

COMPLEXITY AND ANTHROPOLOGY

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Anthropology has historically embraced a rich diversity of questions and methods. For the purposes of this essay it is convenient to group them into the conventional categories of *Geisteswissenschaften* and *Naturwissenschaften*; humanistic and scientific studies. The coexistence of these two approaches within anthropology has itself been an enduring source of controversy; humanistic anthropologists tend to be dubious about the application of scientific methods to anthropological subjects, while the scientists vary in their tolerance for humanistic methods in proportion to their adherence to a Popperian or positivist belief in the unity of scientific method. The entry of the nascent field of “complexity” into anthropology promises to complicate this picture. For our purposes, a simple definition of “complexity” as the study of nonlinear processes will be adequate. Nonlinearities abound in anthropology, and as awareness of their properties spreads it seems inevitable that few topics in anthropology will remain untouched.

This essay begins with a descriptive tour of examples of the application of ideas from complexity to anthropological questions, roughly divided into the *Geistes-* and *Naturwissenschaften*. Themes to be touched on, which will be defined below, include emergence, agency, network dynamics, multi-scale interactions, path dependence, evolvability and robustness. In each case, after outlining an anthropological question we consider the extension of simple mathematical models to some interesting empirical examples. The essay concludes with a brief summary of major themes.

1.1 Complexity and the Geisteswissenschaften: structuralism

For roughly the past half century, humanistic approaches to sociocultural anthropology have been dominated by the structural anthropology of Claude Lévi-Strauss, and the “post-structuralism” of his many successors, among them the Tel Quel group in Paris (1960-1982) which included Roland Barthes, Georges Bataille, Maurice Blanchot, Jacques Derrida, Michel Foucault and Julia Kristeva. Structuralism posed a profound challenge to the earlier humanistic tradition in anthropology, which sought to uncover the subjective meaning of cultural symbols and practices. Structuralists did away with the question of the subject’s awareness of meaning, replacing it with an account of how language produces meanings that define subjects. The prominent structuralist Roland Barthes (1915-80) argued that the implications of this epistemological reversal could hardly be exaggerated, predicting that the “infinity of language” would replace the Kantian-Husserlian “infinity of consciousness.” The ascendancy of structuralism in anthropology in

the 1960s created an ongoing philosophical crisis with respect to the nature of the anthropological subject, which continues today. *indexmorphemes*

Interestingly, it is probably easier to give a coherent account of the structuralist program from the perspective of complexity, than from that of humanistic anthropology. Structuralism defines various components of language, such as phonemes and morphemes, in terms of logical operations on trees or networks. This marked a radical departure from traditional interpretive approaches to language and culture. A century ago, the Swiss linguist Ferdinand de Saussure (1857-1913) defined the linguistic sign as comprised of two elements, the sensible sound-image (signifier) and the intelligible concept (signified). Saussure argued that linguistic signs are unmotivated and acquire their meaning only through differential relations with other signs.¹ He suggested that the same dynamics occur at the level of phonology: the boundaries of phonemes are defined by paired contrasts with the other phonemes that they most closely resemble. Thus in English the slight difference between [p] and [b] marks the boundary between two phonemes, creating a meaningful distinction between, for example, “pit” and “bit.” In this way, binary contrasts or antonymy define signifiers: the written phonetic symbol [b] points to a particular sound (or range of sounds produced by different speakers). Roland Barthes later described this as first-order signification; i.e. the denotative meaning of the signifier. Barthes developed a concept of higher-order signifiers which enabled him to extend the structuralist approach from language to cultural phenomena. For example, the denotative or first-order meaning of the English signifier “blue” depends on the other color terms with which it can be contrasted. Barthes argued that second-order meanings are also defined by binary contrasts. Thus blue is traditionally associated with male infants, and pink with female infants, in American hospitals. This association is an example of metonymy: blue is to pink as male is to female. Barthes argued that such metonymic associations are ubiquitous, generating symbolic classificatory systems for cultural objects.

This idea was further developed by anthropologists such as Marshall Sahlins, who used it to analyze the systemic properties of cultural symbols. For example, Sahlins argued that the Fijian words for “sea” and “land” are first-order signifiers defined by their binary opposition: that which is sea is not land [Sahlins, 1976]. This contrast is extended by metonymic chaining: in Fiji, men are associated with the sea and women with the land; further, chiefs are also associated with the sea and commoners with the land. The seaward side of a Fijian house thus is associated with male and chiefly power. Similarly, the sea itself is subclassed into the lagoon (landward sea) and the outer or seawards sea. Fishing is a male occupation, but if women fish, they do so in the lagoon.

In this example, a relationship of binary opposition between two first-order signifiers “sea” and “land”, forms the root of a tree of symbolic associations (Fig. 1) in which the initial defining contrast is repeated with other paired oppositions, like seawards land and inland land.

¹“The linguistic sign unites, not a thing and a name, but a concept and a sound-image.” [Saussure, 1983, chapter one].

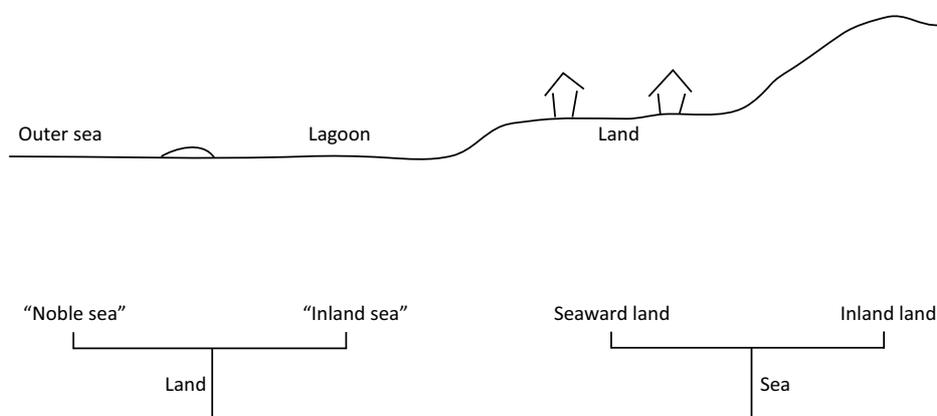


Figure 1. A structuralist analysis of Fijian classification.

Figure redrawn from: Sahlins, M. D. (1976). *Culture and practical reason*. University of Chicago Press.

The tree model was criticized by post-structuralists, who argued that there are no privileged first-order signifiers which unambiguously root trees of symbolic associations (thus the Sea/Land opposition in Sahlins's example would not be accepted as foundational). According to this argument, signification is not fully defined by any single oppositional pair in the chain of signifiers, but rather by metonymic associations. The post-structuralist psychoanalyst Jacques Lacan argued that the mind glides like a butterfly through networks of signifiers, each of which points beyond itself to other signifiers. Hence the correct model is not a rooted tree, but rather a network of signifiers: the chain of differences spreads throughout semantic space and never comes to rest in an ultimate 'signified' [Sandwell, 1996, 365-6]. This argument was elaborated by Jacques Derrida, who drew attention to the 'free play' of signifiers: they are not fixed to their signifieds but point beyond themselves in an 'indefinite referral of signifier to signified' [Derrida, 1978, 25]. Hence both Derrida and Lacan portray relationships among signifiers as networks, not trees. While for Saussure the meaning of signs derived from how they differ from each other, Derrida coined the term *différance* to allude to the ways in which meaning is endlessly deferred. He concluded that there is no 'transcendent signified' [Derrida, 1978, 278-280; 1976, 20].

Derrida and other post-structuralists famously developed these ideas into a relativistic epistemology, arguing that the meaning of texts can never be fixed. This conclusion echoed that of many Anglo-American analytic philosophers, who at about the same time (1970s) had begun to acknowledge that their quest for an unambiguous observation language had failed. Meanwhile in linguistics, the structuralist program sputtered to an end as it became clear that networks defined by binary oppositions are not very informative for linguistic phenomena more complex than phonemes and morphemes.

1.2 *Language networks and the topology of the possible*

When Derrida, Barthes and Lacan began their studies of networks of signifiers, not much was known about the mathematical properties of networks. But subsequently this topic moved to the forefront of research in complex systems. In the past decade a number of complexity researchers have begun to pick up where the structuralists left off, exploring the application of network models to language. In the original structuralist models, binary opposition was the sole logical operator, and the problem of logical closure was unresolved. (Thus while phonemes or color terms may form small closed networks in which the boundary of each signifier depends to some extent on the others, this is not obviously true for other signifiers). Like the post-structuralists, complexity researchers investigate the properties of networks of signifiers. But their most recent work extends network analysis to syntax, which the structuralists never attempted, and considers other semantic relationships besides binary opposition, or antonymy.

As with much research in complexity, the study of language networks is often motivated by the physicist's passion for discovering universals. The study of networks and graph theory has revealed many common features in such diverse phenomena as food webs, social networks, software maps, power grids, genomes and neural connections. That languages might also display such regularities was suggested by the early work of George Zipf [1902-1950], who showed that if all the words in a text are ordered by rank, from the most common to the rarest, their frequency (number of appearances) decays inversely with their rank [Zipf, 1949]. Most words are rare, whereas a few (such as *the, of, and, to, I, etc.*) are very common. Zipf observed that this relationship appears to hold for all natural (spoken) languages.

A recent study by Ferrer i Cancho *et al.* builds on Zipf's work, using network theory to develop a simple model for the emergence and structure of syntax. Syntax can be thought of as a set of rules to combine words in such a way as to make sentences meaningful. Some authors, such as Derek Bickerton, have argued that syntax required a pre-adaptation of the human brain. Ferrer i Cancho *et al.* propose a simpler explanation. In their model, words are associated with objects. In accordance with Zipf's law, a few words are very polysemous (refer to many objects), while most denote only one or two. Figure 2a depicts this variation: word 1 denotes object 2, while word 3 denotes two objects, 3 and 4. In Figure 2b, this data is reorganized into a network displaying the linkages of words via their objects of reference. This simple network has many words with few links, but a few, like word 11, act as multi-linked or polysemous hubs. Ferrer i Cancho *et al.* conclude that connectedness arises naturally from Zipf's law, independently of the details of the linguistic setting [Cancho, *et al.*, 2005].

What is interesting about this network is what is called the "small world" phenomenon: despite its potentially very large size and sparseness (i.e. most words have few links), it is usually easy to reach one node (word) from another along a few links, thanks to the scattered presence of some very well-connected hubs.

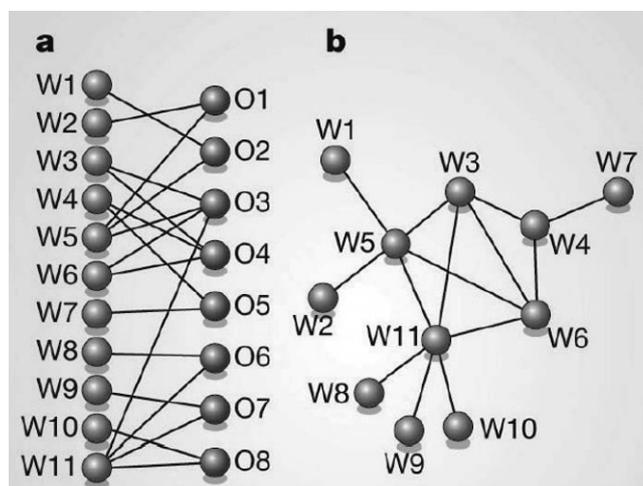


Figure 2. Building a protolanguage network. A) A bipartite set of connections can be built by linking signals (words, red) to objects (blue). Most words are specific, referring to only one or two objects, whereas a few of them have many links. B) A new network is obtained by linking words that share at least one object of reference. The resulting network has many words with few links, but some acting as hubs. Ferrer i Cancho et al. believe that syntactic rules might have emerged from such a scale-free network architecture

Here degree distributions are defined as the frequency $P(k)$ of having a word with k links. Most complex networks are characterized by highly heterogeneous distributions, following a power law (scale-free) shape $P(k) \sim k^{-\gamma}$, with $2 < \gamma < 3$.

Figure redrawn with permission from: Sole, R. (2005). Language syntax for free?. *Nature*, 434(7031), 289.

Ferrer i Cancho et al. suggest that the sometimes illogical and quirky appearance of syntactic rules in natural languages might be merely a by-product of this scale-free network structure, and that Zipf's law may be a necessary precondition for the development of syntax and grammar.

Another physicist, Ricard Solé, has suggested that languages exhibit well-defined network properties at all levels: phonetic, lexical, syntactic, semantic [Solé, 2005, 289]. Like Ferrer i Cancho, he emphasizes the functional significance of the small-world phenomenon. Figure 3 illustrates the patterns formed by various semantic relationships, including binary opposition (antonymy) and hypernymy (words or phrases whose semantic range is included within that of another word). While hypernymy produces tree-like networks, other relationships create shortcuts through the entire semantic network, producing an overall small-world effect.

Another example, also taken from Solé, shows how syntactic networks can be built up from textual data, using a passage from Virginia Woolf's *A Room of One's*

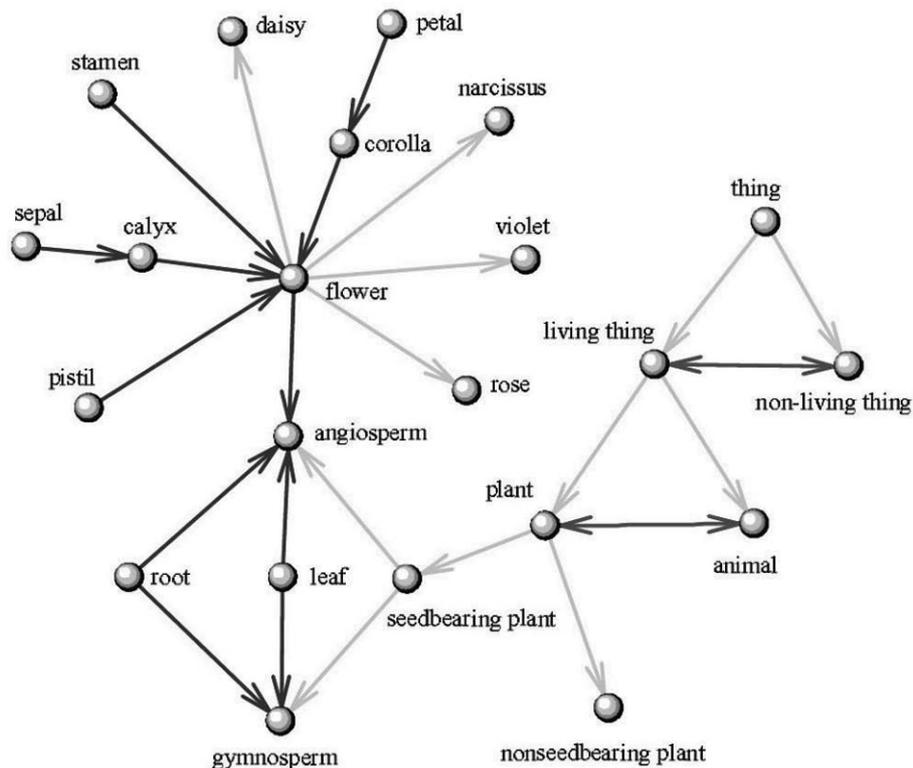


Figure 3. Semantic webs can be defined in different ways. The figure shows a simple network of semantic relations among lexicalized concepts. Nodes are concepts and links semantic relations between concepts. Links are coloured to highlight the different nature of the relations. Yellow arcs define relations of hypernymy (Flower \rightarrow Rose implies that Flower is a hypernym of Rose). Two concepts are related by a blue arc if there is a part-whole relation (metonymy) between them. Relations of binary opposition (antonymy) are bidirectional and coloured violet. Hypernymy defines a tree-structured network and other relations produce shortcuts that leads the network to exhibit a small world pattern, making navigation through the network more easy and effective.

Figures 3-6 redrawn with permission from: R. V. Sol, B. C. Murtra, S. Valverde, L. Steels. Language Networks: their structure, function and evolution. Working Papers of the Santa Fe Institute 05-12-042, 2005.

Own. Here is the passage:

But, you may say, we asked you to speak about women and fiction — what has that got to do with a room of one's own. I will try to explain. When you asked me to speak about women and fiction I sat down on the banks of a river and began to wonder what the words meant. They might mean simply a few remarks about Fanny Burney; a few more about Jane Austen; a tribute to the Brontës and a Sketch of Haworth Parsonage under snow; some witticism if possible about Miss Mitford; a respectful allusion to George Eliot; a reference to Mrs. Gaskell and one would have done. But at second sight the words seemed not so simple.

Starting from this text several types of language networks can be created based on different types of relationships among words. Figure 4 shows a co-occurrence network; Figure 5 creates the corresponding syntactic network, taking as a descriptive framework dependency syntax [Melčuk, 1988].

The network shown in Figure 5 takes verbs as the nucleus of well-formed sentences, and builds arcs that begin in complements and end in the nucleus of the phrase. Like Ferrer i Cancho's toy model, the resulting structure is a small world network.

The network properties of natural languages define what Walter Fontana has called the topology of the possible,² a concept that would surely have pleased Jacques Lacan. The discovery of shared topological features, such as the emergent “small world” properties of both semantic and syntactic networks, promise new insights into the cognitive and social processes that underlie the creation, maintenance and transmission of human languages. Like the structuralists before them, complexity researchers are also beginning to explore the epistemological implications of language topologies. An interesting recent example is a simulation of the emergence of linguistic categories by Puglisi *et al.* [2008]. These researchers begin with the question of how linguistic categories, which are culture-dependent conventions, come to be accepted at a global level without any central coordination. For example, the few “basic” color terms that are present in natural languages are a remarkably consistent subset of an almost infinite number of perceivable different colors. Extensive simulations showed that a simple negotiation scheme, based on memory and feedback, is sufficient to guarantee the emergence of a self-organized communication system that is able to discriminate objects in the world, requiring only a small set of words [Puglisi *et al.*, 2008, 7939].

These initial explorations of the network properties of language suggest several tentative conclusions. Clearly, there are statistical universals in language networks,

²Fontana developed this concept in the context of evolutionary biology, with reference to the genotype-phenotype map: “. . . what is needed is a criterion of *accessibility* of one phenotype from another by means of mutations on their underlying genetic representation. Such a notion of accessibility can then be used to define a concept of *neighborhood* which generates the structure of phenotype space in the absence of a distance notion. . .” [Fontana, 1993, 15].

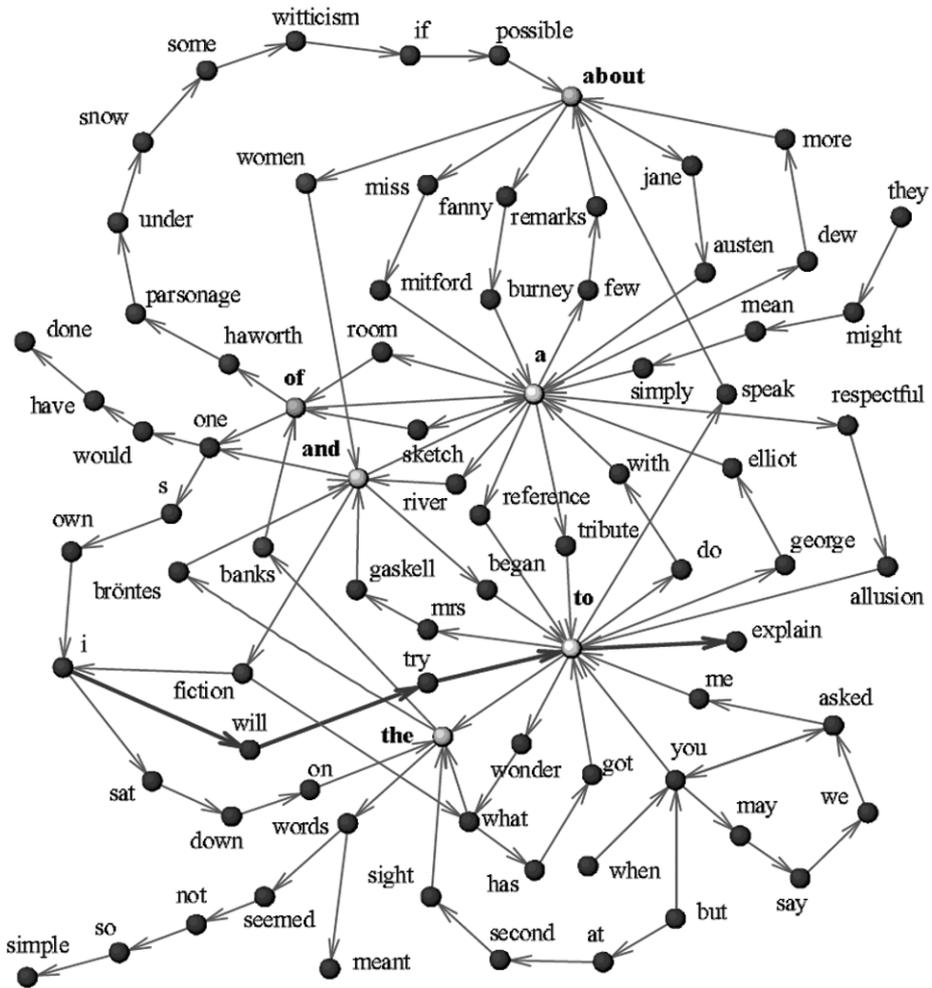


Figure 4. A co-occurrence network. Words are depicted as nodes; the lighter their color, the higher their degree. Paths on this network can be understood as the potential universe of sentences that could be constructed with this lexicon. An example of such path is the sentence shown in red.

which are similar to the features found in other ‘scale free’ networks arising in physics, biology and the social sciences. As Solé *et al.* observe, [2005], this points to new types of universal features of language, which do not focus on properties of the elements in language inventories as the traditional study of universals (e.g. phoneme inventories or word-order patterns in sentences) but rather on statistical properties. Second, the pervasive nature of these network features suggests that language may be subject to the same kinds of self-organization dynamics as other natural and social systems.

1.3 Agency and social networks

Social networks are a venerable topic in the social sciences. But recent work from a “complexity” perspective shifts the analytical focus from descriptive enumerations of social relationships, to abstract models of the effects of dynamical rules on the historical trajectories of networks. As in the studies of language networks described above, these studies explore the topologies of the possible: the consequences of network structures, in terms of the kinds of interactions they facilitate.

In the social sciences, the concept of “agency” has two meanings. One pertains to the capacity of persons to depart from their assigned social roles, to choose not to follow norms; in short, to swim against the tide. Alternatively, agency can also mean a person’s social efficacy; their ability to mobilize resources, influence others, or take effective action. Social networks provide a way to carry out comparative, empirical studies of the latter form of agency (e.g. social efficacy). Structural network measures are traditionally used to identify influential actors, based on the assumption that such measures offer a robust way to identify influential individuals in a community [Wasserman and Faust, 1994]. This can become the starting-point for more detailed explorations of topics such as the situatedness of environmental knowledge.

For example, Atran *et al.* used network models to explore differences in rates of deforestation in the vicinity of three communities located in the Petén region of Guatemala: native Itza’ Maya, Spanish-speaking immigrant Ladinos, and immigrant Q’eqchi’ Maya [Atran *et al.*, 2005]. Petén’s forests are a common-pool resource that is rapidly being depleted, and Q’eqchi’ forest-clearance rates are more than five times greater than those for Itza’. Measurements of soils, biodiversity, and canopy cover indicate that Itza’ promote forest replenishment, while Q’eqchi’ foster rapid forest depletion, and Ladinos fall somewhere in between. To discover the reasons for these differences, Atran *et al.* asked questions designed to elicit both farmers’ personal knowledge of ecology, and whom they turn to when making decisions about resource use. They found significant differences in the structure of both types of networks among the three communities, which helped to explain the variation in deforestation rates. Over time, these rates are sensitive to the depth and accessibility of ecological knowledge available to farmers. A similar study by Bodin *et al.* constructed network models for social relations and ecological knowledge among fishermen in a coastal Kenyan village [Bodin and Crona, 2008]. Like

Atran *et al.*, they found large differences in local ecological knowledge between different occupational groups, such as inshore and offshore fishers.

In these studies, the connectedness of individuals in network diagrams is often interpreted as an index of their social capital (e.g. [Borgatti and Foster, 2003]). Using survey data, researchers can also investigate variation in the “social embeddedness” of knowledge and more specific forms of social capital [Granovetter, 1985]. But as informative as the resulting networks may be, they are essentially snapshots of conditions that existed at the time the survey was done. Recently, several scholars have begun to investigate changes in network structures over time. This added temporal dimension has encouraged the development of new analytical methods. Two of the most interesting examples will be briefly discussed here.

John Padgett and Paul McLean used network analysis to investigate the emergence of financial capitalism in Renaissance Florence at the Medici bank, and sister institutions [Padgett and McLean, 2006]. They argue that “the poisedness of a system to reconfiguration by an invention is as much a part of the phenomenon to be explained as is the system’s production of the invention itself” [ibid., 1464]. The particular invention they trace is the discovery, in the late 1300s, of a new organizational form: a set of legally autonomous companies linked through one person or a small set of controlling partners, called a cambio bank. This new “network-star” ownership structure largely displaced earlier legally unitary companies, often built collectively by patrilineal kinsmen, which were common in the early 1300s.

Using archival sources, Padgett and McLean were able to trace multiple networks of relationships (partnerships, kinship, dowries, etc) for nearly complete lists of cambio bankers in four time periods: 1348–58, 1369, 1385–99, and 1427. In 1350 Florentine companies were extremely specialized by industry, but by 1427 they had become much more diversified [ibid., 1482]. The desire to interpret these changing patterns of relationships led Padgett and McLean to expand their concept of agency, to include collective institutions like patrilineages and banks as well as individuals:

Actors are clusters of relational ties. In the activity plane of economics, for example, collective actors called companies are composed of partnership ties. These companies trade with each other. In the domain of kinship, for another example, collective actors called patrilineages are composed of genealogy ties. These patrilineages marry each other. And in the domain of politics, collective actors called factions are composed of clientage ties. These factions do political deals with each other. [ibid., 1468]

This perspective might seem to eliminate agency in the usual sense altogether. Not so, however, because institutions like banks are treated not as unitary actors, but rather as comprised of multiple networks linking specific individuals. The focus is on “careers and biographies as these wend their way across organizations and domains...”. In other words, both organizations and people are shaped, through

network coevolution, by the history of each flowing through the other" [ibid., 1470-1]. Changes in one network, such as dowries or marital ties, have consequences for other networks, such as partnerships. As these patterns slowly ripple across social networks, the new forms of banking emerge.

A similar approach was developed by David Stark and Balázs Vedres to analyze the reformation of the Hungarian economy during the transition from communism to capitalism, another period of rapid and profound economic change [Stark and Vedres, 2006]. This study traced changes in the ownership structure of 1,696 of the largest Hungarian enterprises from 1987 to 2001, with particular attention to the role of foreign investment. They argue that "the transformation of a national economy is not a unitary process obeying a single logic but is formed out of the interweaving of multiple processes with distinct temporalities. . . .thus, in place of the properties of the global network we focus on variation in local properties" [ibid., 1399].

To apply network analysis to the ownership data, Stark and Vedres defined ties between firms as equity ownership of at least 1%, among the largest Hungarian firms. Types of ownership were classified into four categories: State, Hungarian firm, Hungarian person, and foreign owner. This enabled them to pose historical questions, such as: when communism ended, did domestic networks grow unchecked? Or did the economy segregate into two domains, one controlled by foreign capital and the other by Hungarians?

Figure 6 shows the history of a single firm's ownership patterns. It begins as an isolate under State ownership. After three years, it becomes the periphery of a small star. In 1992 the topography of the firm's local network is a cohesive cluster, and after three years, these network ties are transformed into a strongly cohesive group. Eventually, it shrinks back into a dyad.

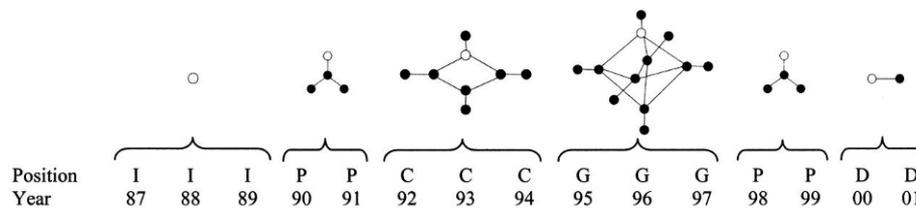


Figure 6. A Hungarian firm's ownership pattern can be represented as a network which changes structure through time.

Redrawn from: Stark, D., & Vedres, B. (2006). Social times of network spaces: Network sequences and foreign investment in Hungary. *American Journal of Sociology*, 111(5), 1367-1411.

Using this approach 1,696 network histories were constructed. Analytical techniques originally developed for understanding genetic sequences were adapted to search for the most common trajectories of change. Ultimately, 12 pathways accounted for 59% of the variance in inter-sequence distances. Thus, a small number

of pathways explain a great deal of the change that occurred in the ownership of most of the largest firms in Hungary during this period. The authors make the further point that these shifting patterns of relationships were not merely the residue of external events, but may have had adaptive significance in themselves: “Hungary’s transformation from state socialism to an emerging market economy with sizable foreign investment did not occur despite its inter-organizational property networks but, in part, because of and through these networks” [ibid., 1399]. The authors conclude that developing economies do not necessarily face a forced choice between networks of global reach and those of local embeddedness.

Historians are not always able to acquire the necessary volume of information to quantify network relationships. Nevertheless, Elisabeth Wood has shown that social processes that occur during civil wars can leverage pre-existing social networks and may fundamentally change them after the war ends [Wood, 2008]. Political mobilization usually occurs before armed conflict begins, as state and non-state actors seek to gain resources and power. Local elites access kinship and clientelist networks to protect their interests from insurgents or opposing local elites. Sometimes an insurgent group, such as the Revolutionary United Front in Sierra Leone’s Civil War, forcibly recruited members without drawing on local social networks, which led to a heterogeneous and weakly organized internal structure. State militaries may purposely recruit from a wide range of social groups, ignoring local networks in order to build national unity within the armed force. Civilians who remain neutral during conflict often become isolated from kinship and labor networks. Thus, pre-existing social networks shape the nature and outcome of the conflict. Further, as the conflicts continue the networks themselves may be reshaped. Thus Balcells Ventura observed how patterns of lethal violence that occurred during the Spanish Civil war affected voting patterns forty years later [Ventura, 2007].

Any historical analysis needs to address the question of what gets the ball rolling. In these three studies, lots of balls receive a nudge here and a twitch there, until some of them find themselves in unfamiliar territory. A new “structure” or pattern of relationships emerges, in the shape of a Medici bank, or evolving clusters of Hungarian firms. Social ties at the level of the individual give rise to patterns or structures, like banks or patrilineages, which in turn influence social life at the level of the individual. This view of social process is not entirely new; Anthony Giddens’ influential theory of “structuration” gives a similar account of agency:

Human social activities, like some self-reproducing items in nature, are recursive. That is to say, they are not brought into being by social actors but continually recreated by them via the very means whereby they express themselves as actors. In and through their activities agents reproduce the conditions that make these activities possible. [Giddens, 1984]

Giddens’ ideas about “structuration” appeared in the early 1980s, a time when many social theorists were troubled by absence of agency in Lévi-Strauss’ struc-

turalism. By depicting social actors as the creators of structure as well as its instruments, Giddens sought both to restore agency and to emphasize temporal processes of change. But his theory was pitched at a very general level, a description of the human condition rather than a methodology for investigating specific processes of change. In contrast, the network studies described above offer insights into the topology of the possible for particular historical settings. Evolving networks are inevitably path dependent; future states are constrained by the past. But as these studies show, agency in the more powerful sense of the ability to shape genuine innovations, like Medici banks, can arise from the ordinary form of agency exhibited by people going about their daily business of commerce, marriage and politics.

2.1 Complexity and the Naturwissenschaften: evolutionary dynamics

The examples we have just considered address two fundamental questions in anthropology: the role of symbols in social life, and the relationship between agency and social structure. Here we take up another venerable question on which contemporary anthropology is sharply divided: are Darwinian processes at work in the social or cultural realms? As before, we begin by defining the issues from the perspective of complexity theory; sketch the outlines of a relevant mathematical model, and briefly consider some empirical examples.

Darwinian models in anthropology generally assume that behaviors, like genes, are constantly being scrutinized by selection. Thus “analyses typically take the form of the following question: in what environmental circumstances are the costs and benefits of behavior X such that selection would favor its evolution?” [Smith and Winterhalder, 1992, 23]. To investigate selection at the level of individuals, we compare their fecundity. The “fittest” individuals are those that produce the most offspring. Because there is always variation in fecundity, at this level it would appear that selection is always at work. But one of the key insights in the mathematical analysis of complex systems is the concept of emergent properties. In this context, one can ask, what would be the population-level consequences of selection at the level of the individual? Figure 7 illustrates three alternatives. In the first case (Fig 7a), selection is not present so the make-up of the population as time goes forward depends on drift (about which more will be said below). If selection occurs (Fig. 7b) the effect at the population level is to reduce the diversity of the population. But the evolutionary consequences of selection depend on how long it persists. Fluctuating dominance, in which some individuals in each generation attain higher reproductive fitness, but do not pass this on to their descendants, produces Red Queen dynamics (Figure 7c). The Red Queen forestalls evolution by preventing any individual or group from gaining a lasting advantage. As she explained to Alice, sometimes “it takes all the running you can do to keep in the same place.”

What about the neutral case? Until the 1960s, biologists assumed that almost

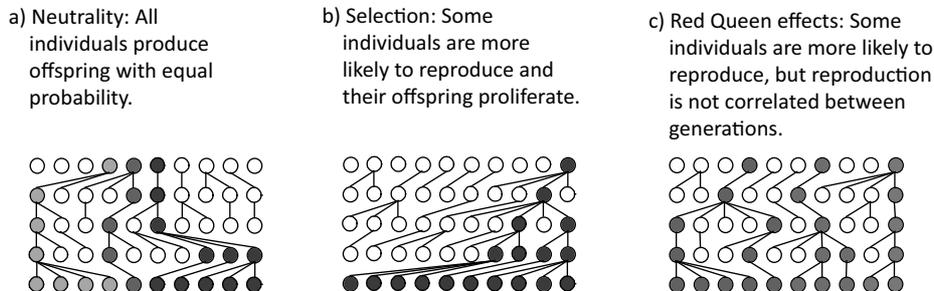


Figure 7. Selection, neutrality and Red Queen dynamics. Here each color represents a single entity with the capacity for reproduction (such as a person, a behavior or a strategy). (a) A population at neutral equilibrium; (b) another undergoing directional selection due to differential fecundity with a high inheritance coefficient; (c) Red Queen dynamics, in which higher fecundity is not strongly inherited.

all mutations are under selection. But in 1963 geneticist Motoo Kimura asked what genetic variation would look like if selection were not present. Even in the absence of selection, Kimura reasoned, evolutionary change will occur as a result of chance, and this can be analyzed with tools from probability theory. As Kimura wrote in 1983, “It is easy to invent a selectionist explanation for almost any specific observation; proving it is another story. Such facile explanatory excesses can be avoided by being more quantitative” [Kimura, 1983].

The processes that lead to neutral equilibrium can be explained with the statistician’s favorite example, a bag of colored marbles. To model the effects of drift, the experimenter reaches into the bag and grabs two marbles. One is randomly tossed aside and the other is magically duplicated; the latter (identical) pair of marbles is put back into the bag. Starting with a bag of ten marbles, each with a different color, all the marbles in the bag will be the same color after a few replacements. This process will take much longer with bags of 100 or 1000 marbles. Thus drift reduces the number of colors in the bag. Mimicking the effects of mutation can counteract this process: from time to time a marble with a new color is added to the bag as a replacement for a discarded marble. Neutral equilibrium is reached when the introduction of new colored marbles by mutation (or migration) matches the rate at which existing colors are removed by drift.

A charming example that demonstrates the application of the neutral theory to culture was recently published by Hahn and Bentley, who investigated the changing frequency of baby names in the United States. One can easily imagine selectionist explanations for the prevalence of names; for example, in each generation parents might preferentially choose the names of culturally dominant or prestigious individuals for their children. The alternative, neutral hypothesis, predicts a distribution of names governed solely by chance. While any number

of selectionist models could be proposed for the frequency distribution of baby names, there is only one neutral distribution for any given dataset. This neutral distribution depends solely on the total population size and the rate at which new names appear.

In 2002, the Social Security Administration published the thousand most common baby names in each decade of the twentieth century, based on a sample of 5% of all social security cards issued to Americans. Most parents chose a pre-existing name for their infant, but occasionally a new name was introduced. Hahn and Bentley found that the distribution of names from one decade to the next fits a power-law distribution with an r^2 value above 0.97. A very few names were extremely popular, while others persisted at decreasing frequencies. However, the prevalence of certain names also changed as the century progressed.

To explain this stable distribution of name frequencies despite changes in the popularity of particular names, the researchers created a simulation based on Kimura's neutral theory, and compared these results with the observed data. In a neutral model, random drift causes changes in the frequencies of names as they are repeatedly sampled; some are lost, other arise *de novo*, while still others drift up or down in frequency. To simulate this process, N new babies appear at each time-step and are named by copying the name of a randomly chosen baby from the previous time-step. A small fraction, m , of the N babies receive a name that was not present earlier. The neutral theory predicts that, at equilibrium, the number of variants (baby names) with frequency x at a single moment is given by $\theta x^{-1}(1-x)^{\theta-1}$ where $\theta = 4Ne\mu$ [Slatkin, 1996]. A regression between the logs of the average values of the model and the data yielded $r^2 = 0.993$ for boys' names and $r^2 = 0.994$ for girls' names. Power law distributions can result from many causes. In this case, the neutral theory predicts not only the power law distribution, but also its slope, with near-perfect accuracy. Chance, not selection, determines the frequencies at which baby names occur in the US population.

In genetics, the neutral theory was hotly debated for decades. As Kimura observed in his 1968 paper, the prevalent view in the 1960s held that almost all mutations are under selection, and this opinion was slow to change. But as Stephen J. Gould wrote in 1989, "These equations give us for the first time a baseline criterion for assessing any kind of genetic change. If neutralism holds, then actual outcomes will fit the equations. If selection predominates, then results will depart from predictions" [Gould, 1989]. This led to a fundamental reformulation of how selection was viewed in molecular biology: geneticists now infer selection only when it can be shown that the assumption of neutrality has been violated. As E.G. Leigh observed in a recent retrospective about the neutral theory, "no population geneticist, not even Kimura, sought to deny the importance of adaptive evolution. Instead, all major workers "were interested, at least to some degree, in how neutral processes affected adaptive evolution" [Leigh, 2007, p. 2076]. In ecology, as Leigh further noted [ibid, p. 2087], everyone, even the advocates of the neutral theory, recognize that neutral theory is wrong when taken to extremes: adaptive processes clearly do matter. In genetics, the question of precisely which

regions of the genome are under selection is being revisited using neutral theory [Hey, 1999].

But in anthropology, Darwinian models of cultural evolution continue to focus on selective processes occurring at the level of the individual, rather than the population-level consequences [Richerson and Boyd, 2006]. Most research in human behavioral ecology is explicitly pan-selectionist, asking “what are the fitness effects of different strategies in particular environments?” [Clarke and Low, 2001] rather than “are the behaviors we observe actually under selection?” In “The Spandrels of San Marco and the Panglossian paradigm”, their well-known critique of pan-selectionism in biology, Gould and Lewontin commented on the need for an explicit test for ‘adaptationist’ explanations:

We would not object so strenuously to the adaptationist programme if its invocation, in any particular case, could lead in principle to its rejection for want of evidence. We might still view it as restrictive and object to its status as an argument of first choice. But if it could be dismissed after failing some explicit test, then alternatives would get their chance. [Gould and Lewontin, 1979]

The neutral theory provides such a test, for cultural evolution as well as genetics and ecology. It shifts the analytical focus from selection at the level of the individual, to the population-level consequences of both selection and neutral processes over the course of multiple generations. In place of the pan-selectionist assumptions of evolutionary game theory and behavioral ecology, it provides a mathematically explicit null model. For example, a recent study investigated the magnitude of selection effects stemming from reproductive competition among men in 41 Indonesian villages [Lansing *et al.*, 2008]. Many studies have argued that reproductive skew biased toward dominant or high-ranking men is very common in human communities: “In more than one hundred well studied societies, clear formal reproductive rewards for men are associated with status: high-ranking men have the right to more wives” [Clarke and Low, 2001]. Demographic statistics collected over short time scales support these claims [Winterhalder and Smith, 2000]. Although variation in male fitness is known to occur, an important unanswered question is whether such differences are heritable and persist long enough to have evolutionary consequences at the population level.

In this study, genetic data showed that dominance effects generally do not persist over multiple generations. The lack of evidence of reproductive skew in these communities means that heritable traits or behaviors that are passed paternally, be they genetic or cultural, are unlikely to be under strong selection. The discovery that neutral processes can explain most haplotype frequency distributions in these communities parallels earlier results from the development of neutral theory in genetics and ecology. As Kimura observed in his original article, the prevalent opinion in the 1960s held that almost all mutations are under selection [Kimura, 1968]. This opinion was slow to change. More recently, ecologists similarly have suggested that a neutral model, in which species in the same trophic level are

functionally equivalent or neutral with respect to each other, might adequately explain species-abundance distributions in ecological communities [Hubbell, 2001]. In anthropology, the recent availability of appropriately sampled community-level polymorphism data now enables us to distinguish both genetic and cultural selection from neutral demographic processes with surprising precision. In these Indonesian communities, male dominance seldom translates into increased fertility among descendants over evolutionary timescales.

In both genetics and ecology, the neutral theory played an important role in introducing a systems-level dynamical perspective to evolutionary theory. One advantage for anthropology as a relative latecomer to this perspective is that anthropologists are in a position to benefit from several decades of theoretical work, including a substantial body of elegant mathematics. A particularly salient lesson may be the identical outcome of the debates that occupied both genetics and ecology for years, both of which pitted pan-selection against pan-neutrality. In both fields, this debate was largely resolved by adopting a view of neutrality as a null model, rather than as a strict alternative to Darwinism [Alonso *et al.*, 2006; Hu *et al.*, 2006].

2.2 *Coupled human and natural systems*

Our final topic is the interaction of societies with local environments. A key theoretical issue that arises from the study of such interactions, from the perspective of complex systems, is how patterns may emerge from multiple processes occurring at different scales and how spatio-temporally variegated outcomes may optimally resolve conflicts among conflicting goals irreconcilable in logic. In one of the most cited papers on this topic, Simon Levin observed that patterns are often generated by the collective behavior of smaller scale units, which “operate at different scales than those on which the patterns are observed” [Levin, 1992]. Ecological journals are filled with examples of such processes, with a growing emphasis on global-scale phenomena such as climate change. But these ideas have been slow to spread to the social sciences. Karl Marx famously dismissed the peasants as a “sack of potatoes”, and for most social scientists, it is probably still true that one piece of countryside looks much like the next. Even anthropologists are seldom inclined to search for the kinds of pattern-and-scale interactions that Levin describes.

The examples to be considered here have to do with the management of rice paddies on the island of Bali, and dipterocarp forests on the island of Borneo. We suggest that the failure of planners to appreciate the role of emergent patterns in both of these cases led to disastrous errors. It's particularly interesting to note that the dynamical processes that were vital to both cases are quite similar, even though the underlying ecologies are very different. To highlight this similarity, we begin with a model that captures the key insight. The model is “Daisyworld”, a thought experiment created by chemist James Lovelock [Lovelock, 1992]. Daisyworld has several useful features: the biology is as simple as Lovelock could make it; the

model shows precisely 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 near its limits.

Daisyworld is an imaginary planet orbiting a star like 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 given average planetary temperatures, 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. Like our own sun, the luminosity of Daisyworld's star is assumed to have gradually increased. A simulation 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 for the daisies, as shown in Fig. 8.

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 (~ 1.4) will the daisy's former role in temperature stabilization become apparent.

Lacking this understanding, planners hoping to exploit Daisyworld's economic potential as an interstellar flower supplier 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-

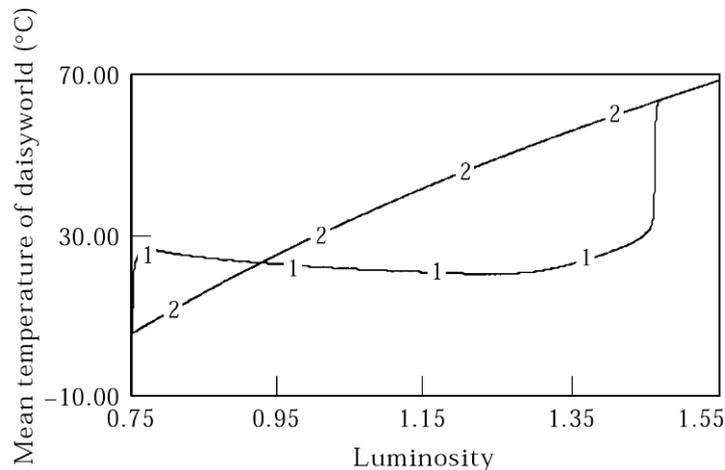


Figure 8. Results of a simulation of temperature regulation on Daisyworld. As the sun ages and its luminosity increases from 0.75 to 1.5 times the present value (1.0), the temperature of a bare planet would steadily rise (line 2). In contrast, with daisies present, the temperature stabilizes close to 22.5 C (line 1).

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.

2.2.1 Emergence in Balinese water temple networks

The Daisyworld model offers insight into the emergence of a complex adaptive system based on the role of water temples in managing wet-rice cultivation on the Indonesian island of Bali [Lansing *et al.*, 1998]. In Bali, rice is grown in paddy fields on steep hillsides fed by elaborate irrigation systems dependent on seasonal rivers and ground water flows, dominated by an elevated volcanic crater lake. Gravity-fed irrigation works route the water to the various fields. The rugged topography and interconnections among the fields create a very interdependent system that can, at times, be quite fragile and subject to major disruptions. Decisions about irrigation are made by groups of farmers who share a common water source, in a Balinese institution called a *subak* [Lansing *et al.*, 2009].

Water performs a variety of complex biological processes in the rice paddy ecosystem. Careful control of the flow of water into the fields creates pulses in several important biochemical cycles necessary for growing rice. Water cycles have a direct influence on soil PH, temperature, nutrient circulation, aerobic conditions, microorganism growth, weed suppression, etc. In general, irrigation demands are highest at the start of a new planting cycle, since the dry fields must first be

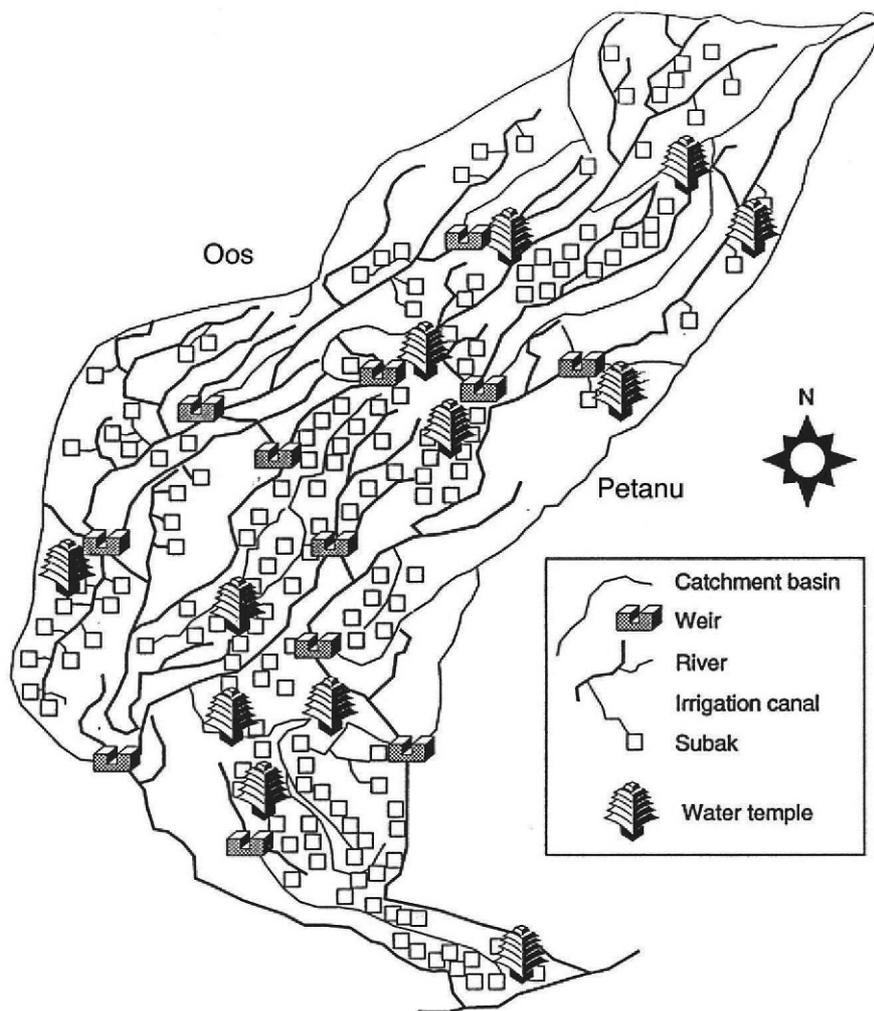


Figure 9. The Bali model.

saturated with water.

The flooding and draining of blocks of terraces also has important effects on pests (including insects, rodents, and bacterial and viral diseases). If farmers with adjacent fields can synchronize their cropping patterns to create a uniform fallow period over a sufficiently large area, rice pests are temporarily deprived of their habitat and their populations can be sharply reduced. Field data indicate that synchronized harvests result in pest losses of around 1% compared to losses upwards of 50% during continual cropping. How large an area must be fallow, and for how long, depends on specific pest characteristics. If too many subaks follow an identical cropping pattern in an effort to control pests, then peak water demands will coincide. The existing watershed seldom provides sufficient water to meet the full needs of all subaks in such a case.

Paralleling the physical system of terraces and irrigation works, the Balinese have also constructed intricate networks of shrines and temples dedicated to agricultural deities and the Goddess of the Lake. At meetings held in the temples, subaks decide on their irrigation schedules and what crops they will plant. These meetings provide a way for the subaks to coordinate cropping patterns with their neighbors, using the framework of ties that exists between the water temples. But is this system of bottom-up control effective? The key question is not whether flooding and fallowing can control pests, but rather whether the entire collection of temples in a watershed can strike an optimal balance between water sharing and pest control.

Using empirical data on the location, size and field conditions of 172 subaks in the watershed of the Oos and Petanu rivers in southern Bali in 1987-8, Lansing and Kremer modeled changes in the flow of irrigation water and the growth of rice and pests as subaks decided whether to cooperate with their neighbors. The "Bali Model" shown in Figure 9 simulates the flow of water from the headwaters of the two rivers to the sea, at monthly intervals. The amount of water available for any given subak depends on seasonal patterns of rainfall and ground water flow, and the amount of water diverted by upstream subaks for their own needs. As a new year begins, each of the 172 subaks is given a planting schedule which determines which crops it will grow, and when they will be planted. As the months go by, water flows, crops grow, and pests migrate across the landscape. When a subak harvests its crop, the model tabulates losses due to water shortages or pests. At the end of the year, aggregate harvest yields are calculated for the subaks. Subsequently, each subak checks to see whether any of its closest neighbors got higher yields. If so, the target subak copies the cropping schedule of its (best) neighbor. If none of the neighbors got better yields, the target subak retains its existing schedule. When all the subaks have made their decisions, the model cycles through another year. These simulations begin with a random distribution of cropping patterns (a typical example is shown in Fig. 10). After a year the subaks in the model begin to aggregate into patches following identical cropping patterns, which helps to reduce pest losses. As time goes on these patches grow until they overshoot, causing water stress and patch sizes to become smaller. Yields fluctuate but gradually rise. The

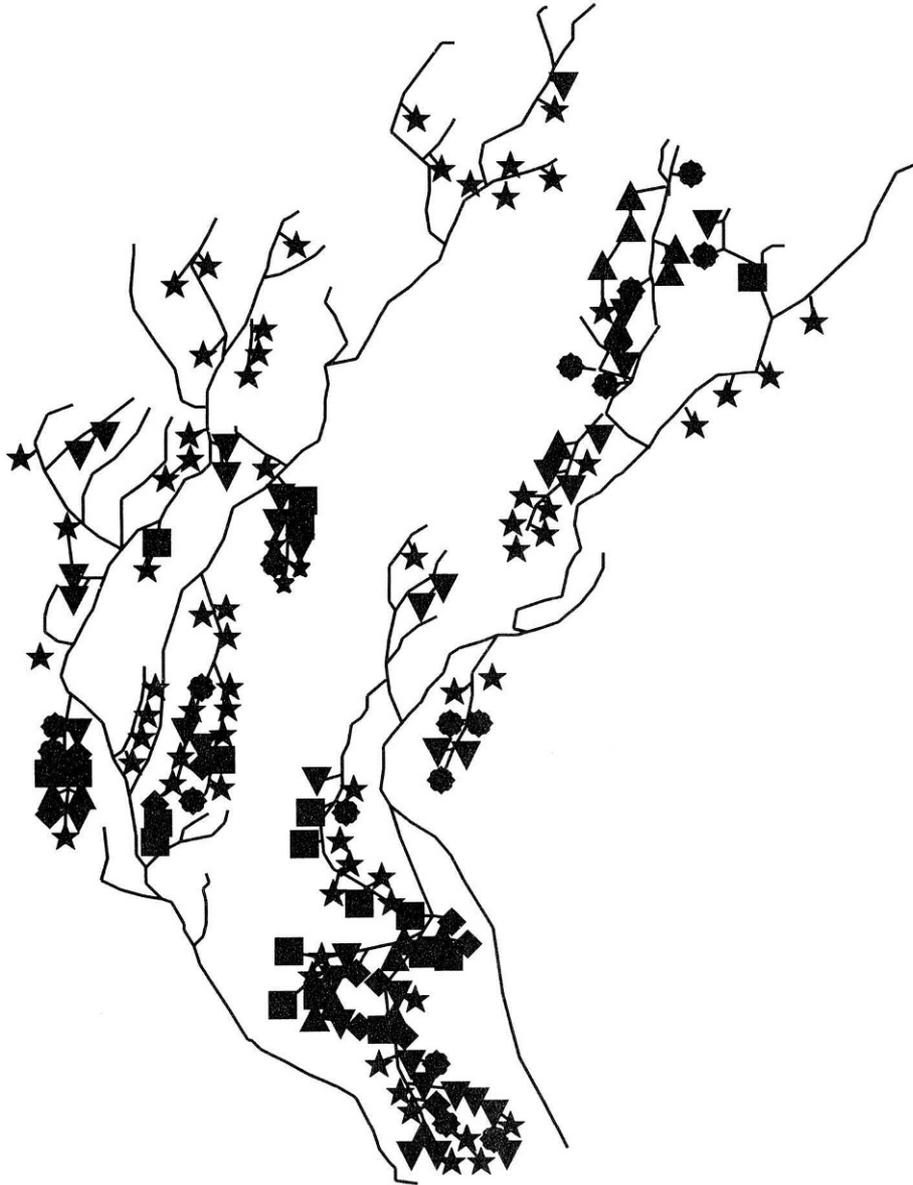


Figure 10. Initial conditions for a simulation model of irrigation flows and rice and pest growth for 172 subaks. Differences in cropping patterns are indicated by different symbols (subaks with the same symbols have identical cropping patterns).

program continues until most subaks have discovered an optimal cropping pattern, meaning that they cannot do better by imitating one of their neighbors.

Experiments with this model indicate that the entire collection of subaks quickly settles down into a stable pattern of synchronized cropping schedules that optimizes both pest control and water sharing. The close relationship between this pattern as calculated in the model (Fig. 11), and the actual pattern of synchronized planting units (Fig. 12) is apparent. In the model, as patterns of coordination resembling the water temple networks emerge, both the mean harvest yield and the highest yield increase, while variance in yield across subaks declines (Fig. 13). In other words, after just a few years of local experimentation, yields rise for everyone while variation in yields declines. Subsequent simulations showed that if the environment is perturbed, either by decreasing rainfall or by increasing the virulence of pests, a few subaks change their cropping patterns, but within a few years a new equilibrium is achieved [Lansing, 2006, 67-88].

These results helped explain the decline in rice production in Bali that began in the 1970s, after farmers were ordered to stop planting native Balinese rice according to the temple calendars, and instead plant hybrid “Green Revolution” rice as fast as possible [Lansing, 1991]. While the “Green Revolution” rice could grow faster and produce more grain than the native plants, these potential gains were offset by the disruptions caused by abandoning the temple calendars. This effect can be demonstrated in the simulation model by running it in reverse: beginning with a patchwork of synchronized multi-subak groups, and breaking up synchrony by encouraging the subaks to compete with one another.

2.2.2 *Emergence in the dipterocarp forests of Borneo*

Are the water temples of Bali a unique case? This question came up soon after the Bali Model analyses were published. Perhaps the Maya or the ancient Khmer had invented something like the Balinese water temples? But so far, the most interesting comparison comes from a site much closer to Bali. And it has nothing to do with irrigation, temples or rice.

In 1967, the year the Green Revolution in rice began in most of Indonesia, another government program opened the forests of the Outer Islands to logging for export. Like the Green Revolution, this policy inadvertently set in motion an experimental test of the resilience of a tropical ecosystem. And like the Green Revolution, it produced immediate, spectacular results. By the early 1970s, logging exports were generating annual export earnings of over US\$1.5 billion, eventually rising to as much as \$6 billion.³ As the Ministry of Forestry proclaimed in 1990,

The logging industry is a champion of sorts. It opens up inaccessible areas to development; it employs people, it evolves whole communities; it supports related industries. . . It creates the necessary conditions for

³“Over the past two decades, the volume of dipterocarp timber exports (in cubic meters) from Borneo (Kalimantan, Sarawak and Sabah) exceeded all tropical wood exports from tropical Africa and Latin America combined” [Curran *et al.*, 2004].

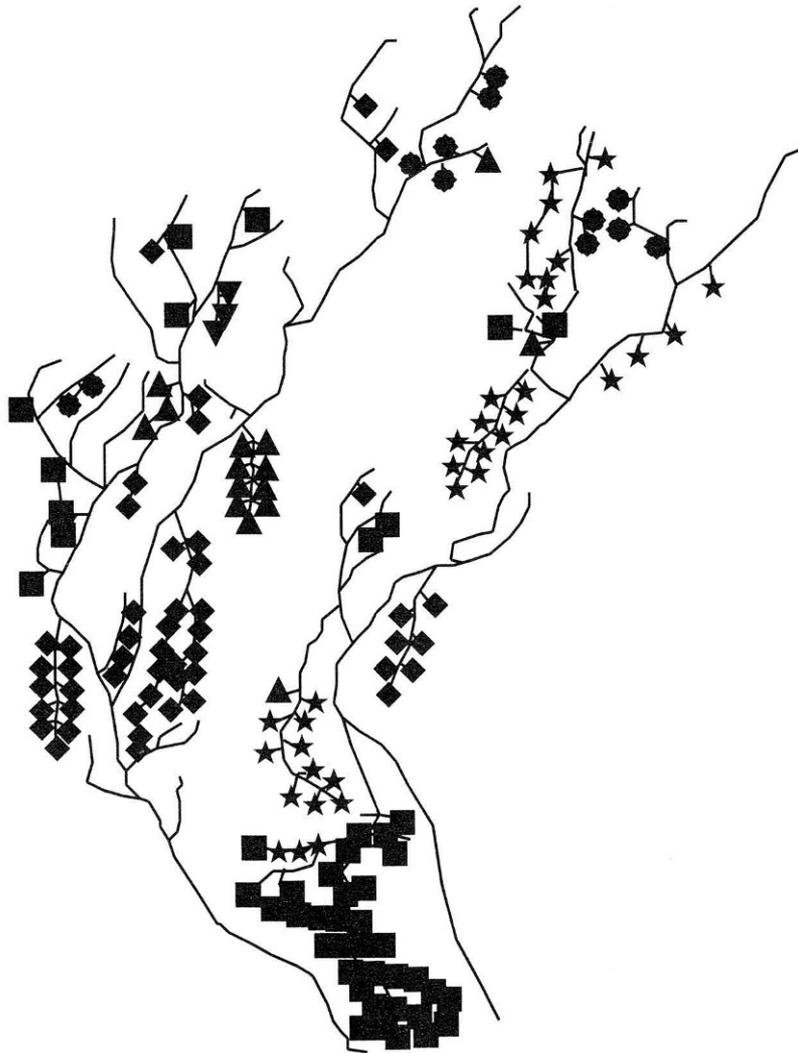


Figure 11. Model cropping patterns after 11 years

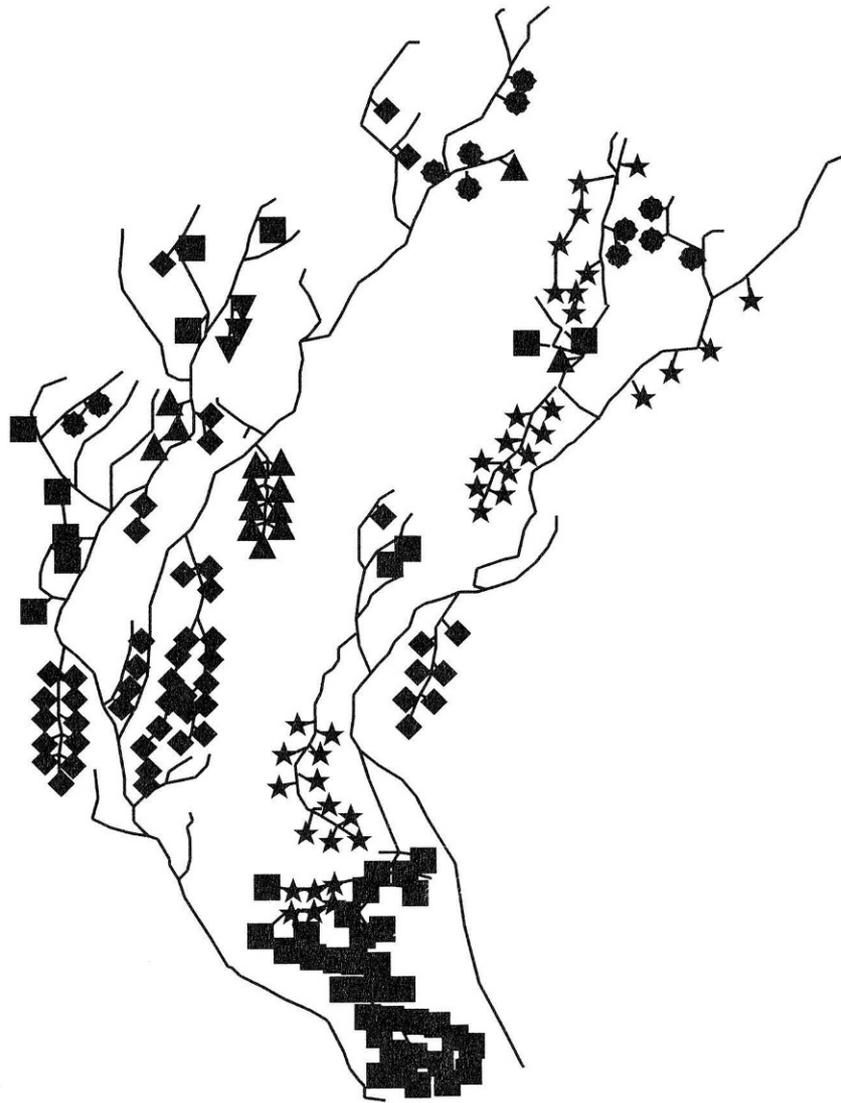


Figure 12. Actual observed cropping patterns (1987)

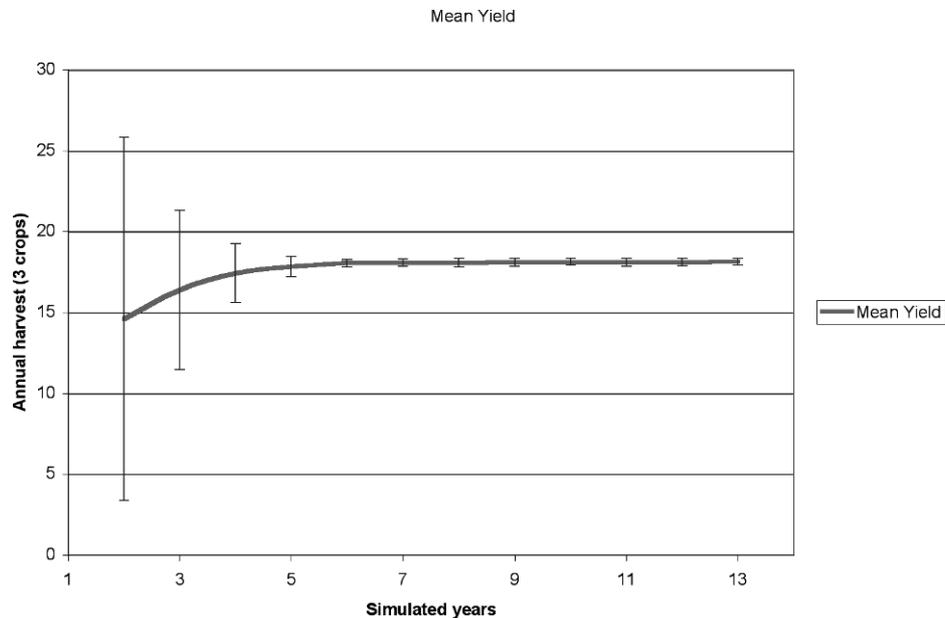


Figure 13. Reduction in variance of harvest yields as cooperation spreads in the simulation model of the Oos and Petanu watersheds. Rainfall, rice and pest parameters based on data collected in 1988.

social and economic development. Without forest concessions most of the Outer Islands would still be underdeveloped. [Government of Indonesia, 1990]

By the 1980s, in response to indications of forest degradation from logging, the Ministry began to promote industrial tree plantations for the pulp and paper industry, supported by interest-free loans from the “Reforestation Fund” and international investment. Along with reforestation, the government also encouraged the creation of palm oil plantations on logged land. Sawmills, logging roads and palm plantations proliferated in the 1990s, and exports of pulp, paper and palm oil boomed. In 2002, export taxes on raw logs were eliminated and Indonesian firms were permitted to sell logs to anyone. Plans for biodiversity conservation were based on selective logging and reforestation, and the creation of national parks [Gellert, 2005].

The dominant canopy tree family in Borneo and Sumatra is the *dipterocarpaceae*, which consists of ~ 267 tree species that make up over 85% of Indonesia’s tree exports. The sustainability of the timber industry thus depends on the regenerative capacity of dipterocarp forests. In 1999, ecologist Lisa Curran and her colleagues reported the results of a comprehensive 14 year investigation of the ability of the dipterocarps to reproduce. Regrowth depends on the survival of sufficient

quantities of seedlings. Many forest animals and birds are seed predators, so the trees are engaged in a continuous race to produce more seeds than the predators can consume. Curran found that long ago, the trees evolved essentially the same solution to the problem of controlling predation that was later discovered by the Balinese farmers: reproductive synchrony. Dipterocarp forests produce nearly all of their seeds and fruits within a very small window in time, in a phenomenon known to ecologists as “mast fruiting.” For seed predators, this means that large quantities of dipterocarp fruits and seeds only become available in short irregular bursts that occur every 3–6 years, triggered by the El Niño Southern Oscillation (ENSO). ENSO is a global climatic cycle that causes an extreme reduction in rainfall in Borneo from June to September. The ENSO dry spell is used by the trees as a signal to initiate flowering and reproduction. Seed predators respond by synchronizing their own reproductive cycles to ENSO years, and by moving across the landscape, far from their usual ranges, to feed on dipterocarp seeds.

Over the past three decades, the harvesting of timber caused widespread fragmentation of what had formerly been a vast contiguous expanse of dipterocarp forest in Borneo, disrupting regional reproductive synchrony. Once synchrony was lost, small-scale local masts could not produce enough seedlings to escape being eaten by predators. Curran found that “Seed escape, and thus regeneration, only occurred in major mast events when all dipterocarp species across large areas participated” [Curran and Leighton, 2000]. This closely parallels the Balinese case. In the rice terraces of Bali, the “Green Revolution” caused disruption of the synchronized planting schedules formerly organized by water temple networks. This led to crop losses, as migrating pests moved across the landscape consuming one harvest after the next. Similarly, in Borneo the mast synchrony of canopy trees in ENSO years was triggered by signals transmitted through the root system. When the forests became fragmented, it was no longer possible to overwhelm predators with a vast synchronized mast.

We now know that in both Bali and Borneo, large-scale reproductive synchrony emerged as a solution to the problem of controlling seed predators. But in both cases, this cyclical pattern was invisible to planners. In Bali, the farmers were able to respond in the nick of time and restore control to the temple networks. But the trees were not so fortunate. The latest research by Curran and her colleagues shows that the lowland forests of Indonesian Borneo have lost the capacity to regenerate, probably beyond hope of recovery. As a consequence, ENSO — formerly a great forest regenerator — has become a destructive regional phenomenon, triggering droughts and wildfires with increasing intensity. By the 1990s, much of Indonesian Borneo had been deforested, leaving logging debris in place of canopy trees. When ENSO arrived in 1998, forest fires raged across the island and four hundred million metric tons of carbon were released into the atmosphere. Even peat swamps caught fire, adding another two hundred million tons of carbon. (For comparison, the Kyoto target for reduction in carbon emission for the whole earth was five hundred million tons).⁴

⁴Curran estimated that in 2005, less than 35% of the lowland forests (<500 m a.s.l.) were

Thus in both Borneo and Bali, synchronized growing cycles emerged as a solution to the problem of controlling predator populations in the winterless tropics, imposing a clockwork pattern on the life cycles of many species. At least in this respect, the water temple networks of Bali are not unique. Might other, similar systems exist elsewhere? If so, would they always be driven by the need for predator control? How much of the functional structure of the water temple networks is directly tied to the ecology of Bali or the biology of pests? These questions remain open. The temple networks came into view partly as a result of the Green Revolution, which exposed their ecological role, and partly through our expanding familiarity with the properties of complex adaptive systems like Daisyworld. Indeed, the enduring message of this case may be how easy it was to miss the significance of the temple networks, just as planners failed to appreciate the functional significance of the “forest clock” in Borneo.

3 CONCLUSION: COMPLEXITY AND ANTHROPOLOGY

In one of the foundational articles that launched complexity studies, physicist P.W. Anderson quoted Marx's observation that quantitative differences become qualitative differences. “More is different”, Anderson observes, because at each new level of complexity entirely new properties appear [Anderson, 1972]. By tracing patterns of interaction among the elements of a system, one can sometimes discover emergent properties at a higher level. This phenomenon is common to all of the examples we have considered here, from semiotics to agency, innovation, cultural evolution and human-environmental interactions. But until recently our mathematical tools were not well suited to investigate emergence, or other properties of out-of-equilibrium dynamical systems. As recently as 1990, Karl Popper argued that social scientists who wish to take advantage of mathematics have the choice of only two approaches [Popper, 1990, 18-19]. The first is essentially Newtonian and is best represented by general equilibrium theories, for example in economics. Such theories take the form of systems of differential equations describing the behavior of simple homogeneous social actors. Change occurs as a result of perturbations and merely leads from one equilibrium state to another. The second type of theory is statistical. If one cannot write the equations to define a dynamical system, it may yet be possible to observe statistical regularities in social phenomena. Both approaches have obvious weaknesses: the assumption of equilibrium is forced by the mathematics, not by the observation of social behavior, and sifting for patterns with descriptive statistics is at best an indirect method for discovering causal or developmental relationships.

The landscape looks very different today. Out-of-equilibrium systems are the main topic of complexity research, and there has been a proliferation of new analytical methods to investigate them. Of particular interest to anthropologists are the models of “artificial societies”, of which the “Bali Model” described above is

still standing, most of them already degraded (*personal communication*).

an example. Artificial societies are computational models comprised of populations of social agents that flourish in artificial environments. While the behavior of the agents is governed by explicit rules, their behavior can change in response to changes in the environment or as a consequence of learning and memory. In this way the behavior of agents can become heterogeneous in ways that cannot occur in conventional equilibrium models. Further, agents can retain this local variability, which becomes dynamically relevant to future possibilities. Repeated simulations enable the investigator to study how such model systems evolve over time, and to investigate their global properties. These features have helped make artificial societies the most common route by which anthropologists and archaeologists have become interested in the study of complex systems [Lansing, 2002].

But today, forward-in-time simulations of artificial societies are just one of many approaches to complexity research in anthropology. Thus in molecular anthropology, a maximum likelihood approach is used to assess backward-in-time models of stochastic processes [Majoram and Tavaré, 2006]. These methods are now being adopted in historical linguistics, triggering something of a methodological revolution as coalescent models are adapted to linguistic data [Pagel, Mace, 2004]. Maximum likelihood methods are also being introduced to network analysis, supplementing descriptive statistics with forward-in-time network simulations [Robins and Morris, 2007]. Along with these probabilistic methods, anthropologists have also begun to study formal models of nonlinear dynamical systems and complex adaptive systems. Robustness and resilience are among the themes that have recently emerged. The notion of robustness captures our intuitive sense of one of the key determinants of long-term success or failure. This topic comes to us from physics and engineering, and focuses on the ability of a system to maintain specified features when subject to assemblages of perturbations, either internal or external [Jen, 2005]. In contrast, the concept of resilience originated in ecology with C.S. Holling, in his studies of the properties of adaptive cycles [Holling, 2001]. Both approaches encourage the investigator to think about tradeoffs between robustness (or resilience) and evolvability. Stepping further back, it is clear that many anthropological questions involve the analysis of systems that possess structures, topologies, networks and adaptive dynamics. The study of these phenomena by anthropologists has just begun.

We conclude with a final thought about the relationship of complexity studies to the historic divide in anthropology between the Geistes- and Naturwissenschaften. It is interesting to speculate whether the concepts and methods we have considered may have the potential to render this distinction obsolete. In the famous debate between Karl Popper and the “Critical theorists” of the Frankfurt School, Theodor Adorno offered an interesting rationale for his critique of the equilibrium theories and descriptive statistics of positivist science. Adorno argued that social theory must be able to conceive of an alternative to contemporary society: “only through what it is not will it disclose itself as it is...” [Adorno *et al.*, 1976, 296]. This led him 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.” To break the seal of reification on the existing social order, he argued, it is necessary to go beyond descriptive statistics or equilibrium models to explore historical contingency. But the mathematical tools that might assist this kind of investigation did not yet exist. Today, they do.

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