context, it is a set of basis images that allows any abstract image to be approximated with precision ε.

Practical abstract image spaces are compact (e.g., Moore, 1964, p. 67); for example, in topological terms, a continuum is a (non-trivial) connected compact metric space (Moore, 1964, p. 158), and finite discrete spaces are also compact. Therefore we can apply the following theorem:

Theorem: Any compact metric space has an ε-net for each $\varepsilon > 0$ (Nemytskii & Stepanov, 1989, p. 315).

For $j = 1,2, \dots$ consider the j^{-1}-nets $B_j \equiv \{b_{j,1}, b_{j,2}, \dots, b_{j,n_j}\}$. Obviously $B \equiv \bigcup_{j=1}^\infty B_j$ is a countable base for the space (Nemytskii & Stepanov, 1989, p. 315). We can order the elements of *B* according to increasing fineness of approximation $B = \{b_{1,1}, b_{1,2}, \dots, b_{1,n_1}, b_{2,1}, \dots, b_{2,n_2}, b_{3,1}, \dots\}$. We call this a *ranked order* for a base and use it in our Urysohn embeddings. For any given ε, this allows us to truncate the abstract image representations $U(x)$ to $j = \lceil 1/\varepsilon \rceil$, which means that at least one component of the representation is within ε of *x*. Therefore the representations are vectors in a finite-dimensional space.

Through the use of an appropriate ε-net, any abstract image can be represented (to a precision of at least ε) in the Hilbert space by a finite-dimensional vector of the image's distances to each of the basis images. Since the vectors are finite dimensional, we can dispense with the $1/k$ scaling of the Urysohn embedding and define the vector elements $u_k \equiv \delta(x, b_k)$. Alternately, and more conveniently, an image can be represented by a complementary vector of its *similarities* to the basis images: $\mathbf{s} \equiv \mathbf{1} - \mathbf{u}$, i.e., $s_k \equiv 1 - \delta(x, b_k)$. To summarize: compact abstract image spaces (whether continuous or discrete) can be represented to a precision ε by finite-dimensional vectors of either similarities or differences to a finite set of basis images in an corresponding ε-net. However, many simple image spaces (such as the examples considered below) do not require the Urysohn embedding and can be represented directly as vectors in a finite-dimensional Euclidean space. The U-machine can operate on these vectors directly.

Computation in the vector space can be implemented by simple neural-network-style algorithms, which are straight-forward to implement and facilitate learning and adaptation. The trajectory in the vector space is generated by integration of a system of differential equations defined over the vector space and over the inputs provided by the user (appropriately mapped into the vector space). The differential equations are defined by linear combinations of simple nonlinear basis functions, such as radial basis functions. The coefficients of the linear combinations can be determined in a variety of ways, including explicit programming, offline computation of optimal coefficient matrices, and online neural-network learning algorithms.

For example, for a state trajectory $\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, \mathbf{c})$, where $\mathbf{c}$ is the control input, we may use the following universal approximation theorem to compute state updates (e.g., Haykin, 1999, pp. 208–9, 249–50):

Theorem (Universal Approximation): Suppose continuous $\mathbf{f}: [0,1]^m \times [0,1]^n \to [0,1]^m$ and $\varepsilon > 0$ are given. Suppose σ is a sigmoid function, that is, a non-constant, monotonically increasing, bounded, continuous function. Then there exist an integer l, $m \times l$ matrices $\mathbf{B}$ and $\mathbf{U}$, and $m \times l \times m$ matrices $\mathbf{V}$ and $\mathbf{W}$ such that $|F_i(\mathbf{x}, \mathbf{c}) - f_i(\mathbf{x}, \mathbf{c})| < \varepsilon$ for each vector component i ($1 \le i \le m$) when:

$$F_i(\mathbf{x}, \mathbf{c}) \equiv \sum_{j=1}^{l} U_{ij} \sigma \left[B_{ij} + \sum_{k=1}^{m} V_{ijk} x_k + \sum_{k=1}^{n} W_{ijk} c_k \right].$$

We can abbreviate this equation by the vector formula $\mathbf{F}(\mathbf{x}, \mathbf{c}) = \boldsymbol{\sigma}(\mathbf{B} + \mathbf{V}\mathbf{x} + \mathbf{W}\mathbf{c}) \cdot \mathbf{U}^{\mathrm{T}}$. This is a simple two-layer neural network, with a sigmoidal layer followed by a linear layer. The bias matrix $\mathbf{B}$ and the weight matrices $\mathbf{U}$, $\mathbf{V}$, $\mathbf{W}$ can be computed from examples by well-known methods (see, for example, Haykin, 1999).

Surface Structure

An *image projector* maps an abstract Hilbert-space representation into a concrete image so that an abstract trajectory in Hilbert space generates a corresponding sequence of concrete images. In mathematical terms, a projector uses the similarity coefficients in the Hilbert-space representation to construct an approximation of the concrete image from the concrete basis images.

The system will provide an open-ended library of projectors that can be used with any particular abstract flow. For example the small-integer sequence can be projected into a variety of different image sequences, some more concrete, some more abstract. The programming of a projector will depend on (1) the structure of the abstract flow, (2) the topology of the concrete image space (including its metric or similarity measure), and (3) the details of the Urysohn embedding. Initially, we intend to implement some basic projectors suitable to the archetypal image flows explored in the prototype implementation.

For example, if $\mathbf{s} = (s_1, \ldots, s_n)$ is the abstract image (represented as similarities to abstract basis images), and c_k are concrete basis images of the abstract basis images b_k and these concrete images can be added, then one way to generate a concrete image of $\mathbf{s}$ is a weighted average of the concrete basis images:

$$C(\mathbf{s}) = \frac{1}{n}\sum_{k=1}^{n} s_k c_k = \frac{\mathbf{c}^{\mathrm{T}}\mathbf{s}}{n}.$$

Only special classes of concrete images can be meaningfully added, but in other cases the concrete base images are continuous functions of real parameter vectors, $c_k = f(\mathbf{p}_k)$, and the concrete image can be generated from a weighted average of these parameter vectors, $C(\mathbf{s}) = f\left(\frac{1}{n}\sum_{k=1}^{n} s_k \mathbf{p}_k\right)$. More complicated image interpolation or morphing operations can be applied in accord with the similarities s_k.

For a given abstract trajectory, different concrete projections may be more or less likely to stimulate a creative inspiration in a particular scientist working on a particular problem. Therefore it is valuable for the scientist to experience different projections of the same abstract flow. Although it would be easy to allow the user to select the projector, it may be more productive to use one or another kind of "blind variation," that is, variation undirected by the goal at hand (Simonton, 1999, chs. 2–3). To begin, we intend to include several possibilities. First, the initial projector may be selected randomly. Second, the user may choose to restart the flow with a different randomly selected projector. Third, at any point in the image trajectory, the user may ask that the system to switch to a new random projector. Finally, the user may specify that the system will spontaneously change projectors from time to time.

If concrete image flows and controls (e.g., buttons, sliders) have to be displayed on a single screen, then the images should be displayed on the left, as this has been shown to improve creativity, probably due to preferential activation of the right hemisphere (Hines & Martindale, 1974).

Navigation

With our system the scientist explores a space of inspiring images by following archetypal paths of image transformation. Therefore it is natural to use metaphors of navigation and path following in describing the process and the software tools used to control it.

Several tools allow diversion of the image trajectory from the path it would have otherwise followed. A common application of these tools is the further exploration of an image flow, by diverting it in different ways, in order to seek additional or better inspirations. One simple way to divert the trajectory is *parameter perturbation*. Some image flows (e.g., those associated with emergence, self-organization, and growth) will have continuously variable parameters that affect the path taken through image space. The scientist-user can control these parameters (e.g., by a mouse, joystick, or gamepad) to affect the evolution of the image flow in order to explore different regions of the space. Another diversion tool expands the dimension of an image flow, thereby affording the trajectory additional degrees of freedom in which to move. This is implemented by allowing additional dimensions of the Hilbert space to affect the trajectory by entering into its computation. A diversion of the opposite sort is obtained by projecting the abstract image flow into a lower dimensional space. There are two varieties, depending on whether the trajectory is calculated in the lower dimensional space (thus altering the trajectory), or whether the trajectory is calculated in the original higher dimensional space before projection to a lower dimensional space for projection into a concrete image. In either case, the user may cycle through different nonempty subsets of the original set of dimensions as a means of exploring the image flow.

As previously discussed, the user can control the projection of the abstract trajectory into concrete images (e.g., by choosing different projectors). Unlike other navigation controls, this does not affect the abstract trajectory, but rather, by radically altering the visual experience of the trajectory, it has the effect of shifting the user into a completely different concrete image space (a different concrete image flow). Thus it is a kind of navigation between concrete image spaces.

As previously mentioned, image flows are not simple sequences, but in accord with the interactive nature of archetypal structures, may have *branch points* at which the trajectory can go in different directions. At a branch point the user can choose the direction of the trajectory, or it may be determined randomly or deterministically by the dynamics of the flow. Indeed, we can view parameter perturbation as a having a branch point at every point in a flow.

Users can control their trajectory through image space in several ways. For example, they can control the rate of the image flow. This allows them to skim through uninspiring parts and linger where the flow of ideas is stronger. However, the same images presented at different rates may affect the viewer differently, and so it is useful to be able to experience the same flow at different rates. Different time scales bring out different qualities of the flow.

Capture

It is to be expected that the scientist-user will wish to return to inspiring regions of the image space, either because they have wandered into less inspiring regions or because they want to seek additional inspiration. Therefore the entire trajectory is automatically recorded so that the scientist can return to any part of it and explore alternatives. By a simple click, users can "drop a marker" at any interesting place in the image flow, so that they can return to it later. The user does not need to name these markers, since that would be an interruption and too distracting, but the markers are cross-linked with other captured information (such as spoken or written comments), which facilitates finding a desired marker. Recorded branch points and other marked points can be revisited by jumping forward or backward in their sequence.

If the scientist has any ideas during the image flow, they may speak them and they will be recorded digitally and cross-linked to a location in the trajectory. The purpose of this mechanism is not to record ad lib lectures, but to capture isolated words, phrases, and short comments that will remind the user what was inspiring about an image, or that can be elaborated more systematically later. The scientist can also jot down notes or formulas, or sketch quick diagrams that suggest themselves along the way. Our goal is to capture these in a way that does not interfere with the scientist's absorption in their problem. A digital tablet or wireless pen of some kind could be used. As with spoken notes, they are cross-linked with points in the image trajectory. Cross-linking of captured ideas (spoken, written) with points in the image flow allows inspirations to be captured and explored in more detail at a later time. Some inspirations will be sterile but others, hopefully, will fuel scientific creativity if they are pursued.

Architecture

In this section we describe the architecture of the intuition engine in more detail. Because flows can be deterministic or stochastic, an abstract image flow can include a deterministic component *D* and a stochastic component *S*. The state vector of the stochastic system is updated $\mathbf{s}' = S(\mathbf{c}_S, \mathbf{s})$, where $\mathbf{c}_S$ is a vector of control parameters provided by the user that govern, for example, the mean and variance of the pseudo-random processes. The new abstract image is defined by the deterministic system, which takes as input control parameters $\mathbf{c}_D$ provided by the user, the previous deterministic state $\mathbf{x}$, and the stochastic state vector $\mathbf{s}'$; that is, $\mathbf{x}' = D(\mathbf{c}_D, \mathbf{x}, \mathbf{s}')$. The new abstract image $\mathbf{x}'$ is passed to a projector, which displays the corresponding concrete image. The following pseudo-code describes the main loop:

$(\mathbf{c}_D, \mathbf{c}_S) :=$ acquire control parameters from user;

$\mathbf{s} := S(\mathbf{c}_S, \mathbf{s})$;

$\mathbf{x} := D(\mathbf{c}_D, \mathbf{x}, \mathbf{s})$;

pass $\mathbf{x}$ to current projector and update display;

With respect to software modularization, the control interface is considered part of an image projector, since controlling an image flow is often by means of interacting with its concrete representation, for example by touching or pointing at a location in the image.

Evaluation and Evolution

Our system is intended to be a flexible, adaptive, and evolving method for promoting scientific creativity. The system is extensible in that its libraries of both abstract image flows and image projectors are open-ended. This is a manual means of adaptation and evolution, since programmers must add the new flows and projectors. Eventually we intend to investigate more automatic means of adaptation, most likely by neural-network-style reinforcement learning. Users will indicate trajectories that have proved valuable in their scientific research, and this will modify the parameters of the image flow to make these productive trajectories more likely to be followed.

Computer-Assisted Hypnosis Module

There is a large body of research investigating the relationship between hypnosis and creativity (for recent surveys see Lynn & Sivec, 1992; Shames & Bowers, 1992). Some of this research investigates relations between hypnotic susceptibility and creative personalities, but that is not directly relevant to our investigation. Other research has used hypnosis to remove psychological impediments to creativity and to impart a more creative cognitive style (Council, Bromley, Zabelina & Waters, 2007; Shames & Bowers, 1992). This research is more relevant to our goals, but only insofar as the hypnotic suggestions are part of the experience and not preparatory to it (i.e., so long as they are part of the *setting* as opposed to the *set*).

Finally, some research has supported similarities between hypnotic and creative states (Bowers, 1978; Council et al., 2007; Gur & Raynor, 1976; Martindale, 1999; Stein, 1974, pp. 68–70). These similarities include primary-process thought, loosened reality orientation, openness to new experiences, disinhibition, decreased fear of criticism and failure, deep involvement, time distortion, imagery, and increased right-hemisphere activation, all of which are important in creativity, as previously discussed. Therefore, we anticipate that creating such a state in the scientist will facilitate creativity.

While a creative state of this sort might be induced by a human hypnotist, it would be more consistent with the automation goals of our system to use the *computer-assisted hypnosis* (CAH) system developed by Grant and Nash (1995), which has been well tested and has been in use for many years. The software is relatively straight-forward and it would be simple to incorporate a CAH module into the system, which could help put the user into a psychological state more conducive to inspiration. In particular, by activating or deactivating this module we could investigate the potential contribution of CAH to scientific creativity. Eventually we intend to explore the use of immersive virtual reality for the CAH module (Patterson, Tininenko, Schmidt & Sharar, 2004; Patterson, Wiechman, Jensen & Sharar, 2006).

Example Image Flows

Dynamic Quaternity

The *quaternity* is an archetype that Jung studied at great length (Jung, *CW* 9, pt. 2, ch. XIV, *CW* 14, ¶¶1–12; von Franz, 1974, Part II). Indeed, “Jung devoted practically the whole of his life’s work to demonstrating the vast psychological significance of the number four” (von Franz, 1974, p. 115). It arises from a pair of oppositions, as found for example in the four classical elements earth, water, air, and fire, which result from the opposed qualities warm-cool and moist-dry (Aristotle, *Gen. & corr.*, 330b4–6). Thus earth is dry and cool, water is cool and moist, air is moist and warm, and fire is warm and dry. The four humors (black bile, phlegm, blood, yellow bile) are another example. As a result of its double-opposition structure, the quaternity is a common symbol of balance and stability. Each pair of complementary opposites generates a continuum between the extremes, with a neutral or balance point in the middle. Overall balance is represented by the coincidence of the two neutral points, forming crossed oppositions. In two dimensions, therefore, balance, stability, and equilibrium are symbolized by a “square of opposition.”

However, Jung also stressed the dynamic aspects of the quaternity, for example, the rotation of the elements (earth to water to air to fire back to earth, or vice versa). The dynamic quaternity is ubiquitous, for example in the seasonal cycle (moist spring, warm summer, dry autumn, cool winter) and the life cycle (moist youth, warm adult, dry elder, cold death) (cf. also Yeats' "Four Ages of Man"). The dynamic quaternity provides richer opportunities for inspiring image flows than does the static one. It is a continuous cycle, but generated from two polar oppositions.

The simplest abstract image space accommodating the dynamic quaternity is the space of normalized complex numbers, that is, numbers of the form $e^{i\phi}$, for $\phi \in [0,2\pi)$, which is isomorphic to the special orthogonal group SO(2) of planar rotations. The opposed qualities are represented by the real numbers $+1, -1$ and the imaginary numbers $+i, -i$.

The basic dynamics of the image flow is a rotation, which can have an increasing or decreasing imaginary exponent representing opposite directions of rotation. Simple controls allow the user to determine the direction and rate of rotation, or to perturb either randomly. Therefore, in the simplest case, the abstract image flow is defined $z(t) \equiv e^{i\omega(t)t}$, where the angular rate $\omega(t)$ is a parameter (a bounded real number) controlled by the user. If the user can directly control the angle of rotation via $\theta(t)$, then the flow is $z(t) \equiv e^{i[\omega(t)t+\theta(t)]}$.

Jung has noted the close connection between the quaternity and its center (Jung, *CW* 12, ¶327). Two different polarities are integrated into a unity by sharing a common center (Jung, *CW* 12, ¶310), as do the real and imaginary axes in the Argand diagram. Conversely, a center sometimes generates a quaternity from itself (Jung, *CW* 12, ¶327). The center, therefore, comes to symbolize a reconciliation of the oppositions and the paradoxes of a psychological problem; Jung calls it "the place of creative change" (*CW* 12, ¶186). Initially there is a circumambulation of the center as solution, but this hidden goal attracts the path inward in a convergent spiral trajectory, in which the same issues are revisited repeatedly but with an ever-growing approximation to the solution (Jung *CW* 12, ¶¶34, 325); that is, it is a fixed-point attractor. Jakob Bernoulli alludes to the archetypal character of the spiral in his famous epitaph: *Eadem mutata resurgo* ("Though changed, I arise the same"), as Jung (*CW* 12, ¶325) observes.

Therefore, the quaternary image flow can be more inspiring if it is allowed to spiral inward toward a center (damped oscillation) or outward toward a circumference. This is accomplished by including the magnitude of the complex number in the abstract image: $z(t) \equiv r(t)e^{i[\omega(t)t+\theta(t)]}$. The magnitude $r(t)$ is governed by its own differential equation subject to user-controlled parameters, which govern the magnitude's rate of contraction or (bounded) expansion, or its oscillation. Alternately, we may constrain the magnitude $|z(t)| < 1$ by a sigmoid function:

$$z(t) \equiv \frac{e^{i[\omega(t)t+\theta(t)]}}{1+e^{-r(t)}}, \qquad \text{with } r(t) \in (-\infty, \infty).$$

There is no need to restrict the orbits to be circular. Since quaternities are naturally imaged by squares, we can have diamond-shaped orbits with $z(t) = x(t) + iy(t)$ where $\dot{x} = \operatorname{sgn} y$ and $\dot{y} = -\operatorname{sgn} x$. Indeed, we can allow the user to define quite arbitrary "restoring forces," for example, on the real axis, $\ddot{x} = -f(x)$. Suppose that $f(x)$ is continuously differentiable for $|x| < c$ for some $c > 0$, and that $xf(x) > 0$ for all $x \neq 0$. Then define the dynamics by $\dot{x} = y$ and $\dot{y} = -f(x)$. For $|x| < c$ the state will move in periodic orbits (Brauer & Nohel, 1989, pp. 197–9).

There are many possible concrete image flows for the dynamic quaternity, but most of them are relatively simple because the quaternity itself is simple. Perhaps the most direct projection uses the real and imaginary components of the abstract state to control the horizontal and vertical position of a displayed object. In this case the object moves cyclically as governed by the dynamical equations, perhaps spiraling in or out in accord with the controls. Similarly, the phase and magnitude of the complex number could control the orientation and size of any displayed object.

Another representation, which might better reflect the complementary relation between the variables (for example, as position and velocity, or as potential and kinetic energy), is to represent both the real and imaginary parts on parallel scales. Similarly, the complex state could be used to control the color of any image in a double-opponent system: the sine of the phase angle controls hue along a yellow-blue axis, its cosine controls it along a red-green axis, and the magnitude of the complex number controls either saturation or brightness.

More naturalistic concrete images can be used for the dynamic quaternity, such as images of the seasons. The projector would use an appropriate ε-grid of images defined over the region of the complex plane that constitutes the state space of the abstract flow.

Logistic Map

I am not aware of any psychological evidence for chaos as an archetype, but the onset of chaos has come to be recognized as a critical phenomenon in many disciplines, and so it is a good candidate for an image flow. Perhaps the simplest example of deterministic chaos is the *logistic map*, $x_{n+1} = rx_n(1 - x_n)$, with $x_n \in (0,1)$. This recurrence relation exhibits a variety of dynamical behaviors depending on the rate parameter $r \in (0,4)$ (e.g., May, 1976). As r is increased, the behavior of the map shifts from a fixed-point attractor, to a period-2 attractor, through a regime of accelerating period doubling (period 4, period 8, etc.), until at the "accumulation point" $r_c \approx 3.569945672$ the behavior becomes chaotic. In the chaotic regime there are isolated "islands of stability" exhibiting periods of 3, 6, 12, etc.

To use the logistic map as an image flow, we allow the user to change the state x_n or the rate parameter r at any time, either by setting them to specific values or by randomization. In this way the user can explore the edge of chaos and the phenomena surrounding it. The rate parameter can be adjusted directly by a slider, but the sensitive dependence on its value near the critical region invites other ways of controlling it, such as an exponential scale around the critical point. For example, we can use $r = r_c + 2.1\left(e^{|\rho|} - 1\right)\operatorname{sgn} \rho$, where is $\rho \in [-1,1]$ is the user's control and r is limited to (0,4).

Because the logistic map generates a discrete sequence of real numbers, it does not immediately suggest rich concrete representations. In our prototype implementation we make the sequence easier to visualize by interpolating points between successive x_n values in order to convert the discrete sequence into an approximately continuous function $x(t)$. We map these real values $x(t)$ into both the brightness and size of an object (such as a circle) to make their variation more apparent. In parallel we present a graph of $x(t)$, since it is often suggestive. The user can also control the rate at which the sequence is generated, since this affects perception of the image flow. Setting the state to a particular value can be done with a slider or by clicking on the image to set its size.

There are of course many other chaotic systems that may provide inspiring image flows.

Future Plans

The prototype implementation of the software system will include only those components required to demonstrate the concept and to begin evaluation of its usefulness. These include the U-machine interpreter for computing abstract trajectories, software for navigation and branch-point/marker management, an initial library of projectors for converting the abstract trajectories to concrete sequences of images, graphics modules, and support for a simple input device such as a mouse, trackball, joystick, or touch screen.

In order to have the prototype system operational as quickly as possible, we will use off-the-shelf, open-source software whenever possible. This is especially the case for the human interface, including the graphics modules. The U-machine engine, the navigation and marking facilities, and an initial library of projectors for interfacing the U-machine to the graphics software, will have to be programmed by us.

We are identifying a set of archetypal structures informally, based on the psychological literature and our own research. We listed some examples of these archetypal structures above, and have prototype implementations of the dynamic quaternity and logistic map. We plan some informal evaluations of our methodology by comparing creativity with and without it, and between archetypal and non-archetypal image flows. We are considering association tests, where creativity is correlated to wider association trees (Mednick, 1962). In subsequent research we plan a more formal evaluation using validated assessment instruments.

Another immediate task is to identify assessment instruments that can be used to evaluate the effect of our system on scientific creativity. In spite of the fact that many existing instruments focus on small-C creativity and problem solving, we are optimistic that we can find suitable methods in the literature.

We will outline briefly our longer-range plans. One significant goal of the later phases of this investigation will be to begin using formal assessment instruments to determine the effect of various system components on scientific creativity. This will permit us to refine our method, eliminating ineffective aspects and further developing the valuable ones. In particular we intend to increase the library of archetypal flows and their projectors. Some of this will be accomplished by mining the literature of depth psychology and allied disciplines, but we hope also to identify or develop instruments that will allow us to identify archetypal flows by means of their effect on creativity. The prototype software, which is the goal of the first phase of this project, will have a basic human interface comprising readily available hardware (e.g., monitor, pointing device) and interface software. In subsequent work we intend to explore a more immersive environment (e.g., 3D goggles, headphones) and a wider range of input mechanisms (e.g., microphone, graphics tablet, data glove, motion sensor). These extensions should not affect the core U-machine software, but they will require modifications to the projector software.

Conclusions

Our research differs from prior investigations of computer-enhanced creativity in several important respects. First, it focuses on high-impact scientific creativity, rather than on lower-impact everyday creativity. Second, it directly addresses the unconscious processes that occur during the incubation phase, which may lead to unanticipated insights. Third, it concentrates on innate unconscious processes, because these underlie conceptual models that are especially intuitive and fruitful. Finally, because the computerized system is based on a particular model of significant scientific creativity, it can be used as an empirical test of the role of innate unconscious processes in scientific progress.

The computerized tool permits the definition of abstract image flows that conform to unconscious archetypal dynamics. The abstract images are mapped to concrete images intended to stimulate and guide unconscious creative processes in the scientist-user, who explores the space of images governed by the flow. The system is open-ended and adaptable, so that it can evolve as our understanding of the wellsprings of scientific creativity improve.

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Key Terms and Definitions

Archetype: The psychological aspect of an innate behavioral adaptation. When activated by a *releaser* (internal or external stimulus), it regulates perception, motivation, affect, and behavior to serve some biological function.

Big-C Creativity: Historically significant creativity, which in science usually depends upon a major reconceptualization of a problem domain.

Compact Space: A topological space is *compact* if and only if every open cover contains a finite subcover. Less formally, a compact metric space is *complete* (contains all of its limit points) and *totally bounded* (of finite "diameter" as measured by its metric).

Evolutionary Psychology: An approach to psychology that seeks to place the behavioral adaptations of *Homo sapiens* in their evolutionary context.

Hilbert Space: An abstract vector space, with an inner product, that is *complete* (includes all its limit points). Less formally, a Hilbert space is a Euclidean space of potentially infinite dimension.

Image Flow: A continuous sequence of images conformable to an archetype.

Incubation: In the context of creativity, a suspension of conscious work on a problem during which the unconscious mind continues involvement with the problem.

Inspiration: In the context of creativity, the apparently spontaneous emergence into consciousness of the solution to a problem after a period of *incubation* (q.v.).

Mandala: A circular image, typically with fourfold symmetry, symbolic of the cosmos or psychological wholeness. Mandalas can be two-dimensional, three-dimensional, or dynamic (e.g., danced).

Phylogenetic: Refers to evolved characteristics common to all members of a species.

Primary and Secondary Processes: Primary processes, which serve the pleasure principle and biological drives, are characterized by imagination and play. Secondary processes, which serve the reality principle, are characterized by reason and analysis.

Projector: An image projector is a software module that maps an abstract image (an element of a Hilbert space, q.v.) into a concrete visual image. It thus generates a concrete image flow from an abstract image flow.

Second-countable Space: A metric space is second-countable if and only if it has a *countable dense subset*, that is, every element of the space is either in the subset or is the limit of a sequence of elements in the subset. For example, the reals are second-countable because every real number is either rational or the limit of a sequence of rational numbers.