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Generative Art Theory

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Introduction

What people often find most fascinating in the realm of digital art are not the replacements of physical tools by computer applications such as Adobe Photoshop™ or Corel Painter™, but rather works in which the computer seems at times to directly create the art on its own. To date there is, of course, an artist behind the scenes, creating the situation that allows the computer to act this way. Nevertheless, the relative independence of the computer is perceived as being qualitatively different from the characteristics of other tools in art history.

Art created by means of an apparently autonomous system or process is most frequently referred to as "generative art," a realm of digital art practice that has boomed since the start of the 21st century. In fact, the growth of generative digital art has been so robust that, for many people, "generative art" and "computer art" have become synonymous terms. In this chapter I hope to show that generative computer art is in fact a subset of the larger field of generative art. It will be seen that generative art can leverage virtually any kind of system, not just computers, and that it in fact is as old as art itself.

It is in some ways natural that "computer artists," in their enthusiasm for a relatively new field, would want to claim the term "generative art" exclusively for themselves. To many people the computer seems uniquely suited to independently generate visuals and sounds of aesthetic interest. However, conflating the term "generative art" with the term "computer art" would come at an unacceptable cost. We would need a new term for the now orphaned forms of earlier generative art. We would lack a term for post-digital work we could otherwise call generative art. But, perhaps most importantly, we would lose an opportunity to explore unified art theory that uniquely spans all systems-based art practices, digital or not.

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To theorize generative art as a systems-based practice we can turn to the branch of science devoted to the study of systems across all scientific disciplines, namely complexity science. In the following I will explicate a more specific definition of generative art, use concepts from complexity science to tie together the commonalities among types of generative art through history, and discuss issues of art theory that are specific to generative art at large and thus apply to digital generative art.

What Is Generative Art?

The question "what is art?" is a notorious one. For some, it is a prime example of intellectualism about to run amok. For others, it is the required starting point for any serious discussion of aesthetics and the philosophy of art. And for yet others, it is both.

If one takes an analytic rather than continental view of philosophical aesthetics, there are many theories of what art is. In approximate historical order these include:

- art as representation;
- art as expression;
- art as form;
- art as experience;
- art as open concept and family resemblance (neo-Wittgensteinianism);
- art as institution;
- art as historical definition.

While it would be possible to discuss these theories in depth using the language of aesthetics in philosophy, the theories of art as representation, expression, form, and experience are also adequately self-explanatory for practical purposes. The neo-Wittgensteinian notion of art as open concept and *family resemblance* is more easily understood than the name might imply. The idea simply is that art has no stable essence, but that there is a body of recognized art at any given point in time. Over time the boundary enclosing art can be stretched to include new forms that seem to share a "family resemblance" to currently accepted art (Carroll 1999).

The intuitive notion of family resemblance ultimately came to be viewed as ill defined and problematic. The "art as institution" theory takes a social construction approach, positing that the "artworld" is an informal yet self-regulating entity that confers the status of art upon objects, with standards shifting over time. In a sense, family resemblance is what the artworld says it is. Historical definition is yet another attempt to establish resemblances. In this case, those with a proprietary claim on an object specify that the object be considered as art in the way other objects before it have been.

Over time the definition and scope of art has informally broadened. Nevertheless there sometimes is confusion as to what makes for *art* versus *good art*. By any contemporary standards the drip paintings of Pollock are obviously art. But one can easily imagine that some traditionalists must have exclaimed, "That's not art!" at the time of the paintings' creation. More arguable would have been the statement, "That's not good art." In fact, within most contemporary notions of aesthetics the bar for qualifying as art is rather low and inclusive. The bar for qualifying as good art, however, is much higher and more contentious.

In a similar way some artists or critics in the field of generative art have such rigid standards as to what makes for good generative art that they are prone to dismiss other work as not being generative at all. But like the bar for art itself, the one for what qualifies as generative art is rather low, as we will see. What remains is the quite a bit higher and more contentious bar for what passes as good generative art.

There is another commonality between the "What is art?" and "What is generative art?" questions. These questions aren't simply a request for the definition of the word; they are a request for the articulation of a *theory of art*. To the extent that they are answerable at all, they will at least require responses to the competing theories noted above.

In a similar way, a solid definition of generative art will have to include a theory of generative art that responds to competing theoretical frameworks. Thus a reasonable point of departure for such a definition is a survey of existing self-claimed generative art.

Some Generative Art Communities

Computer/electronic music

The use of computers as systems for music composition goes back at least to the seminal paper by Brooks, Hopkins, Neumann, and Wright in 1957 (Schwanauer and Levitt 1993). In that paper, they describe the creation of a statistical system of Markov chains for analyzing a body of musical scores. Having gathered statistics from that body, the system is then used to create new scores that mimic the style of those analyzed. In the 1960s analog electronic music synthesizers such as the Moog, Buchla, and others offered systems in which all inputs and outputs had compatible voltages. This allowed outputs to be fed back into inputs, creating generative systems that could "play themselves." Some advocated for the complete rejection of piano-like keyboards and other controllers that copied traditional instruments. From the 1970s to the present, users of audio-specific programming languages and environments such as MUSIC 5, Csound, Max, and Supercollider have created a culture of algorithmic music composition.

Computer graphics and animation

There is a vast body of literature from the Association for Computing Machinery's (ACM) Special Interest Group on Graphics and Interactive Techniques (SIGGRAPH) and other organizations that describes the use of generative software systems. Examples include Perlin Noise for the synthesis of smoke, fire, and hair imagery (Perlin 1985), the use of L-systems to "grow" plants (Prusinkiewicz, Lindenmayer, and Hanan 1990), and the use of physical modeling to create linkages, cloth surfaces, collisions, and other objects without painstakingly choreographing every detail by hand. These assorted techniques have been documented in a body of publications, perhaps most notably those from SIGGRAPH, and have yielded results popularized in animated feature-length films and video games.

The demoscene, VJ culture, glitch art, circuit bending, and live coding

Leveraging generative software techniques, hacked game machines, and early inexpensive personal computers, youth culture movements developed low-cost alternatives for use in nightclubs and other social settings. Referred to as "the demoscene," these do-it-yourself programmers organized party-like gatherings where they would get together to show off feats of programming skill in an aesthetic context (Tasajärvi 2004). Frequently using data projectors, part of the challenge was the creation of complex graphics despite the fact that the available 8-bit technology lacked in speed, memory, and resolution. Hackers who demonstrated superior skills in the creation of surprisingly complex graphics were rewarded with higher social status and the respect of fellow programmers. With the emergence of VJs (the visual equivalent of DJs) in clubs, artist/programmers found new venues for their real-time graphics systems.

More recent is the advent of "live coding" where musician/programmers improvise by writing code that is immediately rendered as sound for a live audience. Part of the performance typically includes projections of the code as it is keyed in and executed. Also notable in this context are glitch art and circuit bending. In glitch art the data of digital media files or code is somehow corrupted, resulting in strange, often garish or psychedelic-looking imagery or animation. Circuit bending is a hardware-based correlate where musicians make arbitrary hardware modifications to sound toys and instruments in search of unusual or even bizarre sounds.

Open source digital art, tools, and social websites

Users of open source programming environments and tools such as Processing, Pure Data, openFrameworks, and others increasingly congregate on dedicated web sites where work is shown, technical help offered, and new ideas are shared.[1] Microcontroller platforms such as the Arduino, used for digital installations and other physical computing, have joined in this phenomenon. The initial attraction frequently is the low cost of entry, but the social network of users has increasingly become the leading asset attracting generative artists and musicians.

Industrial design and architecture

Parametric design practice extends the use of computer-aided design (CAD) software as a passive tool for creating plans and blueprints, and adds generative elements for the modulation and de novo creation of form. Visual tools such as Grasshopper,[2] a graphical algorithm editor, provide designers and architects with algorithmic leverage while freeing them from having to program in textual code.

Popular theories of generative art

Clearly, any attempt to define generative art would have to include all of the above forms of engagement, as there is no obvious reason to privilege one form of contemporary generative art practice over another. And few people would want to stop with just the above list. One could also include, for example, robotic art and math art as clusters of generative art activity.

There also are examples of generative fine art. In the 20th century, for example, artists such as John Cage, William Burroughs, and Marcel Duchamp embraced randomization to generate surprise and variation. Minimalists such as Carl Andre, Mel Bochner, and Paul Morgenson used simple mathematical systems to generate compositions. Sol LeWitt used combinatorial systems, creating complex works from simple components. The conceptual artist Hans Haacke also explored physical generative systems in his early work.

When asked, many generative artists will define generative art in a way that sculpts out a subset resembling, not surprisingly, their own work. Typical examples include:

- Generative art is art that uses randomization.
- Generative art is art that uses genetic systems to evolve form.
- Generative art is art that is constantly changing over time.
- Generative art is art created by running code on a computer.

The problem with such attempts at definition is that they mistake options and choices within the field of generative art as being requirements for generative art. The other option is to create a big tent that accommodates all kinds of generative art and discussion.

Defining Generative Art

What will a useful definition and theory include?

Defining generative art is, not surprisingly, in some ways similar to defining art itself. Just as any definition of art is actually proposing a theory of art, a definition of generative art involves positing a theory of generative art. A possible difficulty in this endeavor is that "art" is part of the term "generative art." This implies the significant complication of having to define art as a prerequisite to understanding generative art. The strategy employed in the following is to leave the definition of art an open issue. We will define generative art in such a way that art, however it is defined, can be divided into generative and non-generative subtypes.

Another problem emerging from the question "What is art?" is the perceived need to provide a crisp definition that neatly cleaves objects into two unambiguous sets of art and non-art. In philosophical aesthetics, however, the approach is more nuanced. The neo-Wittgensteinian model, for example, suggests that the definition of art evolves at art's borders. The border is expanded outward when artists operating outside of the boundary create work that nevertheless has a family resemblance to the art existing within the boundary. In a similar way we should expect that there is work existing at the boundaries of generative art. We can hope for a crisp definition or theory, but do not have to despair if it has a fuzzy aspect to it in the sense that some works are more generative than others.

There are additional considerations that will contribute to a robust definition of generative art. First of all, the definition should include both past and current work that is generally accepted as being generative. In addition, it should be open to new forms of generative art yet to be invented. And finally, generative art should be defined in such a way that some art *is* excluded from its field. If the term "generative art" does not exclude some art, then "art" and "generative art" are synonyms, and "generative art" becomes an unnecessary redundancy.

For example, some people will argue that humans themselves are generative systems, and that, since humans ultimately create all art, all art is generative art. From a certain point of view this is a useful observation, pointing to the status of life as a literal embodiment of generative systems. But if the term "generative art" is supposed to be useful we should understand that it denotes art created by non-human systems. Since the definition of generative art encapsulates a theory of generative art, it should lead the way to explanations and predictions within broader realms of art theory and aesthetics.

Generative art defined

In 2003 I offered what has come to be the most widely cited definition of generative art to date.[3] Supported by other writings it accomplishes the goals outlined above. It also promotes the use of complexity science as a way to sort out and compare all manner of generative art systems:

> Generative art refers to any art practice in which the artist uses a system, such as a set of natural language rules, a computer program, a machine, or other procedural invention, that is set into motion with some degree of autonomy, thereby contributing to or resulting in a completed work of art. (Galanter 2003)

The key element in generative art is the use of an external system to which the artist cedes partial or total control. This understanding moves generative art theory into discussions focused primarily on systems, their role, their relationship to creativity and authorship, system taxonomies, and so on.

While the above definition is further explained in my original paper (Galanter 2003), some discussions working solely from that single sentence have led to misunderstandings which we will try to clarify in the following.

Generative art is not a subset of computer art

At the time of the Industrial Revolution, the steam engine became the reigning technology, and popular culture used it as a metaphor for all kinds of purposes. In the mid-20th century atomic energy and all things "atomic" took on a similar cultural role. In contemporary culture computers and networks have become the reigning technologies to capture the paradigmatic imagination of the public.

It therefore isn't surprising that for many people this definition has reinforced a common misconception and resulting confusion: that generative art is essentially a kind of computer art. However, what this definition refers to as a "procedural invention" can include a chemical reaction, the use of living organisms, condensation and crystallization processes, melting substances, self-organization, self-assembly, and other physical processes, including some that have yet to be discovered.

It is worth noting here a highlight from the history of generative art: the invention of the Jacquard loom. Prior manual textile machines already allowed weavers to apply repetitive operations in the generative creation of patterned fabrics. With the Industrial Revolution, some of these systems were automated. It was Jacquard's 1805 invention, introducing the notion of a stored program in the form of punched cards, that revolutionized the generative art of weaving. One of Jacquard's primary goals was to allow the automation of patterns of greater complexity. Later both Charles Babbage and Charles Hollerith adapted Jacquard's method of punch card programming in their efforts to invent the computer. Computers did not pave the way for generative art; generative art helped to pave the way for computers.

Generative art only requires a weak form of autonomy

A second confusion surrounding the definition involves the required use of an autonomous system for making generative art. Some critics object that no mechanical system can be considered completely autonomous, because such a system is wholly dependent on humans for its continuing operation. Others insist that autonomous systems require free will and consciousness, which pulls this theory of generative art into debates about complicated and contentious philosophical matters.

In the above definition of generative art, the notion of an autonomous system is simple and modest. It follows the use of the same terminology in robotics. Some robots are controlled, moment-by-moment, by a human operator at a console not unlike those used to steer model cars or fly model airplanes by radio. More sophisticated robots use sensors, GPS units, image processing computers, and other technologies to allow them to navigate and adapt to their environment without a human driver. Robots such as these are referred to as being "autonomous" without any implications or claims regarding free will or consciousness.

It is in this sense that generative art systems are "autonomous." They do not require moment-to-moment decision making or control by the artist. They are functionally autonomous relative to the artist.

Not all rule-based art is generative art

A third confusion relates to rule-based art. In a previous article (Galanter 2006) I outlined a number of types of rule-based art, noting that some are generative, but others are not. Josef Albers and Piero Manzoni, for example, created paintings on the basis of self-imposed constraint rules. Albers created color studies involving only concentric rectangles, and Manzoni did paintings that were all white. Ed Ruscha published an art book of photography with a thematic constraint rule allowing only photos of small fires and milk. Bruce Nauman created minimal performances by following rules in the form of instructions for physical movement. On Kawara has done a series of paintings consisting of the respective day's date lettered in paint. The rule calls for making such a painting every day, but says nothing about lettering style, color, and so on (Zelevansky et al. 2004; Rose et al. 2005).

None of these rule-based artworks can be considered generative art because the artist never ceded control to a functionally autonomous system. There is an in-principle dependence on the artist from moment to moment, and at no point does the artist lose fine-grained control over the art-making process. In most cases the proposed rules suggest a *kind* of action to be taken, but do not fully determine a *specific* action to be taken. That is to say, the rules lack a functional autonomy. As these examples show, it is a mistake to use the phrases "rule-based art" and "generative art" interchangeably.

Here are some types of (non-autonomous) rules that do not result in generative art:

- constraint rules—e.g., Manzoni;
- abstract scores for free interpretation—e.g., Earle Brown's composition *December 1952* (Vickery 2012);
- inspirational rules—e.g., Brian Eno's card set called *Oblique Strategies* (1978);
- thematic rules—e.g., Ruscha as noted above;
- performance scripts or rituals as rules—e.g., Nauman as noted above;
- non-specific ideas for geometric construction—e.g., McEntyre and Vidal (discussed here later).

For comparison, these are some types of (autonomous) rules that do result in generative art:

- algorithms stated in text that can unambiguously be translated into computer code;
- combinatorial rules—e.g., Sol LeWitt's *Incomplete Open Cubes* (1974);

- numerical sequences as rules—e.g., Mel Bochner's *Triangular and Square: Numbers* (1972);
- detailed line composition or drawing rules—e.g., many of Sol LeWitt's wall drawings;
- rules establishing serial composition—e.g., many of Carl Andre's sculptures;
- tiling and other symmetric composition rules—e.g., much Islamic art and architecture;
- chance operations—e.g., as typically associated with John Cage and William Burroughs.

That many of the examples of rule-based art come from the period of conceptual art should not be surprising. Also note that both rule-based art and generative art are fuzzy at their borders. Some works exist in the gray zone of either or both. Moreover, a given work of art may be either dominated by the application of rules or the use of generative systems, or only slightly affected by the generative or rule-based aspect.

The question whether any given work is merely rule based or truly generative is important. Equally important are questions as to why an artist has chosen to work that way, and whether the use of rules or generative methods is part of the concept or merely a pragmatic means to some other end. These questions and more are discussed here in following sections.

Generative art is as old as art

Going back in time, we find examples of symmetry and pattern in the creation of art wherever we find human artifacts that go beyond minimal survival needs. Among even the most so-called "primitive" peoples we find abundant examples of the use of geometric patterns in textiles, symmetric designs evolving around a point, repeating border designs, and so on (Hargittai and Hargittai 1994).

The artistic use of tiling, in particular, is nothing less than the application of abstract systems for decorating specific surfaces. The most notable examples of this practice are perhaps the masterworks found in the Islamic world. It is no coincidence that the Islamic world was also one of the significant cradles of mathematical innovation, and that the word "algorithm" has its roots in Arabic.

From 1999 to 2000 a team led by archaeologist Christopher Henshilwood of the South African Museum in Cape Town uncovered some of the oldest known art artifacts anywhere (Balter 2002). Etched in hand-sized pieces of red ochre more than 70,000 years old is an unmistakable grid design made of triangular tiles that would be clearly recognizable to anyone, from generations of Islamic artists to the 20th-century graphic artist M.C. Escher.

While the etchings, like all ancient archaeological finds, are surrounded by a certain amount of controversy, many find them to be compelling examples of abstract geometric thinking with an artistic bent. In an article on the etchings in *Science* magazine, anthropologist Stanley Ambrose of the University of Illinois, Urbana-Champaign says, "This is clearly an intentionally incised abstract geometric design [...] It is art" (Balter 2002).

One can only imagine the excitement this early artist experienced in making the discovery that one could make marks of aesthetic interest not by simply copying what the eye sees, but by instantiating a systematic abstract idea over and over again on various surfaces. LeWitt presumably would have approved.

Generative art defined a second time
In later writings, I have suggested modifications to the original definition in order to combat the common misinterpretations mentioned previously:

> Generative art refers to any art practice in which the artist cedes control to a system with functional autonomy that contributes to, or results in, a completed work of art. Systems may include natural language instructions, biological or chemical processes, computer programs, machines, self-organizing materials, mathematical operations, and other procedural inventions. (Galanter 2008)

It is worth noting that the earlier criteria for a useful definition and theory are met here. For example, while the definition refers to "art" it does not make presuppositions as to what art is. Art is left as an open concept, and yet our definition divides it into generative and non-generative subtypes. The definition is fairly crisp in that any use of a functionally autonomous system qualifies a given work as being generative. Yet it is easy to see how some pieces might be more system-determined than others, and therefore the border of the definition can be fuzzy in that some pieces are in a sense more generative than others.

As we will show in subsequent sections, this definition creates a wide tent under which all manner of old, current, and future generative artworks are welcome. But the term also remains useful and non-redundant because there is a wide range of art that is clearly not generative; work in which the artist never relinquishes control to a system. In fact, most contemporary art is distinctly *not* generative, and one would likely have to randomly visit a large number of galleries or museums before encountering any generative work. In any case it is clear that the "all art is generative art" problem has been avoided.

Creating a big tent for generative art turns most debates about what is or isn't generative art into more nuanced discussions about options, theories, and opinions available within the field of generative art. The term simply is a reference to how the art is made, and in itself makes no claims as to why the art is made that way or what its content is. It is a definition that invites further thought and discussion rather than foreclosing on it. This notion of generative art also remains uncoupled from any particular technology, and as such directs attention to the art-theoretical issues that are invariant, even as this or that technology comes and goes. Generative art need not be "high tech," which is an advantage in a world where "high tech" is a moving target.

Since generative art is defined as a *way* of making art, it remains available for making art with all manner of content. Being in a room full of painters, one would not assume that these artists have anything in common other than using paint to make art. Similarly, artists creating generative work might have little else in common than using a certain way of making art. This speaks to the robust potential of generative art, and by implication, generative digital art.

Perhaps most telling, there are issues related to generative art, digital or not, that do not impact non-generative art, which will be explored in the following.

Other Uses and Related Terms

The term "generative art" has been used, somewhat obscurely, in other contexts with other meanings. The Romanian sculptor Neagu, for example, founded a mostly fictitious collective called the Generative Art Group (1972). Generative art as a form of geometric abstraction where basic elements are rotated, translated, and modulated in scale was practiced by the Argentinians Eduardo McEntyre and Miguel Ángel Vidal (Osborne 1981). The term has often also seen unrelated generic use. For example, Richard Serra has referred to some of his works as "generative" in the sense that they introduced a new basic form he would go on to use in a series of later works (Serra et al. 1980).

Critic Lawrence Alloway introduced the term "Systemic Art" when he organized the well-known exhibition *Systemic Painting* (1966) at the Solomon R. Guggenheim Museum in New York. He understood systemic art as a form of abstraction using simple standardized forms that are repeated on the basis of a clear organizing principle. Noland's series of chevron paintings, begun in 1963, would be a prime example. Alloway may have shifted his intended meaning closer to that of generative art when he also extended the term to process-oriented color field painting (Osborne 1981).

"Generative Systems" was introduced by Sonia Landy Sheridan as an academic program at the School of the Art Institute of Chicago in 1970. It was a response to the telecommunications and imaging technologies, but also political and pedagogical ideas, of the time. The hue shifts and distortions created by the color copier technologies that artists used at the time could be viewed as related to the understanding of "generative" here.

Beginning with the album *Discreet Music* (1975), musician Brian Eno popularized the term "generative music" with a meaning relatively consistent with "generative art" as it is used here. There was, however, a somewhat narrow focus on repeated note patterns, phase shifts, and tape loops that had already been introduced in the 1950s by composer Terry Riley, and further developed in the 1960s by composer Steve Reich.

The architect Celestino Soddu helped to popularize the use of the term "generative art" by creating the International Generative Art Conference in 1998. While the conference continues to invite all manner of opinion on generative art, Soddu's own definition leans toward a genetic approach that captures the aesthetic of the artist/programmer rather than leading in arbitrary directions. The original call for participation states:

> Generative Art builds possible worlds by creating evolutionary rules that produce events that if, on one side, they are unpredictable and amazing, from the other one they mirror the identity and recognizability of the idea, they are the natural representation of it. (Soddu 1998)

The encoding of an artist's vision as a system is certainly a valid approach to generative art, but it isn't the only valid one. In some cases, for example, the generative artist creates a system without a pre-existing vision of what the result should be. The artist then explores the system as a new territory and discovers treasures here and there along the way.

Complexity, Systems, and Generative Art

If the defining feature of generative art is the artist ceding control to an autonomous system, it is worth exploring whether a deeper understanding of systems can shed additional light on generative art. For a state-of-the-art view of systems we can turn to the field of complexity science where a revolution in systems thinking is taking place. But before doing that, some previous notions regarding systems, system complexity, and aesthetics should be considered.

20th-Century Notions of Complexity in Aesthetics

Birkhoff's aesthetic measure

In 1933 the mathematician George David Birkhoff proposed what he called the "Aesthetic Measure." With this measure he relates "aesthetic effectiveness" (M) to "the degree of complexity" (C) and "the degree of order" (O) using the formula M = O/C. The operationalization and application of this formula almost immediately turned out to be problematic. Nevertheless it was an interesting attempt in that, as Birkhoff points out, "The well known aesthetic demand for 'unity in variety' is evidently closely connected with this formula" (Birkhoff 1933).

What is often overlooked is that Birkhoff based his formula on what we would now call a (speculative) neuroaesthetic theory (Skov and Vartanian 2009, iv, 302). He describes complexity (C) as the degree to which unconscious psychological and physiological effort must be made in perceiving the object. Order (O) is seen as the degree of unconscious tension released as the perception is realized.

Shannon's information theory and the information aesthetics of Bense and Moles

While we have an intuitive sense of what we mean when we refer to a system as "simple" or "complex," it is not easy to develop a formal technical measure of complexity that corresponds well to our intuitive sense. Unrelated to Birkhoff, *information theory*, as an attempt to better understand communication systems, was developed by Claude Shannon in 1948. Shannon was interested in analyzing the capacity of communication channels, and one of his core ideas was that the more "surprise" a given communication exhibits, the more information it contains (Shannon 1948).

From the information theory view, a stream of characters consisting of just the letter "a" over and over again offers no information whatsoever. A stream of English-language sentences would offer considerably more variation and thus more information. The information density can be further increased, and redundancy reduced, via contractions and acronyms. Cell phone text messages such as "R U there" or "Don't B L8" are examples. Ultimately, a stream of totally random letters delivers the largest amount of information. It offers no redundancy and any attempt at compression will immediately result in an irreversible loss of content.

Abraham Moles combined these notions with findings from perceptual psychology in order to analyze the arts. Using various statistical measures, Moles showed how musical works exist on a spectrum from "banal" to "novel" corresponding to the relative order and disorder they exhibit as information (Moles 1966). In addition, he demonstrated how various forms of media can be thought of as the union of aesthetic possibilities in a high dimension space. For example, considering only pitch, a musical instrument has a single dimension. Adding loudness adds a second independent dimension, and so the possible states map into a two-dimensional space, that is, a plane. Given two such mutually independent instruments the entire media space requires four dimensions, that is, a hyperspace.

Around the same time Max Bense emphasized the notion of analyzing media space in terms of information theory, and then used it as the basis for what he called "generative aesthetics":

> The system of generative aesthetics aims at a numerical and operational description of characteristics of aesthetic structures (which can be realized in a number of material

> elements) which will, as abstract schemes, fall into the three categories of the formation principle, distribution principle and set principle. These can be manipulated and applied to an unordered set of elements, so as to produce what we perceive macro-aesthetically as complex and orderly arrangements, and micro-aesthetically as redundancies and information. (Bense 1971)

Following Shannon, both Moles and Bense equated high degrees of order with simplicity, and high degrees of disorder (i.e., randomness) with complexity. However, as much as information theory has its place in the analysis of communication channels, it does not correspond very well with our experiential sense of complexity in the world generally, or in art specifically. To the extent it equates complexity with disorder, information theory breaks down as a general model of our experience. This is where contemporary complexity science has fashioned a response in the form of *effective complexity*.

Effective complexity

Considered as a system, a crystal is made of atoms arranged in a highly regular lattice forming planes and facets. What emerges at human scale is a high degree of order that is easy to describe and easy to predict; in this sense, crystals seem simple. Because of their highly ordered nature any one crystal seems quite similar to others.

By comparison, molecules that make up the gas in our atmosphere could not be more different. As a system, gas molecules are in constant motion, each with a random direction and momentum, and they are all constantly bouncing off each other without any discernible structure at all. Nevertheless we experience gasses as simple systems at human scale. Gas is easy to describe and predict, and a cubic foot of air in one place seems no different than a cubic foot of air in another.

Things we think of as complex systems defy simple description and easy prediction. Many would agree that the most complex systems we encounter are other living things. Life requires a mix of order and disorder: order to maintain integrity and survival; and disorder to allow flexibility and adaptation.

It was this kind of intuition that led physicists Murray Gell-Mann and Seth Lloyd to suggest the notion of effective complexity (Gell-Mann 1995). As illustrated in Figure 5.1, Shannon's information complexity increases with disorder, but effective complexity peaks where there is a mix of order and disorder.

To underscore the contrast, where Shannon would consider white noise or a display of random pixels as being highly complex, Gell-Mann and Lloyd would likely point out that all white noise sounds alike and all displays of random pixels look alike, and as such we perceive them as having low complexity.

Effective complexity as a framework for generative art

Effective complexity introduces a paradigm where high degrees of order and disorder both create simple systems, and complex systems exhibit a mixture of both order and disorder (Figure 5.2). Given this understanding, we can classify forms of generative art as simple-ordered, simple-disordered, and complex systems. Going beyond classification, however, is the discovery that the history of generative art roughly follows the history of our culture's understanding and embrace of these different system types.

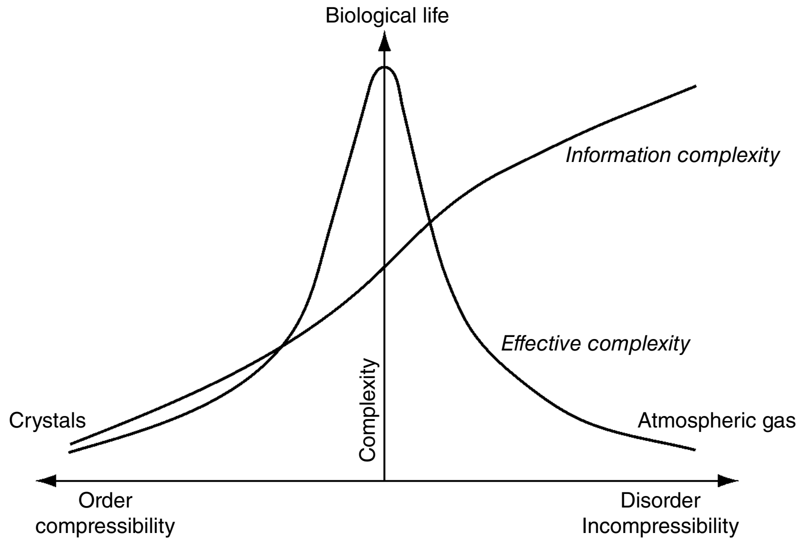

FIGURE 5.1 Order/disorder relationships for information complexity and effective complexity.

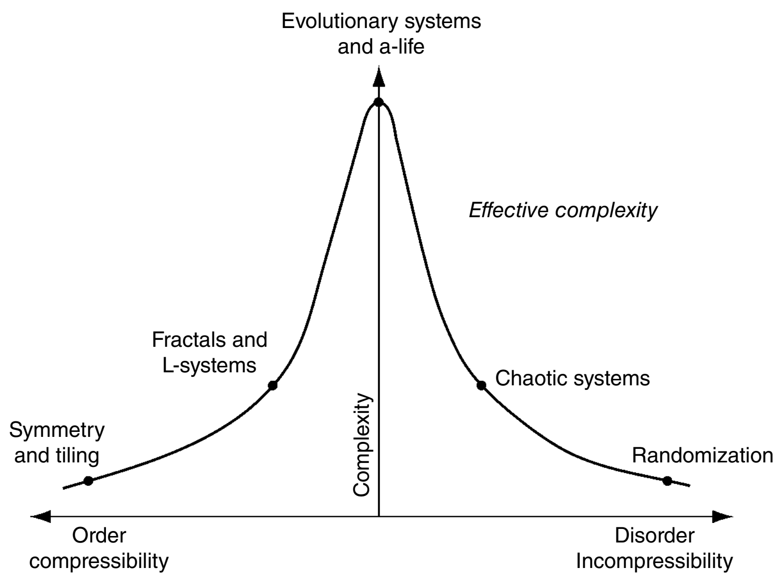

FIGURE 5.2 Systems used in generative art identified by effective complexity.

Highly Ordered Generative Art

Every time and place for which we find artifacts yields examples of symmetry, tiling, and pattern in art. These artifacts provide evidence that simple, highly ordered systems were the first systems applied to art (Hargittai and Hargittai 1994). As noted earlier, samples of generative art over 70,000 years old have been found (see Figure 5.3), establishing that generative art is as old as art itself (Balter 2002).

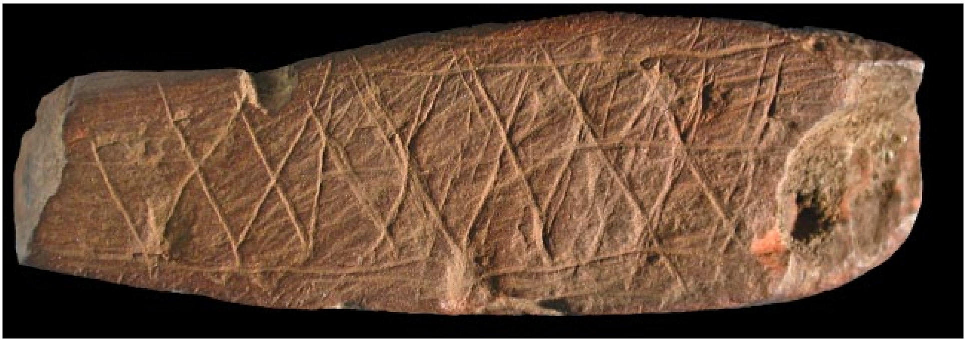

FIGURE 5.3 77,000-year-old generative art etched in red ocher. Photo courtesy of Prof. Christopher Henshilwood, University of Bergen.

Even though these objects are handmade, they qualify as generative because the placement of individual marks has not been decided by the artisan, but dictated by a manually executed symmetry-based algorithm. In principle, an algorithm-executing robot could, for example, tile a checkerboard pattern on a surface of any size using a single algorithm. Here, as pseudo-code, is the program the robot could execute:

```
Set current_position to the lower left corner
Set current_color to black
Do this until the area is full {
   Set saved_position to current_position
   Set saved_color to current_color
   Do this until the right edge is reached {
      Select tile of current_color
      Place tile at current_position
      Set current_color to the opposite of current_color
      Set current_position to one space to the right of current_position
   }
   Set current_position to saved_position
   Set current_position to one space up from current_position
   Set current_color to the opposite of saved_color
}
Done
```

The inner loop, the code indented the furthest and within the inner brackets, repeats the placement of alternating tiles to complete a single row of tiles. The outer loop, the code indented only once and within the outer brackets, repeats to create all of the needed rows. Similar code could be created to produce any regular tiling pattern.

Highly ordered systems in generative art have also appeared in innovative 20th-century art. M.C. Escher was a student of Islamic art and architecture and a popular 20th-century graphic designer. While lacking in formal mathematical training, he obviously had a significant understanding of the generative nature of what he called "the regular division of the plane." Without the use of computers he invented and applied what can only be called algorithms in the service of art (Escher et al. 1982).

As noted earlier, conceptual and minimal artists such as Carl Andre, Mel Bochner, and Paul Morgenson used simple mathematical systems to generate compositions. Sol LeWitt created combinatorial systems he would leave to others to execute as wall drawings. In his essay "Paragraphs on Conceptual Art" he famously offers what could double as a description of generative art by saying, "The idea becomes a machine that makes the art" (LeWitt 1967; Alberro and Stimson 1999; Meyer 2000).

Highly Disordered Generative Art

Compared to the use of highly ordered systems such as patterns and number series, the appreciation of highly disordered systems is a relatively recent pursuit. Prior to the 17th century, mathematics was thought of in the spirit of Platonic forms and Aristotelian logic; order, as opposed to indeterminacy and randomness, was considered a virtue. Chance occurrences were viewed as accidental, irrational, removed from reason, and perhaps even evil in the sense of lacking participation in the Logos. It was not until the 17th century that mathematical models for chance events were developed by Fermat and Pascal.

One of the earliest documented uses of randomization in the arts is often attributed to Wolfgang Amadeus Mozart, but music game systems similar to his were widespread in the 18th century, and the actual inventor is probably lost to the ages. Mozart's version begins with 176 snippets of prepared music. These are assembled in a sequential score based on the throw of the dice. It is interesting to note that the game uses a primitive way to mix order (the short pre-composed snippets) and disorder (the throw of the dice) (Schwanauer and Levitt 1993).

Chance procedures—that is, highly disordered systems—in the arts came into their own primarily in the 20th century. As a young artist, Ellsworth Kelly used inexpensive materials such as children's construction paper along with chance methods to create colorful collages. He was inspired by observing the random patchworks that would develop in the repair of cabana tents on the French Rivera (Bois et al. 1992).

The writer William Burroughs famously used a "cut-up" technique he borrowed from Brion Gysin to randomize his novels (Burroughs and Gysin 1978). Less well known are Burroughs's experiments in visual art using shotgun blasts to explode cans of spray paint, thereby randomly coloring, and partially destroying, plywood supports (Sobieszek and Burroughs 1996).

Certainly one of the most famous advocates for the random selection of sounds in music was John Cage. Cage also experimented with various chance methods to create fine art prints and musical scores (Nyman 1999). Carl Andre explored both order and disorder, often using highly ordered grids or stacks of serial objects, but occasionally a random spill of small parts (Meyer 2001).

While all of these artists used disorder as a system, each of them typically had a different reason for doing so. Mozart and his contemporaries apparently found novelty and rapid results to be amusing. Kelly was initially fascinated by the emergence of form from a process of random decay. Burroughs sought to uncover hidden meaning and probe the unconscious. Cage tried to help the listener experience a Zen acceptance of all sounds as being of equal value. Andre used both order and disorder as a minimalist strategy to achieve simplicity of composition and draw direct attention to the materials themselves.

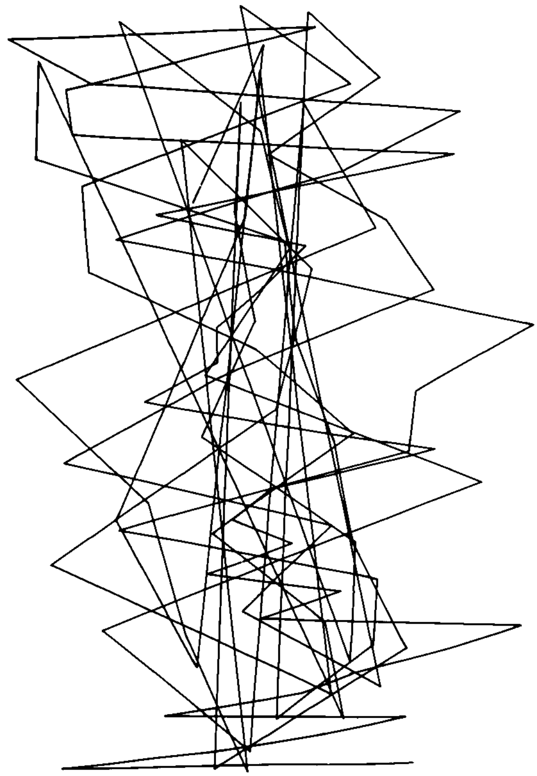

FIGURE 5.4 Michael Noll, *Gaussian Quadratic*, 1963. © AMN 1965.

Early computer artists such as Frieder Nake and A. Michael Noll used pseudo-random number algorithms to exploit disorder. Noll, in particular, attempted to simulate Mondrian's *Composition with Lines* (1917) by starting with a regular array of lines and then perturbing their size and position with random numbers. Noll was among one of the first algorithmic artists to add complexity to highly ordered systems of geometry by including disordered elements. In *Gaussian Quadratic* (Figure 5.4), horizontal positions are established using a Gaussian distribution of random numbers, while vertical positions are predictably fixed using quadratic equations (Benthall 1972; Bentley and Corne 2002).

The use of random numbers remains a mainstay of generative art among contemporary Processing artists/programmers and others.

Complex Generative Art

For most practical purposes, a crystal can be considered a highly ordered physical system and modeled with a simple formula of mass, velocity, and spin. A system of gases is highly disordered, but nevertheless can be modeled with a simple formula of volume, pressure, and temperature. For several centuries science and Western culture have been comfortable with both highly ordered and highly disordered simple systems. And during that time generative artists have used autonomous systems of both kinds.

A biological system, such as a frog, is complex and much more difficult to model. Combining order and disorder, a frog is ever changing and adapting. An attempt to model a frog's bodily functions, the tension of every muscle, the activity of every neural connection, and so on would be a very daunting task.

In recent decades scientists from diverse fields have been working together in a new way to create a novel multidisciplinary understanding of systems, with the founding of the Santa Fe Institute in 1984 serving as a significant milestone. Under the general rubric of "complexity science" and "complexity theory," various kinds of systems have been studied, compared, contrasted, and mathematically and computationally modeled. An abstract understanding of systems that spans the physical, biological, and social sciences is beginning to emerge (Waldrop 1992; Mitchell 2009). The very models of complex systems studied by these scientists are being used as state-of-the-art generative systems by artists.

Principles of complex systems

While both highly ordered and highly disordered systems remain legitimate choices for creating generative art, contemporary generative artists typically aspire to explore and exploit complex systems.

When scientists or knowledgeable artists speak of complex systems they do not mean systems that are complicated or perplexing in an informal way. The phrase *complex system* has been adopted as a specific technical term, or a term-of-art, so to speak. Complex systems typically have a large number of parts or agents that interact with others nearby. These local interactions often lead to the system organizing itself without any master control or external agent being "in charge." Such systems are often referred to as being *self-organizing*, and as exhibiting *emergent* behavior or characteristics that are more than what one would obviously expect from their parts. Complex systems often develop in ways that are dramatic, fecund, catastrophic, or so unpredictable as to seem random. They can also exist as systems in dynamic tension that remain balanced and relatively stable even as they exhibit constant change within.

Complex systems are often referred to as being *non-linear*. The term "non-linear" has multiple discipline-specific meanings that can confuse an interdisciplinary discussion. In the humanities non-linear can mean (1) disconnected, illogical, or irrational, or (2) having multiple narratives, or (3) having a viewer-driven interactive narrative, or (4) being a non-chronological presentation. In the context of complexity science, non-linearity references (1) mathematical expressions with exponential terms (e.g., "x^2") or (2) behaviors similar to the saying "the whole is greater than the sum of the parts," or (3) situations in which small continuous changes result in macro-level phase changes. Examples of the latter might include solid ice melting into liquid water with a slight increase in heat, or catastrophic material failure due to a slight increase in load.

Complexity science offers more than an incremental increase in scientific understanding. Traditional science uses *reductionism*, the hierarchical decomposition of phenomena into smaller simpler components to model, explain, and predict. Complex systems resist such analysis in that they present an emergent whole that seems to be more than the summation of the parts. Complexity science is revolutionary in that it reverses the top-down process of reductionism, and instead offers a synthesis of bottom-up processes.

Areas of application in the life sciences include evolution, brain function, animal societies, metabolism, and much more. More generally, complexity science impacts physics, chemistry, economics, meteorology, computer science, and other sciences. In that complexity science seeks to abstract an understanding of systems across all of these disciplines, the study of complexity is one of integration rather than specialization.

Complex systems often exhibit *chaos*. Chaotic dynamics are non-linear and difficult to predict over time, even though the systems themselves are deterministic and follow a strict sequence of cause and effect. The non-linearity of chaotic systems results in the amplification of small differences, and this is what makes them increasingly difficult to predict over time. This process is usually referred to as *sensitivity to initial conditions*. Sometimes it is called *the butterfly effect*, suggesting that the flapping of a butterfly's wings in Hawaii can result in a tornado in Texas.

Complex systems address issues of *scale* in that large numbers of smaller objects and transactions result in the emergence of a much larger phenomenon. Such systems frequently exhibit *feedback* in that a chain of influences will eventually affect the initiating component. Some complex systems are rather passive, but others, especially life forms, will exhibit *adaptation* in their behavior to preserve their integrity. These are often called *complex adaptive systems*. The hallmark of adaptation in life at the level of species is *evolution*, which also is one of the strongest complex systems applied to generative art.

Complex systems used in generative art

From the mid-1990s onwards, digital generative art has experienced a boom. This is in part due to the creation of easier-to-use, mostly open source, software environments such as Processing, Pure Data, Supercollider, vvvv, openFrameworks, Cinder, and Max.[4] More artists can now write their own programs without losing sight of their artistic goals in a sea of code. Beyond virtual systems, physical computing platforms such as the Arduino have empowered artists by giving them access to sensors, light displays, sound devices, motors, actuators, robots, and so on for reactive and interactive installations.

However, it is the new models offered by the study of complexity science that have been the primary engines behind contemporary generative art. For example, *fractals*—mathematical objects first discovered by Benoit Mandelbrot and exhibiting self-similarity at all scales—have been applied to generative art in the creation of abstract patterns as well as the simulation of natural objects such as clouds, riverbanks, mountains, and other landforms (Mandelbrot 1983). Fractal flames are a particular type of fractal that forms the basis for Scott Draves's network-based screen saver artwork the *Electric Sheep* (2005).

Somewhat related to fractals are *Lindenmayer systems*, also known as L-systems. L-systems are grammar based, using sets of axioms and production rules, and were originally invented to simulate branching structures in plants. L-systems have been applied to generative art in the creation of abstract patterns as well as 2D and 3D renderings of artificial trees, bushes, and flowers in stills and animations (Prusinkiewicz, Lindenmayer, and Hanan 1990). What fractals and L-systems have in common as systems is that they produce highly recursive and thus compressible forms. While they are more complex than the highly ordered patterns discussed earlier, there are other systems ranking higher yet on the complexity curve.

On the disordered side of the effective complexity curve are systems of *chaos*. Chaotic systems are deterministic but exhibit a non-linear sensitivity to initial conditions. While the long-term results of a chaotic system may be so unpredictable as to seem random, there is some short-term predictability. This bit of structure gives chaotic feedback systems greater effective complexity and less disorder than simple randomization.

Artists who have used chaotic feedback include early video artists Steina and Woody Vasulka. The Vasulkas created dynamic systems by creating a video signal loop where the camera is pointed directly into its own display (Vasulka and Vasulka 2001). In 1963—the year that Edward Lorenz discovered deterministic chaos in weather systems (Lorenz 1963)—Hans Haacke's *Condensation Cube* (1963–1965; initially titled *Weather Cube*) displayed similar deterministic yet unpredictable dynamics (Benthall 1972). The piece is a simple transparent acrylic plastic cube sealed with about one-quarter of an inch of water at the bottom. The ambient heat of the room evaporates the water, and then the water vapor condenses on the walls of the cube creating ever-changing chaotic patterns of moisture and running droplets.

Given the growing scientific understanding of increasingly complex systems, it is not surprising that generative artists are now addressing the most complex systems known to date, those of life itself. For example, *reaction-diffusion systems* simulate organic chemical reactions that produce their own catalysts with differing diffusion rates, and by doing so create patterns. Examples of such patterns found in nature include seashells and animal fur. The simulated process can also produce patterns similar to those found in materials such as marble. Because of this, reaction-diffusion systems have been used in the animation industry as well as for abstraction (Turk 1991). Reaction-diffusion systems are typically implemented by breaking a surface up into a fine digital grid, which provides a way of approximating chemical gradients with discrete values for each cell. Diffusion calculations are made at each border between two cells, and overall patterns emerge from these local interactions. This kind of calculation using a discrete grid is a specific elaboration of a general system type called a *cellular automaton* (Turing 1952).

Artificial neural networks, or more simply "neural networks," are inspired by nature's biological computer, the brain. Just as neurons establish networks where associations are created based on the strength of synapse connections, artificial neural networks use weighted virtual connections to associate various input patterns with corresponding output patterns.

Neural networks have been used in *agent-based systems* such as *artificial life* or *a-life* systems. A-life systems are essentially simulated ecologies with resources and virtual entities or agents that reproduce, compete for resources, and sometimes exist in predator/prey relationships. Artists such as Jon McCormack (*Eden*, 2000–2010) and the team of Christa Sommerer and Laurent Mignonneau (*A-Volve*, 1993–1994) have created installations presenting a-life worlds in aesthetically compelling formats.

The realm of *artificial intelligence* (AI) in art is more difficult to define or pin down. AI-based art is generally viewed as the attempt to create programs that apply a set of heuristics or codified rules of thumb gathered from human experts to create art. Well known in this area is Harold Cohen, a painter who in 1973 created *AARON*, a software application that functions as a drawing program and that he has continually updated for over four decades. Cohen has used *AARON* to produce work in a number of forms. He is perhaps best known for large canvases directly painted by robotic extensions under the control of *AARON* (McCorduck 1991).

Some a-life implementations include a genetic system as part of the reproduction activity, allowing generations of agents to evolve. The use of evolution is arguably the most popular and robust high-complexity system employed in contemporary generative art.

Evolutionary art, genetic algorithms, and the fitness bottleneck

Genetic algorithms and *evolutionary computing* are terms used for algorithms patterned after the reproductive mechanisms studied in biology. In industry, genetic and evolutionary techniques are used, for example, to design optimal electronic circuits, aircraft wings, investment strategies, telecommunications routing, encryption methods, and computer games. In general, genetic and evolutionary approaches provide a way to search a large space of possible solutions with greater efficiency than mere random trial and error (Fogel 1999).

In biology the *genotype* is a collection of DNA, sometimes referred to as the "code of life." The *phenotype* is the collection of resulting features and characteristics such as blue eyes, curly hair, gender, and so on. As implemented on a computer, the genotype is a data structure that provides input into an algorithm that then produces the phenotype as a simulated result. The genetic system makes progress by making random changes to genotypes selected from the gene pool, discarding those new genotypes that do not constitute an improvement, and further breeding genotypes that do. This process is done over and over again for many generations allowing increasingly strong phenotypes to emerge from the gene pool (Bentley and Corne 2002).

"Improvement" here is relative to a *fitness function* that captures the design aspects to be optimized. In the case of an airplane wing, the fitness function might seek to maximize lift and minimize weight. In the case of an investment strategy, the fitness function might simply be the estimated profit for a given genotype. Because the evolutionary process is completely automated, optimal solutions can be rapidly approximated by using gene pools with many dozens of competitors evolving for hundreds of generations.

The difficulty for artists using evolutionary systems is that we don't have algorithms for judging aesthetics, and thus we can't code robust aesthetic fitness functions. While there have been attempts at automation, the typical solution to this challenge involves putting the artist back in the loop to manually score each new phenotype. This means the system is no longer entirely automated, and that places a severe upper limit on both the size of the gene pool and the number of generations that can be run. This inability to computationally measure aesthetic quality, thus slowing the entire evolutionary process by orders of magnitude, has been referred to as the *fitness bottleneck* (Todd and Werner 1998).

William Latham arguably created the first computer-mediated evolutionary art in the early 1990s. Initially the results took the form of large digital prints of biomorphic forms reminiscent of insect larvae or crustaceans (Todd and Latham 1992). Later work included animations, video installations, and software for personal computers. Around the same time Karl Sims produced mathematically based abstract images and animations. He went on to evolve plant-like forms for representational animations, as well as virtual creatures that combined genetics, neural networks, and simulated physics to achieve various locomotion goals. In his piece *Galapagos* (1995) the audience provides a fitness function by standing on a sensor pad in front of the display showing the evolutionary form they prefer (Sims 1991, 1994, 1997).

In subsequent years evolutionary techniques proved to be useful despite the lack of automated fitness functions. Since these techniques are a general approach for exploring a design space they can be combined with other generative systems. Updating Sims's gallery-bound approach in *Galapagos*, Draves's piece *Electric Sheep*, for example, gives each user the opportunity of choosing their favorite screen saver on their own computer. These preferences are gathered over the Internet, and the fitness function is effectively crowdsourced (Draves 2005).

Artists continue to experiment with ways to break the fitness bottleneck. Following in the footsteps of Birkhoff's aesthetic measure, Machado and Cardoso's *NEvAr* system uses computational aesthetic evaluation based on a ratio of complexity measures acting as a fitness function[5] (Machado and Cardoso 2005). Todd and Werner were early adopters of a co-evolutionary approach to music composition (Todd and Werner 1998). By using separate populations of critic agents and composer agents, they enabled a consistent aesthetic to emerge in the simulated culture. However, they found that, while the evolved aesthetic was consistent, it in no way reflected or appealed to our human sense of aesthetics. This same result has been observed in other cases of emergent aesthetics as well.

Problems in Generative Art Theory

In the following we will consider a series of problems in generative art theory. These are not problems in the sense that they require single correct solutions, but rather are questions that the artist will want to consider when making a piece; that critics and historians will typically address in their analysis; and that insightful audience members will ponder. They are problems that typically offer multiple opportunities and possibilities.

It is notable that, for the most part, these problems equally apply to both digital and non-digital generative art; to generative art past, present, and future; and to ordered, disordered, and complex generative art. In addition, these same problems or questions are trivial, irrelevant, or nonsensical when asked in the context of non-generative art. The fact that our systems-based definition of generative art includes art with a common set of problems, and that those same problems don't apply to non-generative art, can serve as evidence that the definition is meaningful, effective, and well formed.

The Problem of Authorship

How do traditional views of authorship shift regarding credit, expression, and provenance?

When someone first encounters digital generative art a commonly asked question is "Who is the artist, the human or the computer?" On a more sophisticated level, many see a resonance with poststructuralist thinking on authorship when faced with an artwork that has been created without any human intuition or real-time judgment involved. Some artists in the field of generative art work specifically in the vein of problematizing traditional notions of authorship. In describing the ironic software artwork/application Auto-Illustrator (Ward 2000–2002) Ward and Cox quote Barthes, Foucault, Benjamin, and others to contextualize what they see as the breakdown of the heroic author of modernity (Ward and Cox 1999). Shifting emphasis a bit, McCormack et al. (2014) question the relationships between authorship and agency, creativity, and intent, which are all problematized in generative art but taken somewhat for granted in non-generative art.

Over the past few decades, a significant portion of humanities discourse, and specifically art discourse, has focused on poststructuralist notions such as the "death of the author." In generative art, the author apparently is a machine, so that the art appears to be the reification of poststructuralist theory. Some have gone so far as to suggest that the primary function of generative art is to destabilize notions of authorship. This certainly is an option but, surveying the field, one that is exercised only by a modest subset of artists in the field.

The problem with this authorship-focused view of generative art, and with the poststructuralist critique in general, is that shifting the production of meaning toward the reader rather than author comes at a huge cost. Taken literally and in good faith, this view purports to remove the possibility of art, or even simple speech, as a means of effective communication. History and anthropology show that this cost has, in fact, not been exacted. Communication and its advancement must be possible, or we would never have progressed beyond grunts and hand gestures as a species. More pointedly, if some poststructuralist theorists believed that communication from author to reader ultimately would be impossible, they would not have bothered to publish their work.

Pushing the reader—the audience—to the front of creating meaning in art is to ignore the obvious. For centuries art has acted as a powerful binding force that brings people together, transmits culture from generation to generation, creates common understanding and experience, and provides visions for the future.

Related issues emerge with the question whether computers can be truly creative agents, and generative art requires more subtle variations to that question. In the case of Latham or Sims, for example, the artist and audience can make choices, but only among alternatives created by the computer. To what extent does such selection confer authorship? In most art discourse since Duchamp selection is considered a form of authorship. In cases where works wholly emerge from the computer some might find the answer to be more difficult.

Non-generative art, on the other hand, suffers no such ambiguity. There is no doubt that Leonardo and not his paintbrushes created the Mona Lisa. The problem of authorship for generative art, digital or otherwise, is quite different.

The Problem of Intent

Why is the artist working with and ceding control to generative systems?

Described as a systems-based way of making art, the term "generative art" says something about *how* the artist creates the work, but little about *why* the artist has chosen to work that way. As noted in a previous section, many artists have used randomization, but for different reasons. Cage used chance procedures as a Zen strategy to remove attachment to particular sounds; Burroughs as a Dada-esque method for unleashing the unconscious; Kelly as a simulation of the creation of form by natural entropic forces.

Looking across the long history of generative art, or the relatively short history of digital generative art, there seem to be as many reasons for embracing the generative approach as there are artists working that way. Nevertheless, there also are some notable clusters of use and motivation.

Across cultures from antiquity to the present, the use of highly ordered systems, such as symmetry and tiling, has provided ways to achieve design consistency in space and time. Such designs can be handed off to artisans for construction. For large-scale, labor-intensive practices such as architecture this is of great practical value. In addition, the ability to pass on essentially algorithmic patterning methods allows for the creation of inheritable cultural identity as abstract form. Anthropologists, for example, are now able to identify specific artifacts as belonging to particular peoples by analyzing the abstract mathematical symmetry group membership of the decoration (Washburn and Crowe 1988).

In a contemporary context the artistic intent behind generative strategies is highly varied. In the effects and animated film industry, generative methods are purely pragmatic. The creation of forests or crowd scenes by means of generative techniques is much less expensive than modeling and animating each tree or character individually by hand. Some artists exploit generative systems for similar reasons.

For some practitioners the technical generative system itself is the object of interest. These artists will tend toward a *truth to process* aesthetic where the work is presented in a deconstructed format seeking to minimize the gap between the mechanism of creation and the resulting artifact. In a fully realized scenario, LeWitt's dictum is extended to the point where a machine does not only make the art, a machine *is* the art.

For yet others it isn't the literal system used that is of interest, but rather systems found in nature that become sources of inspiration. Some artists, for example, use genetic algorithms and evolutionary computing because they have an interest in actual biological genetics and evolution. The artworks provide aestheticized simulations with the hope of re-presenting the natural world in a way that reinvigorates awe and reinforces the understanding of that world.

Another group of artists has mathematical interests that lend themselves well to generative interpretation. Yet others want to turn control over to computers to illustrate social, cultural, or even engineering implications of the technology.

Perhaps one of the most common motivations behind the use of generative systems is that they can surprise the artist and provide a springboard for novelty and new ideas. As advances in this mode are made, the computer will move closer to becoming a true collaborator of the artist. There is no single or correct intent behind generative art practice. But any thoughtful artist or critic working in the area of generative art will want to address the problem of intent on a case-by-case basis.

The Problem of Uniqueness

Does it diminish the value of the art when unique objects can be mass-produced?

Whether in the context of market value or cultural value, traditional works of art have been treasured as unique and thus rare objects. Walter Benjamin declared art made through mechanical reproduction, such as printmaking and photography, to have a diminished "aura." Today the ability to produce endless copies has found its fullest fruition in digital media. The dematerialization of the work along with Internet distribution makes duplication essentially a free process.

Digital generative art introduces a completely new problem: rather than offering an endless supply of *copies*, it provides an endless supply of *original and unique* artifacts. The apparently oxymoronic phrase "mass-produced unique objects" in fact describes the reality of generative art. The art can take the form of prints made using digital giclée technology, and the possibility of an endless supply of monoprints on demand is real. 3D printing technologies that turn data into physical objects are quickly improving in quality. It is already possible for artists to create unlimited numbers of singular and unique sculptures, and quality of construction will improve over time.

Some artists may choose to address the paradox of mass-produced unique objects by making it a content issue in their generative art. However, even if it is not an overt part of the content of a piece, the issue of uniqueness in generative art deserves the attention of critics and artists.

The Problem of Authenticity

Given that it is in part created by an unemotional and unthinking system, is generative art really art at all?

The question as to whether generative art is art at all mostly tends to be raised by those not familiar with digital art, and results in a discussion that runs directly into the "What is art?" question.

In an earlier section a number of theories on art were noted. Generative art can certainly fit within the older theories of art that emphasize form or viewer experience. It is only partially compatible with the theory of art as representation, which excludes a great deal of non-generative modern art as well. Generative art can comfortably fit within the contemporary theories of art surrounding social construction and based on family resemblance, the notion of art as institution, or historical definitions.

The type of theory that sees art creation as a function of expression is the one most problematic for generative art. Can it be claimed that a computer can and will express itself? Alternatively, when the computer determines forms not anticipated by the artist, does its creation still qualify as the artist's expression? This is where the fact that digital generative art is part of the long history of generative art can assist. It is useful to point out that the unanticipated results generated by Cage's and Burroughs's use of randomization are generally accepted as being artistically expressive. In a similar way digital generative art, however unpredictable, can also be considered expressive.

The Problem of Dynamics

Must generative art change over time while being exhibited to an audience?

Some people have argued that truly generative art must exhibit change over time, and that static artifacts created by using generative systems outside the view of the audience do not qualify as generative.[6] If the display of dynamics is turned into an absolute requirement it conflicts with a broader systems-based definition or theory of generative art. Given that generative art exhibiting dynamics in real time is a relatively new development, generative art theory is better served by positing that some generative art is dynamic and some is not.

A more salient question is whether dynamism in generative art is an especially powerful choice at this particular time in generative art history. As noted earlier, truth to process in generative art that explicitly addresses the generative process can be quite powerful, and the literal display of system dynamics surely is truth to process in action.

Ultimately there are many reasons why an artist might take a generative approach. Again, the use of generative systems in the film and animation industry is largely pragmatic, and the generative results are "frozen" once realized. Given the artistic goals of filmmaking, this is entirely valid. Whether a given piece is better served by displaying dynamics remains a question to be considered by artists, critics, and audience members on an individual basis.

The Problem of Postmodernity

Is generative art an unavoidably postmodern approach to art?

It has been suggested that digital art, and especially digital generative art, embodies a postmodern attitude and intrinsically addresses postmodern concerns. Part of this argument is built on the convolution of the previously addressed postmodern and poststructuralist ideas about authorship. As first noted by Burroughs and then popularized by performance artist Laurie Anderson, the notion of language as a virus takes on new, multivalent meanings in the context of computer languages and computer viruses.[7]

Due to its use of complexity models as creative engines, digital generative art can also be seen as addressing the realm of simulacra. Artworks that essentially are artificial life environments —complete with competing agents, limited resources, layered information, and evolutionary change—seem to be the reification of concepts on simulacra and simulation offered by Baudrillard (1994). Authors such as Margot Lovejoy are quite explicit their postmodern contextualization of not only digital art regardless of the artist's intent, but of purely technical infrastructure such as computer operating systems also independent of the programmer's intent (Lovejoy 2004).[8]

However, digital generative art can also combat what other artists view as postmodernity's deficits. Postmodern art typically abandons the pursuit of formalism and ideals of beauty as meaningful activity. It practices radical skepticism toward the use of art for revealing non-relativistic truths. At most, postmodern art addresses beauty and truth from an ironic distance, seeing them as naïve pursuits to be left behind.

Generative art can counter these positions head on. First of all, artists creating generative work can explore form as something other than social convention. Using complex systems they can produce form that emerges as the result of naturally occurring processes beyond the influence of man and culture. Most would agree that water was made of two parts hydrogen and one part oxygen long before man was present to say so. Similarly, reaction-diffusion systems, evolution, and all the other systems leveraged by generative art operate autonomously in a way independent of man and human influence. These systems would exist whether or not man existed, and currently operate in places where man has never been. Generative art can establish beauty as something that is not man's arbitrary creation, but rather an expression of universal forces.

Second, artists on that basis can demonstrate, by compelling example, reasons to maintain faith in our ability to understand our world. They can remind us that the universe itself is a generative system, and generative art can restore our sense of place and participation in that universe.

Ultimately, generative art per se is ideologically neutral. It simply is a way of creating art and any content considerations are left to a given artist. After all, generative art is prehistoric and precedes modernism, postmodernism, and every other "ism" on record. Nevertheless, the postmodern condition continues to interest some artists and critics in the realm of generative art, and it serves as a platform for extending, not ending, that discussion.

The Problem of Locality, Code, and Malleability

Is the art in the object, the system, the code, or something else entirely?

Digital generative art raises the question as to where the art resides—that is, its ontological status. For some people, generative art is like all other art, and, to the extent there is an object or event, the latter determines where the art resides. Others, however, prefer to demote the object or event to by-product status, and see the generative system itself as the art. Still others will insist that the code itself is the art.

These debates are not new or unique to digital generative art. Consider, once again, Sol LeWitt's wall drawings. LeWitt would write up instructions, and then different assistants might draw different renderings of the same instructions in different places at different times. One could speculate as to where the art is. Is it the piece of paper upon which LeWitt typed the instructions? Is it the abstract words that might be delivered in different materialities? Is the art in fact the drawing on the wall? Or is the art the union of all these things?

An additional twist, and arguably a new paradigm, has been created with the advent of art as open source software. The first step was that artists doing generative work freely shared their creations as executable applications. This allowed anyone to download the work and run it on a personal computer. Typically the software would not create another object, such as a printout, but would directly display graphics and perhaps generate sound right on the user's computer. Sharing artwork has always been an option, but in this case everyone and anyone could have a personal copy of the work.

The next step was that some artists chose to also share their actual source code. This allowed other artists and programmers to download it, make their own modifications, and then release variations of the original artwork. This type of creative approach breaks with the paradigm of the heroic single artist creating a "fixed" masterpiece. It creates a process where multiple artists evolve an ever changing and growing family of related artworks over time.

Despite the vagaries of making such work economically viable, a number of artists have embraced this new, radically open source, production paradigm, using free sharing hosts such as github.com. The malleable, non-physical nature of code makes such an approach possible while it would not be an option with traditional media. Yet there is no requirement for artists to work this way, and the generative approach provides multiple options rather than dictating any avenues for creativity.

The Problem of Creativity

Are generative systems creative? What is required to create a truly creative computer? Philosopher Margaret Boden has suggested that "Creativity is the ability to come up with ideas or artifacts that are new, surprising, and valuable" (Boden 2004). Most people would agree that digital generative art systems, and generative art systems in general, do not have ideas in a sense that implies consciousness. However, successful generative art systems commonly create new and surprising artifacts. The question of value is yet something else. As discussed in the context of the fitness bottleneck, the assignment of value to the results of generative art systems for the most part requires human judgment.

A reasonable prerequisite for a generative system to be deemed truly creative is that it exercise critical evaluation discriminating between high- and low-quality art. Moreover, the system should be able to modify its own behavior to create more of the former and less of the latter. Unfortunately, computational aesthetic evaluation remains a fundamentally unsolved problem.

In other writings, I have suggested a notion of creativity that can apply to both conscious and unconscious systems (Galanter 2009). In complexity science, systems are deemed to be *adaptive* when they modify their structure or behavior to maintain their integrity in response to changes in the environment. For example, when a beehive is damaged by the weather, the behavior of the inhabitants will shift to either repairing the physical hive, or moving to an entirely new physical hive. This adaptation is an emergent behavior of the social hive that arises from the local interactions of individual bees. Creativity can be viewed simply as the difference between merely complex systems (e.g., the weather) and *complex adaptive systems* (e.g., a beehive.)

A possible objection is that the relatively simple adaptations of bees are already implicit in the overall natural system's structure, which comprises instinctive behavior, and that the invention required of creativity is therefore lacking in the case of the hive. But one can raise the question whether, when compared to the creativity of the human mind, this is a difference in kind or simply a difference in degree. While there may be hive-keeping instincts inherited by the bees, they still have to respond to the physical specifics of the given situation. Every detail, and every response needed, cannot be preprogrammed. In a similar way, the creativity of the human mind is probably already implicit in the structure of the brain despite the apparent inventiveness of individual creative acts. Perhaps both consciousness and creativity can be viewed as emergent properties of complex adaptive systems, and indeed both seem to be in rough proportion to the complexity of the underlying system.

Boden takes pains to differentiate between ideas that are new to the person inventing them, and ideas that are new to the entire world or society. These are the products of what she calls p-creativity and h-creativity, with p- standing for "psychological" and h- standing for "historical" (Boden 2004). This distinction is less about the actual mechanism behind creativity, and more about the social response to the product of creativity. All creativity is in a sense the result of p-creativity. However, some products qualify for the distinction of being h-creative if they are unprecedented in history.

The Problem of Meaning

Can and should generative art be about more than generative systems?
By now it should be obvious that one advantage of defining or theorizing generative art as simply a way of making art is that it maximizes the possibilities for the artist. In artistic practice one can find all manner of intent and meaning in both digital and non-digital generative art.

The above discussion of the problem of intent mentioned a number of possible meanings for generative art. For example, highly ordered systems can create meaning in the form of symbolic markers of cultural identity. By using a generative system design consistency, and thus identity, is ensured across the society. Note, however, that while the result has symbolic meaning, it is not a comment on the particular system used or the general notion of generativity.

A generative system may simply be pragmatic and also create products without intrinsic meaning. It was previously mentioned that in the creation of an animated film, having the modeling department create hundreds or thousands of trees by hand for a forest scene would be very time consuming. It is much less expensive to use an L-system-based generative system to automatically create as many trees as needed. However, the audience will never know L-systems were used, and the film is not "about" generative systems as such, nor is it even about trees.

A piece like Haacke's *Condensation Cube*, however, is indeed about the very generative system it is. The system used doesn't create an independent object for presentation. The system itself is what is put on view. Elsewhere, many artists are unapologetically abstract and formal in their generative practice, seeking only to reinvigorate the sublime and instill a sense of awe. Others may attempt to deliver political opinion, social commentary, religious inspiration, or indeed any meaning humanly imaginable.

To the extent that some generative art is about generativity itself, the notion of *truth to process* deserves a bit more discussion. Past art movements have promoted the notion of "truth to materials." In the context of formalism, it was believed that the most powerful aesthetic would reside in presenting the essential nature of the medium, and that doing so would deliver the purest distillation of significant form. Applied to architecture, this meant that concrete was presented as concrete, and steel beams were revealed as steel beams. For Clement Greenberg, paintings as simulated windows into illusory space presented a compromised formal aesthetic (Greenberg 1986). It was paint on a flat finite support presented purely as paint that harnessed the medium's true form and essential power.

Most artists producing generative work begin with an idea of what the final result might be, or at least what final result might be desired. They then take a top-down rather than bottom-up approach, creating systems that will conform to and yield their preconceived notion. This imposes a teleology that does not exist in natural systems, and does so even though the art is supposed to be inspired by natural systems. One conclusion would be that this imposition of top-down teleology introduces a kind of conceptual incoherence.

A pure truth-to-process approach would be radically bottom-up. The system, whether digital or not, would begin with low-level functions, and these would be assembled to interact and begin a process of complexification building up across multiple scales and levels of emergence. Generative art created in the spirit of truth to process would not obsess about intended form working toward a final object. There would be no intended form, and formal aspects of the final object would be important only in so far as they reference the processes that created them. The art would give the audience a sense of dynamism and offer the generative system itself as the expression of aesthetics. Working this way would move attention away from objects to processes, and from nouns to verbs. It would embrace dynamism over formalism, celebrate the aesthetic of creation as an activity, and posit truth to process as being intrinsically beautiful.

The Future of Generative Art

Computational Aesthetic Evaluation

The notion of computational aesthetic evaluation has been referenced here a number of times, and a reasonably detailed discussion would require at least another chapter (Galanter 2012).[9] But it seems safe to say that if it is a large step from the hand tools of digital art such as Adobe Photoshop™ to the generative art of complex systems, it will take a bigger leap to advance from generative art to systems capable of self-criticism.

Relatively simple formulaic approaches such as Birkhoff's aesthetic measure, the Golden Ratio φ, the Fibonacci series, Zipf's law and related power laws, as well as others have proven to be at best supplemental rather than definitive. The information-theory-inspired *generative aesthetics* of Bense and Moles have proven to be more descriptive than normative. Attempts to create automated fitness functions for evolutionary systems, such as Machado and Cardoso's use of compression-related complexity measures in their *NEvAr* system, have proven to have some limited success, but it is questionable whether such approaches generalize well (Galanter 2012).

Some artists have suggested that a better understanding of the psychology of art and aesthetics could yield models for computational aesthetic evaluation. Years ago Rudolf Arnheim applied principles of *gestalt psychology* such as the *law of pragnanz* to the realm of aesthetic perception (Arnheim 1974). Both Daniel Berlyne's *arousal potential* model and Colin Martindale's neural network model of *prototypicality* are suggestive (Berlyne 1971; Martindale 2007). However, none of these has yet inspired the creation of actual software. The nascent field of *neuroaesthetics* aspires to model aesthetic experience from the bottom up starting at the level of basic neurology. Those with a complexity-science turn of mind are optimistic as to where neuroaesthetics might lead, but so far there again have been no practical results applicable to generative art.

However, despite the apparent difficulty in solving the problem, the attempt to move digital art beyond the raw generativity of the computer to something more like an aesthetically critical artificial intelligence is too compelling a goal to ignore. While success cannot be guaranteed, work is sure to continue.

Generative Art after Computers

Generative art is a way of creating that is technology-agnostic. And just as the first generative art long preceded the computer, it seems inevitable that technologies subsequent to computers will be used to make generative art. Some have suggested that computers represent a kind of "final" technology since they can simulate any other machine or process, past or future. The problem with this suggestion is that simulations only exist in the virtual reality of the computer, and not in the physical reality in which people actually live, work, and play. A significant practical challenge for digital art has always been that of "output," meaning, how the remarkable virtual creations within the computer can be made compelling in the "real" world.

Future generative art technologies are likely to provide new physical possibilities. In fact, some of these are already appearing on the horizon and coming within reach of artists. Synthetic biology, for example, draws lessons from life science to create new organic systems typically starting at the level of DNA sequencing and synthesis. Existing DNA can be used and modified, and new DNA can be built from scratch. Projects such as the BioBrick initiative (Ginkgo Biolabs 2012) can now provide standardized DNA sequences as building block components that can be incorporated into living cells such as E. coli, creating new forms of biology not found in nature.

Some indication of what the future may bring is offered by the E.Chromi project at Cambridge University (iGem 2009). Researchers there genetically engineered E. coli to create biological machines that can sense various chemicals and then synthesize pigments of various colors. A practical application is the creation of easy-to-use tests for environmental hazards. For example, one strain might detect arsenic in ground water and produce a red pigment when it is found. Another strain might detect mercury and produce green pigment.

One can imagine future generative art where, for example, dynamic murals are made by painting thin layers of living cells on the wall. These cells would detect each other, exhibit non-linear dynamics, and self-organize, creating emergent patterns of color. Unlike Eduardo Kac's *Specimen of Secrecy about Marvelous Discoveries* (2006), consisting of framed assemblages of pre-existing living organisms, future bio-art pieces will be created by artists sequencing custom DNA and programming new organisms not unlike the way current digital artists program computers.

Also of growing interest to generative artists is nanotechnology and technology at other tiny scales. This includes *nanomachines*, molecule-sized machines 10^{-9} of a meter in size, *micromachines* 10^{-6} of a meter in size, and *millimachines* that work at the (10^{-3}) millimeter scale. Nano-, micro-, and milli- technologies are currently very broad areas of intense technological development.

One application area ripe for radical miniaturization is that of robotics. It has been speculated that developments in this area may one day lead to the creation of self-assembling materials. Imagine, for example, a sand-like material where grains sense, communicate, and navigate and move across each other. Such grains could then bond, creating emergent 3D shapes at human scale capable of locomotion and shape-shifting.

A number of much larger self-assembling robots have already been created. Examples include the Swarm-bots of Gross et al. (2006) and, more recently, the coin-sized smart pebble robots of Gilpin and Rus (2010, 2012). The pebble robots are capable of a kind of swarm intelligence. For example, when a large number of smart pebbles surround another object, they can cooperate to infer that object's shape, and then copy it by inducing yet other smart pebbles to bond in that shape.

It is not a great leap to imagine generative art sculptures that are in constant flux, perhaps even taking on the forms of the visitors that come to see them. But new forms of generative art appearing on the horizon aside, it is virtually certain that digital generative art is here to stay. Like art in general, generative art proceeds by a process of addition, not substitution.

Notes

1 Some of the web sites for popular (mostly) open source software used to create generative art include:
- Processing, a development environment and online community: http://processing.org
- OpenProcessing, an additional resource for Processing users: http://www.openprocessing.org
- Arduino, an open source electronics prototyping platform: http://arduino.cc
- Pure Data, a visual programming language for music, sound, and performance: http://puredata.info
- Cinder, a professional-quality creative coding library for C++ users: http://libcinder.org
- openFrameworks, an open source C++ toolkit for creative coding: http://www.openframeworks.cc
- vvvv, a multipurpose toolkit for media environments, graphics, video, and audio: http://vvvv.org
- Supercollider, a real-time audio synthesis and algorithmic composition language: http://supercollider.sourceforge.net
- Max is a commercial visual programming language for music, sound, video, installation, and interactive art applications that is both easy to use and powerful: http://cycling74.com/products/max/.

All accessed January 15, 2015.

2 Grasshopper is a graphical algorithm editor that allows users to add generative systems to 3D models created with Rhino. Additional information can be found at these web sites:
- Grasshopper: http://www.grasshopper3d.com
- Rhino: http://www.rhino3d.com.

3 The interest shown in this theory is greatly appreciated. In late 2013 the Google Scholar tracking service listed over ninety published academic articles and papers citing the original paper (Galanter 2003). Further, there are dozens of citations of articles I've written further developing this view. In addition references can be found in a number of books, online magazines, dozens of blogs and online education resources, and assorted artist statements, gallery guides, and conference calls for participation.

4 See note 1.

5 A full technical explanation of their computational aesthetic evaluation approach is beyond the scope of this chapter. However, Machado and Cardoso (2002) note in their article:

> Our point of view is that the aesthetic value of an image is connected with the sensorial and intellectual pleasure resulting from its perception. It is also our belief that we tend to prefer images that are, simultaneously, visually complex and that can be processed (by our brains) easily. […]
>
> We won't try to justify our beliefs about aesthetics, basically because we lack sufficient experimental evidence to support them. We will, however, present the formula that we currently use to automate fitness and the experimental results achieved so far.

In brief, they use the degree to which a given image can be compressed using jpeg methods as a proxy measure for image complexity. In addition, they use the degree to which the same image can be compressed using fractal methods as a proxy measure for the cognitive complexity involved in the brain processing the image. They posit that our experience of aesthetic quality will be roughly proportional to the ratio of image complexity to processing complexity.

6 Although the various points of view summarized in this chapter can be found in the publications cited here, I encountered many of them first in the online community of generative art enthusiasts on the e-mail list called eu-gene. The debate regarding dynamism as a requirement for generative art was just one point of active debate among many. With the growth of generative art from a niche to a popular practice in computer art, the forums for generative art discussion have multiplied, and eu-gene activity has somewhat diminished. It is, however, still active, and can be joined at http://generative.net/read/home. I remain indebted to the eu-gene list for many years of stimulating discussion.

7 The famous supposed Burroughs quote that "Language is a virus from outer space" may, in fact, be apocryphal. Sometimes attributed to his novel *The Ticket That Exploded* (1962), the quote cannot be found in the text but similar ideas are exercised there. One related passage is this example:

> From symbiosis to parasitism is a short step. The word is now a virus. The flu virus may have once been a healthy lung cell. It is now a parasitic organism that invades and damages the central nervous system. Modern man has lost the option of silence. Try halting sub-vocal speech. Try to achieve even ten seconds of inner silence. You will encounter a resisting organism that forces you to talk. That organism is the word.

Using Google's textual search engine (http://books.google.com) the precise quote cannot be found in that novel, nor can it be found in the other two novels from the Nova trilogy, *The Soft Machine* and *Nova Express*, or for that matter his other best known novels *Queer, The Naked Lunch,* and *Junky*.

Precisely quoted or not, Burroughs's notion of language as a virus was picked up by Laurie Anderson in her song of the same name from her performance art piece *Home of the Brave*. Burroughs was prescient in his anticipation of the notion of the meme.

8 The cited book was first published as *Postmodern Currents: Art And Artists in the Age of Electronic Media* and both freely associate not only generative art, but essentially all new media and electronic art, with the umbrella of postmodern and poststructural theory. For example:

> George Landow, in his Hypertext: the Convergence of Critical Theory and Technology demonstrates that, in the computer, we have an actual, functional, convergence of technology with critical theory. The computer's very technological structure illustrates the theories of Benjamin, Foucault, and Barthes, all of whom pointed to what Barthes would name "the death of the author." The death happens immaterially and interactively via the computer's operating system. (Lovejoy 2004)

9 The problem of computational aesthetic evaluation appears to be as difficult as any in the field of artificial intelligence. It calls into play concepts from mathematics, philosophy, computer science, art theory, design practice, psychology, neurology, and more. At the time this text was written, my cited chapter (Galanter 2012) provided the most comprehensive chapter-length overview of the topic available. Included are all the

aspects briefly mentioned here, including formulaic approaches, variations of evolutionary computing, the work of psychologists such as Arnheim, Berlyne, and Martindale, the nascent field of neuroaesthetics, empirical studies, and more.

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