Complex Beauty

Massimo Franceschet

Department of Mathematics and Computer Science, University of Udine
Via delle Scienze 206, 33100 Udine, Italy

Complex systems and their underlying convoluted networks are ubiquitous; all we need is an eye for them. They pose problems of organized complexity that cannot be approached with a reductionist method. Complexity science and its emergent sister network science both come to grips with the inherent complexity of complex systems with a holistic strategy. The relevance of complexity, however, transcends the sciences. Complex systems and networks are the focal point of a philosophical, cultural, and artistic turn of our tightly interrelated and interdependent postmodern society. I argue that complex systems can be beautiful and can be the object of *artification*—the neologism refers to processes in which something that is not regarded as art in the traditional sense of the word is changed into art. Complex systems and networks are powerful sources of inspiration for the artful data visualizer and for the generative designer, as well as for the traditional artist.

1. The Ubiquity of Complex Systems

In 1948 American scientist Warren Weaver wrote a very discerning article entitled "Science and Complexity" [1], anticipating the advent of a new science of networks devoted to the investigations of complex systems. Weaver spoke of "problems of organized complexity." Such problems "involve dealing simultaneously with a sizable number of factors which are interrelated into an organic whole." According to Weaver, the solution of such problems requires science to make a great advance, exploiting a mixed-team (interdisciplinary) approach: "It was found, in spite of the modern tendencies toward intense scientific specialization, that members of such diverse groups could work to gether and could form a unit which was much greater than the mere sum of its parts. It was shown that these groups could tackle certain problems of organized complexity, and get useful answers."

A comprehensive description of the characteristics of complex systems is given by philosopher and complexity researcher Paul Cilliers in a book that draws a fascinating connection between complexity and post-modernism [2]. *Complex systems* consist of a large, interacting number of actors. Interactions are dynamic (they change with time), fairly rich (actors typically influence quite a few others), mostly

short-range (information or whatever else might circulate through relationships is received and spread primarily from immediate neighbors), nonlinear (small causes can have large effects and vice versa), and nonhierarchical (there are feedback loops in relationships). Actors are self-organizing (there exists no central authority) and ignorant of the behavior of the system as a whole (they have local information only). Furthermore, the system is open (interacting with the environment), operates under conditions far from equilibrium (it is kept alive by a constant flow of information), and has a history (the past is co-responsible for the present behavior). Complex systems are widespread in nature, society, information, and technology; a few examples include: the human brain, the metabolic system, natural language, ecosystems and the biosphere, the academic publication system, the economic system, the internet, power grids, linked information systems like the web and Wikipedia, and online social networking services such as Twitter, LinkedIn, and ResearchGate.

The difficulty with complex systems is that they are *complex*, not merely *complicated*. The very peculiarity of a complex system lies in the relationships among its parts. Such an inseparable coupling makes the system more than the mere juxtaposition of its parts; hence, the system as a whole cannot be fully understood by simply analyzing its components. Consider the web, for instance. The content of a web page tells us only half of the story: it is useful to define the relevance of a page with respect to a user's information need. The hyperlinks between pages complete the picture: they contain the precious information that can be used to gauge the importance of a page with algorithms such as PageRank [3]. Similarly, the scholarly papers we write are of incommensurable value; on the other hand, bibliographic citations among them are also important for measuring their impact [4].

Reductionism—an analytical method that analyzes something complex by dividing it into manageable parts that can be investigated separately and then putting the parts together again—is not a useful strategy with complex systems. As Cilliers says: "In 'cutting up' a system, the analytical method destroys what it seeks to understand" [2]. On the other hand, *holism*—which believes that the whole is ultimately irreducible—is a more viable approach to the understanding of complex systems. Complex systems pose real problems of organized complexity, as Weaver anticipated, which demands new ways of thinking.

A feasible, although incomplete, approach to the inherent complexity of complex systems is *network science*—the holistic analysis of real complex systems through the study of the network that wires their components [5, 6]. It is worth noticing that a network is a simplified, partial model of a complex system: it captures only the structure of relationships among actors, which is, nevertheless, the most valuable and tasty aspect of complex systems.

The first tangible contribution of network science has been the collection of network data: the identification, construction, storage, and distribution of a differentiated database of possibly very large real networks. These networks underlie complex systems present in many different contexts, including technological networks (the internet, telephone networks, power grids, transportation networks, and distribution networks), information networks (the web, academic and legal citation networks, patent networks, peer-to-peer networks, and recommender networks), social networks (friendship and acquaintance networks, social networks of animals, sexual contact networks, dating patterns, criminal networks, and collaborations of scientists, movie actors, and musicians), and biological networks (metabolic networks, protein–protein interaction networks, genetic regulatory networks, neural networks, and ecological networks).

Network scientists study methods and realize tools to analyze such a rich repository of real graphs. Some of these methods are new (e.g., algorithms for community detection), others are borrowed from graph theory, bibliometrics, sociometry, and even econometrics. Network science addresses questions at three levels of granularity [7]: node-level analysis, where methods to identify the most central nodes of the network are investigated; group-level analysis, which involves techniques for finding cohesive groups of nodes in the network; and network-level analysis, which focuses on topological properties of networks as a whole, as well as on theoretical models generating empirical networks with certain properties.

In the following, I will argue that complex systems, besides being an established tool to investigate reality, are extremely alluring processes generating beautiful networks. As an unstable, soft blend of order and disorder, wildly distributed in technology, information, society, and nature, complex systems provide a varicolored dataset for the artful information visualizer, a precious implement for the generative artist, and a new source of inspiration for the traditional artist.

2. The Beauty of Complex Systems

There exists a general consensus in aesthetics—the philosophical study of art, beauty, and taste—that beauty lies at the intersection of *order* and *disorder*. Perfect order is tedious and therefore not attractive. Chaos is incomprehensible to the human brain and therefore is equally unappetizing. When we depart from order without resulting in complete chaos, maintaining an unstable balance between regularity and mess, often we get a result that surprises and thrills, so that we may define it as beautiful. Consider a performance of contemporary dance. Each dancer involved typically follows specific choreogra-

phy, determined a priori by the choreographer. On the other hand, each dancer interprets the choreography according to their inclinations, history, and mood. Not infrequently, there is also room for improvisation. These elements—interpretation and improvisation—add a disorderly contribution to the choreographed, pre-given movements. It follows that every staging is the same but also subtly different from the others; it is partially unpredictable.

Architect Richard Padovan describes order and complexity as twin poles of the same phenomenon. Neither can exist without the other— order needs complexity to become manifest; complexity needs order to become intelligible—and aesthetic value is a measure of both. He beautifully expresses this concept with the following words: "Delight lies somewhere between boredom and confusion. If monotony makes it difficult to attend, a surfeit of novelty will overload the system and cause us to give up; we are not tempted to analyze the crazy pavement" [8].

I argue that complex systems live at the intersection of order and disorder. If we look at complex systems at the micro level of actors, they appear relatively simple and regular. Individual actors operate in a rather elementary way, typically following few plain rules, paying attention to the behavior of their local neighbors only. Such a local simplicity, multiplied by the sheer number of actors that compose the system, interacting through the convoluted structure of relationships among them, produces an unexpected, yet organized, global complexity. A simple rule set at a low level creates organized complexity at a higher level. A couple of examples follow. In a bird flock, according to the simplest model [9], each individual bird maneuvers based on the positions and velocities of its nearby flock mates following three simple steering behaviors: separation (steer to avoid crowding local flock mates), alignment (steer toward the average heading of local flock mates), and cohesion (steer to move toward the average position of local flock mates). The global, resulting picture is the mesmerizing patterns of abstract beauty that we all have seen at least once in the sky. Similar behavior has been studied for insects (swarming), quadrupeds (herding), fishes (schooling), and also for humans and robots in certain situations. A second example is Twitter. Each user acts plainly: they tweet tiny messages, entirely self-interested or influenced by a small set of users they follow. But such micro posts, when multiplied by the mass of users and channeled through the underlying labyrinthine network of followers, shape themselves into cultural shifts, global opinions, and even revolutions. The crucial role of the internet and especially social networking services (Twitter in particular) during the uprisings of the Arab Spring has been largely acknowledged. These media were used by insurgents to break isolation from the external world as well as to organize the internal revolution.

Stephen Wolfram dedicated a monumental manuscript to the investigation of the counterintuitive phenomenon in which simple abstract rules produce complex outcomes: "Even a program that may have extremely simple rules will often be able to generate pictures that have striking aesthetic qualities—sometimes reminiscent of nature, but often unlike anything ever seen before" [10]. Our normal intuition fails, since when building things (including programs) "normally we start from whatever behavior we want to get, then try to design a system that will produce it. Yet to do this reliably, we have to restrict ourselves to systems whose behavior we can readily understand and predict—for unless we can foresee how a system will behave, we cannot be sure that the system will do what we want" [10]. But unlike engineering, nature, as well as art, operates under no such constraint.

The phenomenon of complex systems whereby simple conduct at the level of actors creates novel and coherent structures at a higher level is called *emergence* [11]. Economist Jeffrey Goldstein provided a current definition of emergent phenomena, or emergents, in terms of the following properties [12]: (*i*) radical novelty: emergents are not predictable from, deducible from, or reducible to the micro-level components; (*ii*) coherence: emergents appear as integrated, unitary wholes that tend to maintain some sense of identity over time, in spite of the separation of the micro-level components; (*iii*) macro level: the locus of emergent phenomena occurs at a global or macro level, in contrast to the micro-level locus of their components; (*iv*) dynamical: emergent phenomena are not pre-given wholes but arise as a complex system evolves over time; and (*v*) ostensive: emergents are recognized by showing themselves. Because of the nature of complex systems, each ostensive showing of emergent phenomena will be different to some degree from previous ones.

These characteristics make emergence the ideal tool for the generative artist [13]. *Generative art* is an art practice where the artist programs a system, which is set into motion with some degree of autonomy, contributing to or resulting in a completed work of art [14, 15]. A defining feature of generative artwork is unpredictability: the generative artist cedes part of the control to the autonomous system in order to obtain an outcome that arouses surprise and emotion (radical novelty) and that shows itself different at every staging (ostensive). A consequence of unpredictability is computational irreducibility: there is no way to predict how the system will behave except by going through all of its computation [10]. The generative artwork arises as a unitary whole as the autonomous system evolves in time (dynamical coherence), and the final artwork is at a higher granularity level with respect to the low-level logic of the program and the mechanics of the system (macro level). Renowned exponents of the generative art movement include, to cite a few: Keith Peters, Jared

Tarbell, Robert Hodgin, Marius Watz, Casey Reas, Paul Prudence, and Matt Pearson. To pick just one instance, Figure 1 shows *Magnetic Ink*, by Robert Hodgin [16].

But the contribution of complex systems to beauty and art overwhelms the generative art movement. Complex systems are ubiquitous; in particular, their most immediate and tangible manifestations, *complex networks*, are the focus of a philosophical, cultural, and artistic change of our highly interrelated and interdependent postmodern society. Rhizomatic structures offer a new model for knowledge and society aiming at acknowledging decentralization, autonomy, flexibility, creativity, diversity, collaboration, altruism, and ultimately, democracy [17–19]. Networks match and sustain the proliferation of information typical of the postmodern condition, the coexistence of a multiplicity of heterogeneous discourses, instead of a simple, central discourse that unifies all forms of knowledge: "Those who have a nostalgia for a unifying metanarrative—a dream central to the history of Western metaphysics—experience the postmodern condition as fragmented, full of anarchy and therefore ultimately meaningless. It leaves them with a feeling of vertigo. On the other hand, those who embrace postmodernism find it challenging, exciting, and full of uncharted spaces. It fills them with a sense of adventure" [2, 20].
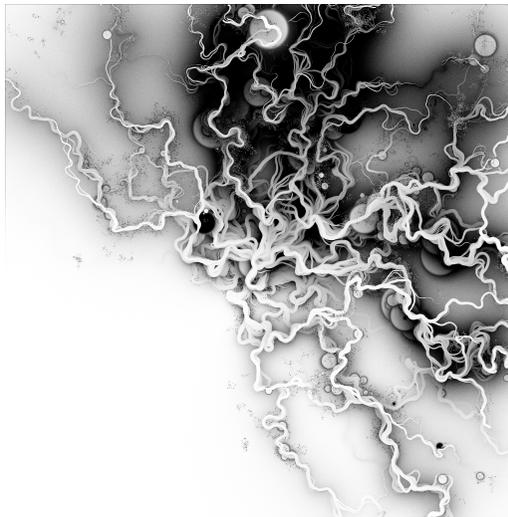

Figure 1. *Magnetic Ink* by Robert Hodgin. The artist describes his artwork as follows: "*Magnetic Ink* began as a tangent from the flocking studies I was working on at the time. The thinking was simple. What if the flocking birds rained down a fine mist of ink onto a sheet of virtual paper. At the same time, they have ribbons that hang from their feet and if they fly low enough, the ribbon will drag on the paper and erase the ink" [16].

Such a perspective shift could not go unnoticed by the artist; a recognized function of art is to sense the times we are living in and interpret them as a form of beauty, so that they can nurture our souls and caress our psychological frailties [21]. Philosophers Gilles Deleuze and Félix Guattari early envisaged the concept of network as artwork, and more generally as a cultural meme [17]: "The rhizome (…) can be torn, reversed, adapted to any kind of mounting, reworked by an individual, group, or social formation. It can be drawn on a wall, conceived of as a work of art, constructed as a political action or as a meditation." Manuel Lima, a creative mind and leading voice in information visualization, observes that "complex networks are not just omnipresent, they are also intriguing, stimulating, and extremely alluring structures. Networks are not just the center of a scientific revolution; they are also contributing to a considerable shift in our conception of society, culture, and art, expressing a new sense of beauty" [18]. Lima is the founder of VisualComplexity.com—a unified resource space for anyone interested in the visualization of complex networks. It showcases hundreds of beautifully visualized real complex networks, most of which are definitely artworks of reality. Two absorbing examples are *Bible Cross-References*, by Chris Harrison, depicted in Figure 2, and *ComplexCity Paris*, by Lee Jang Sub, illustrated in Figure 3.
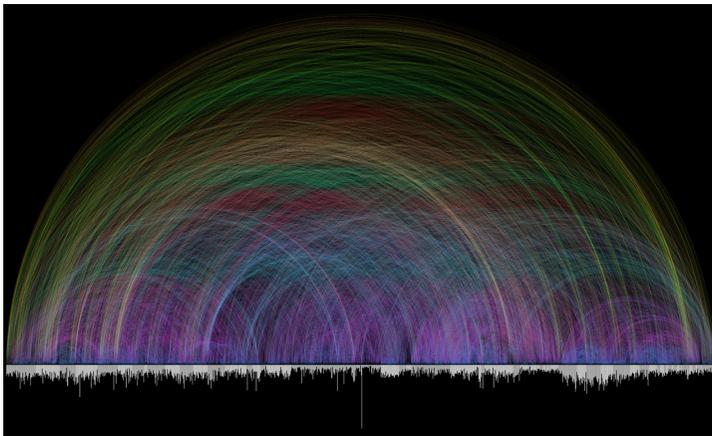

Figure 2. *Bible Cross-References* by Chris Harrison in collaboration with Lutheran pastor Christoph Römhild. This is how Harrison describes his artful visualization: "The bar graph that runs along the bottom represents all of the chapters in the Bible. Books alternate in color between white and light gray. The length of each bar denotes the number of verses in the chapter. Each of the 63 779 cross references found in the Bible is depicted by a single arc—the color corresponds to the distance between the two chapters, creating a rainbow-like effect" [22].

Figure 3. *ComplexCity Paris* by Lee Jang Sub. The artist describes the project as follows: "This project is an exploration to find a concealed aesthetic by using the pattern formed by the roads of the city which have been growing and evolving randomly through time, thus composing the complex configuration we experience today. I perceive the city's patterns as living creatures that I recompose to form an urban image" [23].

In his captivating book *Visual Complexity* [18], moreover, Lima introduces the term *networkism* to identify a small but growing artistic trend, characterized by the portrayal of figurative graph structures of network topologies revealing convoluted patterns of nodes and links. Unlike network visualizations, which are based on a real dataset, the works produced by these artists, mainly paintings and sculptures, are fictitious. The influence of networkism is clearly visible in the works

of Sharon Molloy, Emma McNally, Janice Caswell, Tomas Saraceno, Chiharu Shiota, Dalibor Nikolic, Akiko Ikeuchi, Ranjani Shettar, and Monika Grzymala, to cite a few, where imaginary landscapes of interconnected entities are the prevailing theme. This is how Sharon Molloy describes her work [18]:

> My quest is to reveal how everything is interconnected. From the atom to the cell, to the body and beyond into society and the cosmos, there are underlying processes, structures and rhythms that are mirrored all around and permeate reality. (…) Ultimately I am trying to present a view of reality that reflects our changing times. This work embraces the multiple, the network, the paradoxical and the idea that even the smallest gesture or event has significance, and the power to change everything.

See networkism.org for a digital portrayal of the artworks of these artists. An installation by Chiharu Shiota is pictured in Figure 4.
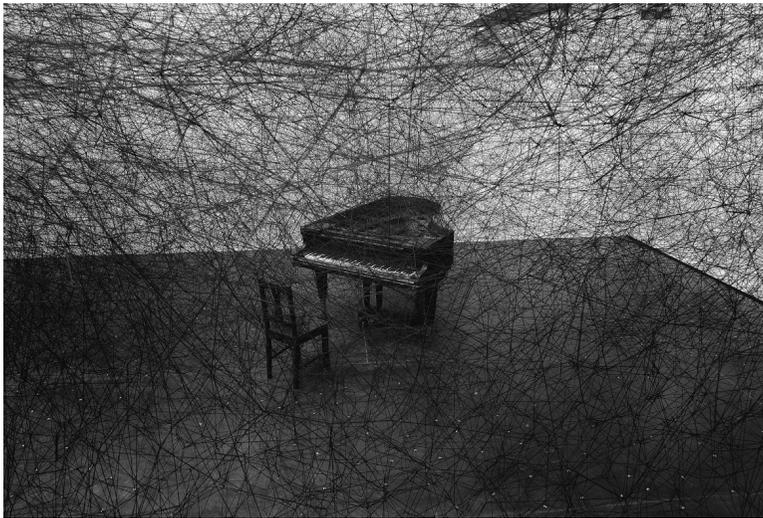
Figure 4. *In Silence*, 2011, by Chiharu Shiota (photograph by Sunhi Mang). Material: Burnt grand piano, black wool. The artwork, featuring an abandoned, charred piano concert concealed beneath a complex network of interwoven yarn, is one of the best-known installations of the artist [24].

3. Coda

I have proposed the idea of the *artification* of science and have exemplified the concept with the aid of complex systems and networks. The benefits of a cross-pollination between science and art are several

and include:

1. New interesting problems arise, for instance, what is a suitable measure of complexity in aesthetics? Traditional complexity and information measures adopted in information theory, like Kolmogorov complexity and Shannon entropy do not work well in aesthetics, since they equate randomness with maximal complexity and maximal information, while aesthetics considers randomness as interesting as boredom.

2. Nonlinear approaches to the familiar increase creativity and originality, two indispensable aspects of good research.

3. Research tastes more interdisciplinary. In policy discourse, interdisciplinarity is often perceived as a mark of good research—more successful in achieving breakthroughs and relevant outcomes.

4. Teaching has a more stimulating flavor and attracts more interested students. Students typically have a less specialized mind that is naturally inclined to appreciate interdisciplinary arguments.

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