Complexity: An Emerging Trend in Social Sciences

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Abstract

The social sciences have had a good run with linear models, in which effects are proportionate to their causes. Nearly all of our theoretical models, in fields as diverse as microeconomics and evolutionary game theory, are equilibrium theories, which examine the properties of various fixed points and analyze the conditions under which they are selected. In contrast, "complexity" uses different mathematical tools to investigate nonlinear processes. But linear models have the advantages of simplicity and power. Is there a real need to import the theoretical apparatus of "complexity" into the social sciences? Or might it be merely the latest example of *Fashionable Nonsense?*

As it turns out, one need not seek very far to discover nonlinear dynamics in the social world. And if more than one attractor exists, the resulting variation in dynamical behavior will be mistaken for noise if one assumes linearity. In the past two or three decades, interest in complexity has burgeoned across the social sciences. Under the banner of complexity, researchers have investigated questions as dissimilar as the causes of the Maya collapse, the spread of disease, the origins of syntax, the structural properties of cities, and the evolution of culture. Presently, the mathematical tools needed to analyze complexity present an entry barrier for many social scientists. But generation time in graduate schools is short, and the physicists who have taken the lead in the application of complexity to social science are beginning to have their elbows jostled by social scientists with a new set of skills. As for the likely impact, it is still early days. But one change that is already visible on the horizon has to do with history, which plays no role in equilibrium analysis, but is intrinsic to many of the questions and methods developed to study complex systems.

INTRODUCTION

The social sciences have had a good run with linear models, in which effects are proportionate to their causes. Nearly all of our theoretical models, in fields as diverse as microeconomics and evolutionary game theory, are equilibrium theories, which examine the properties of various fixed points and analyze the conditions under which they are selected. In contrast, "complexity" uses different mathematical tools to investigate nonlinear

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processes. Nonlinear phenomena are well known in physics, and are ubiquitous in living systems. Consequently, as Stanislaw Ulam is said to have quipped, the term *nonlinear science* is like calling zoology "the study of non-elephant animals."

Still, linear models have the advantages of simplicity and power. Moreover, they may be well suited to the social sciences, which are mostly concerned with the purposive behavior of rational agents and institutions. Further, there is as yet no mathematical definition of complexity, nor is there a theory of what causes it to arise. So, is there a real need to import the theoretical apparatus of "complexity" into the social sciences? Or might it be merely the latest example of *Fashionable Nonsense* (Sokal & Bricmont, 1999), a sexy import from physics that has at most a tangential relevance to the *Geisteswissenschaften*?

COMPLEXITY IN PHYSICS AND BIOLOGY

To address this question, it may be helpful to begin with a brief overview of the origins and meaning of "complexity" in the natural sciences. In 1948, Warren Weaver distinguished two forms of complexity: "disorganized complexity", which can be analyzed with probability theory and statistical mechanics, and "organized complexity" which requires "dealing simultaneously with a sizable number of factors which are interrelated into an organic whole" (Weaver, 1948). In another seminal paper, "More is Different," Philip Anderson argued in 1972 that understanding complexity involves a concept of emergent properties: "At each stage, entirely new laws, concepts and generalizations are necessary, requiring inspiration and creativity to just as great a degree as in the previous one. Psychology is not applied biology nor is biology applied chemistry" (Anderson, 1972). Anderson concluded by quoting Karl Marx's observation that over time, quantitative differences become qualitative differences. Four years later, Robert May observed that "the very simplest nonlinear difference equations can possess an extraordinarily rich spectrum of dynamical behavior, from stable points, through cascades of stable cycles, to a regime in which the behavior (although fully deterministic) is in many respects 'chaotic', or indistinguishable from the sample function of a random process" (May, 1976). May's now-canonical example was the logistic equation. It is a good place to begin, because it demonstrates how both linear and nonlinear patterns can emerge from a simple equation for population growth, in which x is the population and r is its intrinsic growth rate:

$$x_{\text{next}} = rx(1 - x)$$

For most values of r, the equation is linear: increase in x is proportionate to the increase in r. But at $r = 3.44949$, the population begins to oscillate between

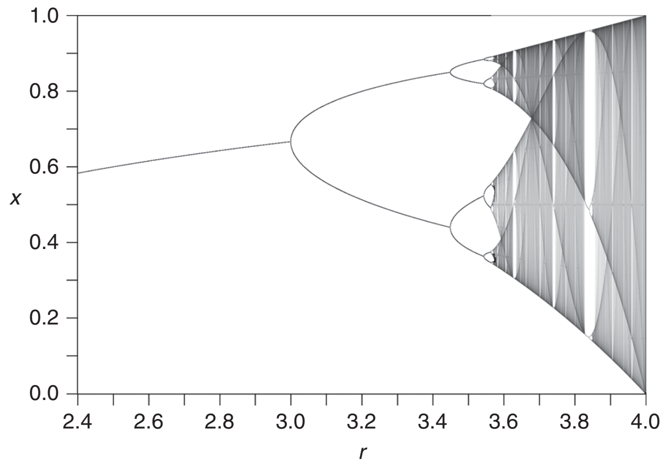

Figure 1 The logistic map, showing linear, cyclical and chaotic behavior at different values of the intrinsic growth rate, *r*. *Source*: Creative Commons. http://en.wikipedia.org/wiki/File:Logistic_Bifurcation_map_High_Resolution.png#filelinks

two values (Figure 1). Between 3.44949 and 3.54409 it oscillates between four values, after which slight increases lead to oscillations between 8, 16, 32, and so on. At 3.56995, regular oscillations begin to be replaced by chaotic fluctuations. At these growth rates, tiny differences in the initial population yield all possible ending populations within a given range. Even more surprisingly, between 3.56995 and 3.82843 several islands of stability appear (Figure 1).

Thus, merely varying the growth rate in the simplest possible equation for population growth generates linear, oscillatory, or chaotic behavior. In the language of complexity, or more specifically of nonlinear dynamics, each of these is called a *regime*, or *attractor*. As long as the growth rate is less than 3.44949, the behavior is linear. But if the growth rate happens to fall in the chaotic regime, prediction is impossible, even if all the parameters are exactly known (May, 1976, p. 466).

This simple example allows us to make three observations. First, one need not seek very far to discover nonlinear processes. Second, linear or equilibrium models will not explain nonlinear systems. And third, less obviously, if more than one attractor or regime exists, the resulting variation in dynamical behavior will be mistaken for noise if one assumes linearity. The last point is particularly important for social science, and we will return to it below. But before doing so, two practical questions will be addressed. First, how relevant are the mathematics of nonlinear dynamics to real-world phenomena? Second, what kinds of insights or explanations are possible if more than one attractor exists, or if a particular system does not settle down into a single, stable equilibrium?

COMPLEX SYSTEMS

To address these questions, it is useful to distinguish between complex systems and complex adaptive systems. A good example of the former is self-organized criticality (SOC), for which the canonical example is not an equation, but an experiment often performed by toddlers at the beach (Bak, Tang, & Wiesenfeld, 1987). Take a flat surface, dribble grains of sand on it until it becomes a pile, and observe the occasional avalanches that occur as the sides grow steep. As the grains of sand continue to fall, the avalanches continue, so that the steepness of the sides of the pile remains constant. At this point, the sandpile has reached its attractor, where the size of the avalanches (the number of grains of sand that move) is inversely related to their frequency. This system has several interesting features, notably that it is self-organizing and produces a robust pattern of emergent, scale-invariant behavior. Many social and cultural phenomena exhibit identical patterns, where the size of events such as earthquakes is inversely related to their frequency. SOC spontaneously generates scale-free networks, in which the degree distribution of nodes (how many connections they possess to other nodes) is inversely related to their frequency. Thus, SOC is governed by a single attractor that produces a characteristic signature, which can be easily detected for a large swath of phenomena, from sandpiles to stock markets, citation networks, the World Wide Web, and financial markets.

Sand piles have a single attractor. The possibility that real-world CS might contain more than one attractor was demonstrated by the discovery of alternate stable states in Dutch lakes. For decades, excess fertilizer flowed into the lakes, triggering algae blooms and eutrophication. But reducing the amount of fertilizer entering the lakes was not enough to restore them to clarity. It turned out that alternate stable states or attractors existed, one turbid and the other clear. In ecology, such alternate stable states or attractors are called *regimes*. The effects of nutrient flows depended on which regime a lake was in, so generalizing across all lakes obscured these differences. But once the existence of alternate regimes was recognized, a simple intervention was sufficient to restore the lakes to health. Temporarily removing the fish allowed sediment to settle and zooplankton populations to increase, whereupon water clarity could be improved by reducing the amount of fertilizer flowing into the lakes (Attayde, Van Nes, Araujo, Corso, & Scheffer, 2010). The comparative study of such processes by ecologists produced new theoretical insights into transitions between attractors. As a dynamical system approaches the boundary between alternate attractors, it will exhibit certain generic properties. These telltale signs have by now been observed in many natural systems (Scheffer *et al*., 2009). This phenomenon has yet to be conclusively demonstrated for social phenomena, but it has triggered a lot of interest, because of the potential relevance for understanding critical transitions in social systems.

COMPLEX ADAPTIVE SYSTEMS: HIDDEN ORDER

As we have just seen, CS are simply aggregates of interacting elements. If the elements are agents, in other words if they exhibit purposive or goal-seeking behavior, then they form a CAS. CASs are ubiquitous in living systems, and we are beginning to notice them in the social world. Is a given social system composed of adaptive agents, and does it produce emergent behaviors that arise from their aggregate behavior? What might such emergent behaviors look like? When do quantitative differences turn into qualitative transformations? Similar to the logistic equation for populations described earlier, even the simplest examples of CASs can contain surprises. To see this, we can turn the logistic equation into an evolving CAS by adding a single environmental parameter, so that growth is affected by something in the environment. The resulting model, created in 1992, helped trigger a revolution in the environmental sciences.

The model is called *Daisyworld* (Lovelock, 1992), and the environmental variable is temperature. Daisyworld is an imaginary planet orbiting a star similar to the Sun and at the same orbital distance as the Earth. The surface of Daisyworld is fertile earth sown uniformly with daisy seeds. The daisies vary in color, and daisies of similar color grow together in patches. As sunshine falls on Daisyworld, the model tracks changes in the growth rate of each variety of daisy, and changes in the amount of the planet's surface covered by different-colored daisies.

The simplest version of this model contains only two varieties of daisies, white and black. Black daisies absorb more heat than bare earth, while whites reflect sunshine. Clumps of same-colored daisies create a local microclimate for themselves, slightly warmer (if they are black) or cooler (if white) than the mean temperature of the planet.

Both black and white daisies grow fastest and at the same rate when their local effective temperature (the temperature within their microclimate) is 22.5 °C, and they respond identically, with a decline in growth rate, as the temperature deviates from this ideal. Consequently, at a given average planetary temperature, black and white daisies experience different microclimates and therefore different growth rates.

If the daisies cover a sufficiently large area of the surface of Daisyworld, their color affects not only their own microclimate but also the albedo or reflectance of the planet as a whole. As with our own sun, the luminosity of Daisyworld's star is assumed to have gradually increased. A simulation

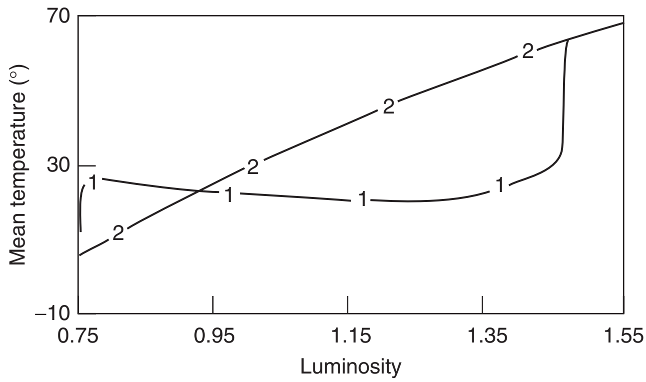

Figure 2 Simulated temperature regulation on Daisyworld. As the luminosity of its aging sun increases from 0.75 to 1.5 times the average value, the temperature of a bare planet would steadily rise (line 2). In contrast, the temperature of Daisyworld stabilizes close to 22.5 °C with daisies present (line 1).

of life on Daisyworld begins in the past with a cooler sun. This enables the black daisies to spread until they warm the planet. Later on, as the sun grows hotter, the white daisies grow faster than black ones, cooling the planet.

So over the history of Daisyworld, the warming sun gradually changes the proportion of white and black daisies, creating the global phenomenon of temperature regulation: The planet's temperature is held near the optimum by and for the daisies, as shown in Figure 2.

Imagine that a team of astronauts and planners is sent to investigate Daisyworld. They would have plenty of time to study the only living things on the planet, and they would almost certainly conclude that the daisies had evolved to grow best at the normal temperature of the planet, 22.5 °C. But this conclusion would invert the actual state of affairs. The daisies did not adapt to the temperature of the planet; instead, they adapted the planet to suit themselves (Saunders, 1994). A Daisyworld without daisies would track the increase in the sun's luminance (line 2), rather than stabilizing near the ideal temperature for daisies (line 1). Only when the sun's luminosity becomes too hot for the daisies to control will the daisy's former role in temperature stabilization become apparent.

Lacking this understanding, planners hoping to exploit Daisyworld's economic potential for the interstellar flower trade would fail to appreciate the possible consequences of different harvesting techniques. While selective flower harvests would cause small, probably unnoticeable tremors in planetary temperature, clear-cutting large contiguous patches of daisies would create momentary changes in the planet's albedo that could quickly become permanent, causing temperature regulation to fail and daisy populations to crash.

The Daisyworld model soon became the canonical example of a self-organizing, self-regulating environmental system. As an example of a CAS, it has several interesting features. The biology is as simple as its creator, James Lovelock, could make it. The model shows how small-scale local adaptations can produce an emergent global structure; and it also shows why such global structures can easily fade from view, becoming noticeable only when the system as a whole has been pushed to its limits. But is Daisyworld simply a mathematical curiosity? Does it have any relevance to the social sciences?

Something very similar to the Daisyworld catastrophe occurred in the 1980s in the rice terraces of Bali. Because this case has been discussed extensively elsewhere,[1] here I provide only a summary highlighting the parallel with the imaginary failure of temperature regulation on Daisyworld. In the 1970s, the Asian Development Bank became involved in an effort to boost rice production in Indonesia. The bank's consultants learned that on Bali, local groups of farmers synchronize their irrigation schedules. In most regions, these schedules produced two rice harvests of native Balinese rice per year. The consultants saw two ways to improve harvests. The first was to encourage the farmers to grow higher yielding "Green Revolution" rice varieties, which produce more grain than native Balinese rice. The second recommendation took advantage of another feature of the new rice: it grows faster than native rice. Consequently, the farmers could plant more frequently. The Ministry of Agriculture adopted both recommendations, and competitions were created to reward the farmers who produced the best harvests. By 1977, 70% of the southern Balinese "rice bowl" was planted with Green Revolution rice, and soon after, planting native rice was forbidden.

At first, rice harvests improved. But a year or two later, Balinese agricultural and irrigation workers began to report "chaos in water scheduling" and "explosions of pest populations." At the time, planners dismissed these occurrences as coincidence, and recommended higher doses of pesticides. However, the parallel with Daisyworld offers an alternative explanation for the harvest decline (Lansing & Fox, 2011). On Daisyworld, the growth of the flowers was driven by a single environmental parameter: temperature. A model of Balinese farming as a CAS requires two environmental parameters, water and pests.

Traditionally, Balinese rice farmers manage their fields collectively in organizations called *subak*. Because irrigation depends on seasonal rainfall, each subak's choice of an irrigation schedule affects the availability of water for their neighbors downstream. The timing of irrigation can also be used to control rice pests such as rats, insects, and insect-borne diseases. This is

1. *Perfect Order: Recognizing Complexity in Bali*. Princeton University Press, 2006. Julian Steward Prize, American Anthropological Association. Lansing and de Vet (2012)

accomplished by synchronizing rice harvests and then briefly flooding the fields, thus depriving the pests of their habitat. The larger the area that is encompassed by the post-harvest flooding, the fewer the pests. But if too many subaks try to flood their fields at the same time, there will not be enough water to go around.

To test the ability of the subaks to discover effective solutions to this trade-off between pest control and water shortages, we constructed a forward-in-time simulation model (Lansing & Kremer, 1993).

By simple trial and error, each subak seeks to discover an irrigation schedule that minimizes losses due to pests or water shortages. A patchwork of synchronized irrigation schedules soon emerges in the model, as groups of subaks adopt identical cropping schedules. As this occurs, rice harvests improve because water shortages and pest damage are reduced for the entire watershed. When the key environmental parameters are stabilized, variation in harvests declines because these benefits spread across the entire system. Conceptually, the model is similar to Daisyworld, except that the flowers of Daisyworld adapt to a single environmental parameter (temperature), while the Balinese farmers adapt to two (pest infestations and water availability). As with Daisyworld, it is an example of a self-organizing CAS, in which the agents are subaks.[2]

Meanwhile, in Bali, the Green Revolution inadvertently created an experimental test of this model. The farmers were told to plant as often as possible, and set aside their traditional system of synchronized planting. This effect can be replicated in the model by running it backwards, and breaking up the co-evolved patterns of synchronized planting schedules. In the model, this produces water shortages and exploding pest populations. When this actually happened in Bali, consultants for the Asian Development Bank interpreted them as chance misfortunes, and urged the farmers to apply higher doses of pesticides while continuing to plant as often as possible. But even very high doses of pesticides proved ineffective. It was only when the farmers spontaneously returned to synchronized planting schemes that harvests began to recover; a point subsequently acknowledged by the final evaluation team from the Bank:

> Substitution of the "high technology and bureaucratic" solution in the end proved counterproductive, and was the major factor behind the yield and cropped area declines experienced between 1982 and 1985 ... The cost of the

2. Interestingly, when the subaks along a river settle down into a globally optimal patchwork of irrigation schedules, the correlation between their cropping patterns resembles a collection of nesting Russian dolls. That is, a patch of subaks following the same irrigation schedule will find itself inside a larger patch containing several irrigation schedules. If the river system is large enough, these patches in turn may be embedded in larger ones. At this point, the entire system is at or near its critical point, with correlations between irrigation schedules at all lengths, resembling an Ising model of spin glasses.

> lack of appreciation of the merits of the traditional regime has been high. Project experience highlights the fact that the irrigated rice terraces of Bali form a complex artificial ecosystem, which has been recognized locally over centuries.[3]

ISLANDS OF ORDER

Granting that exotic mathematical models may shed new light on the gardens of Bali and Daisyworld, a skeptic might be forgiven for wondering if complexity has any broader relevance to social science. In fields such as theoretical ecology, bold claims about the ubiquity of nonlinear systems have been backed up by many recent empirical studies. But in the social sciences, empirical studies are just beginning, and they tend to be spearheaded by physicists and mathematicians rather than social scientists. There are, however, some intriguing results, such as the recent discovery that a great many properties of cities, from patent production and personal income to crime, innovation, and the speed at which people walk and talk are power law functions of population size (Bettencourt, Lobo, Helbing, Kühnert, & West, 2007). There has also been a very productive conversation between mathematicians and social scientists about the dynamic properties of networks. Still, is there more to complexity than the piecemeal application of mathematical ideas about nonlinear dynamics to the social sciences?

This question has recently been addressed by theorists of "complexity economics," notably Brian Arthur. Arthur argues that complexity offers nothing less than a new foundation for economics:

> Complexity economics builds from the proposition that the economy is not necessarily in equilibrium: economic agents (firms, consumers, investors) constantly change their actions and strategies in response to the outcome they mutually create. This further changes the outcome, which requires them to adjust afresh. Agents thus live in a world where their beliefs and strategies are constantly being "tested" for survival within an outcome or "ecology" these beliefs and strategies together create. Economics has largely avoided this nonequilibrium view in the past, but if we allow it, we see patterns or phenomena not visible to equilibrium analysis. These emerge probabilistically, last for some time and dissipate, and they correspond to complex structures in other fields.[4]

Consequently, Arthur concludes, "complexity economics is not a special case of neoclassical economics. On the contrary, equilibrium economics is

3. Project Performance Audit Report, Bali Irrigation Project in Indonesia; Asian Development Bank 1988.
4. Arthur (2013). For an earlier formuation of these ideas, see Arthur (1999).

a special case of nonequilibrium and hence complexity economics." Still, it may take a rather large push to persuade social scientists to adopt this perspective. Are there really "patterns or phenomena not visible to equilibrium analysis," waiting to be discovered?

As before, I offer a simple example. The simplest of all games used by social scientists to study altruism and pro-social behavior is the "Dictator Game" (Kahneman, Knetsch, & Thaler, 1986). It is so simple that, strictly speaking, it is not a game. To play it, a "proposer" determines an allocation (split) of some endowment, such as a cash prize. The second player, the "responder", simply receives the remainder of the endowment left by the proposer. In typical cross-cultural studies, the experimenter gives each proposer the local equivalent of a day's wage, and explains that they may share as much or as little as they choose with another player who is present. Players are assured that the identity of both givers and receivers will not be revealed. For example, a recent study compared offers in the Dictator Game in 15 societies (Henrich *et al.*, 2010). Variation in the average generosity of the players, from one society to the next, was interpreted as support for a hypothesis about the need to trust strangers in larger and more complex societies. To simplify this relationship, the authors constructed a scale of "market integration": how much of one's food is purchased in the market, versus grown at home?

But do whole societies gravitate towards an equilibrium level of prosociality? Or might this assumption obscure the possibility that more than one attractor exists? To find out, we asked farmers in eight Balinese subaks to play the Dictator Game. The subaks in this study are located along the Sungi River in central Bali. Social surveys showed that four upstream subaks were more satisfied with their harvests, and their subak, than four downstream subaks. For the Dictator Game, a group of farmers in each subak were randomly selected as proposers, given the cash equivalent of a day's wage, and offered the chance to share as much or as little as they chose to a fellow member of their subak, selected at random. The identities of both proposers and recipients were concealed. Results are shown in Figure 3.

The average offer for the entire sample of farmers was 30% with a large variance, at the low end of the scale in cross-cultural studies. Buried within this variance, however, were contrasting patterns: Farmers in the downstream subaks were less generous overall, while the most generous farmers of all were those in the two upstream subaks experiencing water shortages. Thus, the variance in responses between the two groups appears to be meaningful, suggesting the presence of more than one attractor. This conclusion was amply supported by a follow-up study. A simple survey of farmer's opinions revealed that the upstream and downstream groups experience similar social and environmental conditions, but respond to them in different ways. For example, differences in class and caste exist in all eight subaks, but

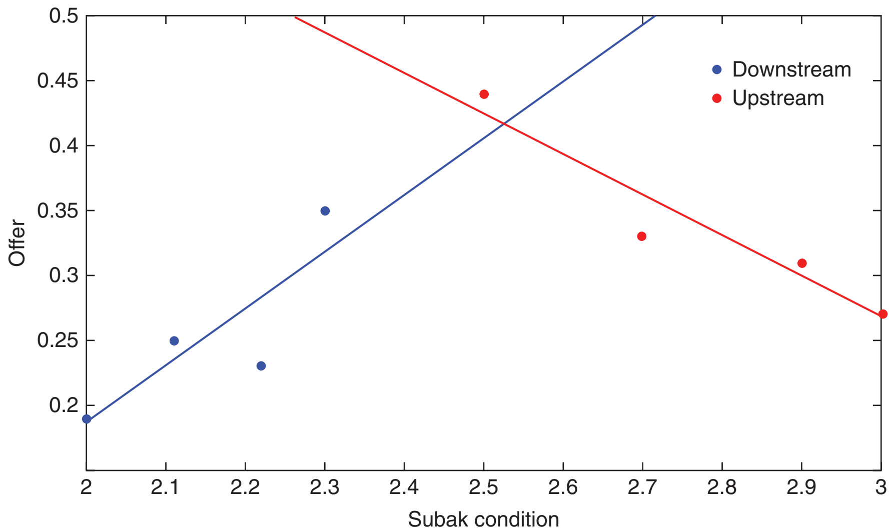

Figure 3 Offers in the Dictator Game in eight Balinese subaks. Among the downstream subaks, the worse the condition of one's subak, the smaller the offer. The opposite pattern emerged in the upstream subaks: the worse the state of one's subak, the more generous the offer. These correlations have opposite effects, so at the level of the global system of eight subaks there was no correlation. *Source*: Lansing *et al*. (2014b), p. 237.

their effects vary systematically between the two groups. The more successful upstream subaks flourish in a small but deep basin of attraction. Confident in their collective ability to meet any challenge, they are exceptionally public spirited. Their neighbors downstream cluster around their own attractor, revealing that muddling through can also be a steady state, with different dynamical relationships among state variables than in the upstream group. Statistically, these differences are highly significant (4 sigma). But they only become apparent if we allow for the possibility of more than one attractor or regime (Lansing *et al*., 2014a).

CONCLUSION: BREAKING THE MEDUSAN MIRROR

In the past two or three decades, interest in complexity has burgeoned across the social sciences. Under the banner of complexity, physicists and modelers have turned their attention to questions such as the causes of the Maya collapse (Weiss & Bradley, 2001), the spread of disease (Craft, Volz, Packer, & Meyers, 2010), the origins of syntax (Ferrer-i-Cancho & Sole, 2001), and the evolution of culture (Tehrani, Collard, & Shennan, 2010). Presently, the mathematical tools needed to analyze complexity present an entry barrier for many social scientists. But generation time in graduate schools is short, and the physicists who have taken the lead in the application of complexity to social science are beginning to have their elbows jostled by social scientists with a new set of skills.

As for the likely impact, it is still early days. But one change that is already visible on the horizon has to do with history, which plays no role in equilibrium analysis. Multivariate statistics, the other standard mathematical tool of the social sciences, can be used to investigate time series, but while it can tell us how some processes have changed over time, the usual methods will not tell us how surprised we should be. These weaknesses were the basis for the critique of positivist social science by the Frankfurt school. The "positivist dispute" is now largely forgotten, but it left a lasting legacy in the enduring division between positivist versus qualitative and historical approaches to social science. Complexity has the potential to open a new chapter in this debate, by reframing the analytical importance of history and change.

The original debate, which came to be known as the *positivist dispute*, began in 1961. The German Sociological Association invited Karl Popper to give a lecture on the logic of the social sciences, and asked Theodor Adorno to offer a critical response. Popper held forth on the importance of statistical validation for social theory. In response, Adorno argued that it is necessary to imagine alternatives to contemporary social reality: "only through what it is not will it disclose itself as it is … " (Adorno, Dahrendorf, Pilot, Albert, Habermas, & Popper, 1976). This led Adorno to a critique of descriptive statistics as the primary tool for social inquiry. He observed that "a social science that is both atomistic, and ascends through classification from the atoms to generalities, is the Medusan mirror to a society which is both atomized and organized according to abstract classificatory principles … " Adorno's point was that a purely descriptive, statistical analysis of society at a given historical moment is just "scientific mirroring" that "remains a mere duplication." For Adorno and other Continental social theorists, the purpose of social science was to illuminate the driving forces producing historical change.[5] And to break the seal of reification on the existing social order, it was necessary to go beyond descriptive statistics or equilibrium models to explore historical contingency. But the mathematical tools needed for this kind of analysis did not exist. Today, they do.

REFERENCES

Adorno, T. W., Dahrendorf, R., Pilot, H., Albert, H., Habermas, J., & Popper, K. (1976). *The positivist dispute in German sociology*, (p. 296). (G. Adey and D. Frisby, Trans.). London, England: Heinemann.

5. "History is the true natural history of Man". Marx, Grundrisse, 109.

Anderson, P. W. (1972). More is different. *Science*, *177*(4047), 393–396.

Arthur, W. B. (1999). Complexity and the economy. *Science*, *284*, 107–109.

Arthur, W.B. (2013). Complexity economics: A new framework for economic thought. Working Papers of the Santa Fe Institute 2013-04-012.

Attayde, J. L., Van Nes, E. H., Araujo, A. I. L., Corso, G., & Scheffer, M. (2010). Omnivory by planktivores stabilizes plankton dynamics, but may either promote or reduce algal biomass. *Ecosystems*, *13*, 410–420.

Bak, P., Tang, C., & Wiesenfeld, K. (1987). Self-organized criticality: an explanation of 1/f noise. *Physical Review Letters*, *59*(4), 381–384.

Bettencourt, L. A., Lobo, J., Helbing, D., Kühnert, C., & West, G. B. (2007). Growth, innovation, scaling, and the pace of life in cities. *PNAS*, *104*(17), 7301–7306.

Craft, M. E., Volz, E., Packer, C., & Meyers, L. A. (2010). Disease transmission in territorial populations: The small world network of Serengeti lions. *Journal of the Royal Society Interface*, *8*, 776–786.

Ferrer-i-Cancho, R., & Sole, R. V. (2001). The small world of human language. *Proceedings of the Royal Society B: Biological Sciences*, *268*(1482), 2261–2265.

Henrich, J., Ensminger, J., McElreath, R., Barr, A., Barrett, C., Bolyanatz, A., … Ziker, J. (2010). Markets, religion, community size and the evolution of fairness and punishment. *Science*, *327*, 1480–1484.

Kahneman, D., Knetsch, J. L., & Thaler, R. H. (1986). Fairness and the assumptions of economics. *The Journal of Business*, *59*(S4), S285.

Lansing, J. S., Cheong, S. A., Chew, L. Y., Cox, M. P., Ho, M.-H., & Arthawiguna, A. (2014a). Regime shifts in Balinese Subaks. *Current Anthropology*, *55*(2), 232–239.

Lansing, J. S., Cheong, S. A., Chew, L. Y., Cox, M. P., Ho, M.-H., & Arthawiguna, A. (2014b). Regime shifts in Balinese Subaks. *Current Anthropology*, *55*(2), 237.

Lansing, J. S., & de Vet, T. A. (2012). The functional significance of Balinese Water Temples: A reply to critics. *Human Ecology*, *40*(3), 453–467.

Lansing, J. S., & Fox, K. (2011). Niche construction on Bali: The gods of the countryside. *Philosophical Transactions of the Royal Society B*, *366*, 927–934.

Lansing, J. S., & Kremer, J. N. (1993). Emergent properties of Balinese Water Temples. *American Anthropologist*, *95*(1), 97–114.

Lovelock, J. E. (1992). A numerical model for biodiversity. *Philosophical Transactions of the Royal Society of London B*, *338*, 365–373.

May, R. M. (1976). Simple mathematical models with very complicated dynamics. *Nature*, *261*, 459–467.

Saunders, P. T. (1994). Evolution without natural selection: Further implications of the Daisyworld parable. *Journal of Theoretical Biology*, *166*, 370.

Scheffer, M., Bascompte, J., Brock, W. A., Brovkin, V., Carpenter, S. R., Dakos, V. … Sugihara, G. (2009). Early-warning signals for critical transitions. *Nature*, *461*, 53–59.

Sokal, A., & Bricmont, J. (1999). *Fashionable nonsense: Postmodern intellectuals' abuse of science*. New York, NY: Picador Press.

Tehrani, J. J., Collard, M., & Shennan, S. J. (2010). The cophylogenies of populations and cultures: Reconstructing the evolution of Iranian tribal craft traditions using trees and jungles. *Philosophical Transactions of the Royal Society B*, *2010*(365), 3865–3874.

Weaver, W. (1948). Science and complexity. *American Scientist*, *36*(4), 536–44.
Weiss, H., & Bradley, R. S. (2001, January 26). What drives societal collapse? *Science*, *291*(5504), 609–610.

J. STEPHEN LANSING SHORT BIOGRAPHY

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In the 1980s, Lansing and ecologist James Kremer showed that Balinese water temple networks can self-organize. Later research showed that over the centuries, water temple networks expanded to manage the ecology of rice terraces at the scale of whole watersheds. In 2012, Bali's water temple networks were recognized as a UNESCO World Heritage.

As the pieces of the water temple story were falling into place, Lansing became interested in self-organizing processes elsewhere in the archipelago. In 2000, he began to work with Indonesian geneticists, linguists, and public health officials to study the co-evolution of social structure, language change, and disease resistance on 14 Indonesian islands. Recent publications and films are available at www.slansing.org.

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