it can address the inherent heterogeneity in who meets whom. This application can be extended to social networks as a way to estimate the spread of disease (*30*) and the evolution of cooperation (*31*) in heterogeneous societies.

Conclusions

Networks are useful descriptors of ecological systems that can show the composition of and interactions between multiple elements. The application of networks to ecosystems provides a conceptual framework to assess the consequences of perturbations at the community level. This may serve as a first step toward a more predictive ecology in the face of global environmental change. Networks are also able to introduce heterogeneity into our previously homogeneous theories of populations, diseases, and societies. Finally, networks have allowed us to find generalities among seemingly different systems that, despite their disparate nature, may have similar processes of formation and/or similar forces acting on their architecture in order to be functional. Although we have only begun to understand how changes in the environment affect species interactions and ecosystem dynamics through analyses of simple pairwise interactions, network thinking can provide a means by which to assess key questions such as how overfishing can cause trophic cascades, or how the disruption of mutualisms may reduce the entire pollination service within a community (*25*). As the flow of ideas among seemingly unrelated fields increases (a characteristic attribute of research on complex systems), we envision the creation of more powerful models that are able to more accurately predict the responses to perturbations of food webs, a major challenge for today's ecologist.

References and Notes

1. C. Darwin, *On the Origin of Species by Means of Natural Selection* (John Murray, London, 1859).
2. J. E. Cohen, *Food Webs and Niche Space* (Princeton Univ. Press, Princeton, NJ, 1978).
3. S. L. Pimm, *Food Webs* (Chapman & Hall, London, 1982).
4. G. Sugihara, thesis, Princeton University, Princeton, NJ, 1982.
5. R. M. May, *Nature* **238**, 413 (1972).
6. M. Pascual, J. A. Dunne, *Ecological Networks. Linking Structure to Dynamics in Food Webs* (Oxford Univ. Press, Oxford, 2006).
7. J. M. Montoya, S. L. Pimm, R. V. Solé, *Nature* **442**, 259 (2006).
8. R. Milo *et al*., *Science* **298**, 824 (2002).
9. D. B. Stouffer, J. Camacho, W. Jiang, L. A. N. Amaral, *Proc. R. Soc. London Ser. B* **274**, 1931 (2007).
10. M. Kondoh, *Proc. Natl. Acad. Sci. U.S.A.* **105**, 16631 (2008).
11. J. Bascompte, C. J. Melián, E. Sala, *Proc. Natl. Acad. Sci. U.S.A.* **102**, 5443 (2005).
12. S. B. Otto, B. C. Rall, U. Brose, *Nature* **450**, 1226 (2007).
13. J. N. Thompson, *The Geographic Mosaic of Coevolution* (Univ. of Chicago Press, Chicago, 2005).
14. J. Bascompte, P. Jordano, *Annu. Rev. Ecol. Evol. Syst.* **38**, 567 (2007).
15. J. A. Dunne, R. Williams, N. Martinez, *Ecol. Lett.* **5**, 558 (2002).
16. J. Memmott, N. M. Waser, M. V. Price, *Proc. R. Soc. London Ser. B* **271**, 2605 (2004).
17. E. L. Rezende, J. E. Lavabre, P. R. Guimarães Jr., P. Jordano, J. Bascompte, *Nature* **448**, 925 (2007).
18. O. L. Petchey, A. Eklof, C. Borrvall, B. Ebenman, *Am. Nat.* **171**, 568 (2008).
19. A. Dobson *et al*., *Ecology* **87**, 1915 (2006).
20. R. D. Holt, in *Multitrophic Interactions in Terrestrial Ecosystems*, A. C. Gange, V. K. Brown, Eds. (Blackwell Science, Oxford, 1997), pp. 333–349.
21. U. Brose, R. J. Williams, N. D. Martinez, *Ecol. Lett.* **9**, 1228 (2006).
22. E. L. Berlow *et al*., *Proc. Natl. Acad. Sci. U.S.A.* **106**, 187 (2009).
23. U. Bastolla *et al*., *Nature* **458**, 1018 (2009).
24. C. J. Melián, J. Bascompte, P. Jordano, V. Křivan, *Oikos* **118**, 122 (2009).
25. J. M. Tylianakis, R. K. Didham, J. Bascompte, D. A. Wardle, *Ecol. Lett.* **11**, 1351 (2008).
26. M. A. Aizen, C. L. Morales, J. M. Morales, *PLoS Biol.* **6**, e31 (2008).
27. I. Hanski, O. Ovaskainen, *Nature* **404**, 755 (2000).
28. D. Urban, T. H. Keitt, *Ecology* **82**, 1205 (2001).
29. R. J. Dyer, J. D. Nason, *Mol. Ecol.* **13**, 1713 (2004).
30. J. P. Aparicio, M. Pascual, *Proc. R. Soc. London Ser. B* **274**, 505 (2007).
31. H. Ohtsuki, C. Hauert, E. Lieberman, M. A. Nowak, *Nature* **441**, 502 (2006).

32. I thank L.-F. Bersier, P. Buston, J. E. Cohen, J. Dunne, M. A. Fortuna, R. D. Holt, P. Jordano, T. Keitt, J. Lavabre, R. M. May, J. Olesen, D. Stouffer, G. Sugihara, J. N. Thompson, J. Tylianakis, and two anonymous reviewers for comments on a previous draft. P. Jordano, A. Aparicio, and M. A. Fortuna provided material for Fig. 1. Funded by the European Heads of Research Councils, the European Science Foundation, and the European Community Sixth Framework Programme through a European Young Investigator Award.

10.1126/science.1170749

PERSPECTIVE

A General Framework for Analyzing Sustainability of Social-Ecological Systems

Elinor Ostrom[1,2]*

A major problem worldwide is the potential loss of fisheries, forests, and water resources. Understanding of the processes that lead to improvements in or deterioration of natural resources is limited, because scientific disciplines use different concepts and languages to describe and explain complex social-ecological systems (SESs). Without a common framework to organize findings, isolated knowledge does not cumulate. Until recently, accepted theory has assumed that resource users will never self-organize to maintain their resources and that governments must impose solutions. Research in multiple disciplines, however, has found that some government policies accelerate resource destruction, whereas some resource users have invested their time and energy to achieve sustainability. A general framework is used to identify 10 subsystem variables that affect the likelihood of self-organization in efforts to achieve a sustainable SES.

The world is currently threatened by considerable damage to or losses of many natural resources, including fisheries, lakes, and forests, as well as experiencing major reductions in biodiversity and the threat of massive climatic change. All humanly used resources are embedded in complex, social-ecological systems (SESs). SESs are composed of multiple subsystems and internal variables within these subsystems at multiple levels analogous to organisms composed of organs, organs of tissues, tissues of cells, cells of proteins, etc. (*1*). In a complex SES, subsystems such as a resource system (e.g., a coastal fishery), resource units (lobsters), users (fishers), and governance systems (organizations and rules that govern fishing on that coast) are relatively separable but interact to produce outcomes at the SES level, which in turn feed back to affect these subsystems and their components, as well other larger or smaller SESs.

Scientific knowledge is needed to enhance efforts to sustain SESs, but the ecological and social sciences have developed independently and do not combine easily (*2*). Furthermore, scholars have tended to develop simple theoretical models to analyze aspects of resource problems and to prescribe universal solutions. For example, theoretical predictions of the destruction of natural resources due to the lack of recognized property systems have led to one-size-fits-all recommendations to impose particular policy solutions that frequently fail (*3*, *4*).

The prediction of resource collapse is supported in very large, highly valuable, open-access systems when the resource harvesters are diverse, do not communicate, and fail to develop rules and norms for managing the resource (*5*) The dire predictions, however, are not supported under conditions that enable harvesters and local leaders to self-organize effective rules to manage a resource

[1]Workshop in Political Theory and Policy Analysis, Indiana University, Bloomington, IN 47408, USA. [2]Center for the Study of Institutional Diversity, Arizona State University, Tempe, AZ 85287, USA.

*E-mail: ostrom@indiana.edu

or in rigorous laboratory experiments when subjects can discuss options to avoid overharvesting (*3*, *6*).

A core challenge in diagnosing why some SESs are sustainable whereas others collapse is the identification and analysis of relationships among multiple levels of these complex systems at different spatial and temporal scales (*7*–*9*). Understanding a complex whole requires knowledge about specific variables and how their component parts are related (*10*). Thus, we must learn how to dissect and harness complexity, rather than eliminate it from such systems (*11*). This process is complicated, however, because entirely different frameworks, theories, and models are used by different disciplines to analyze their parts of the complex multilevel whole. A common, classificatory framework is needed to facilitate multidisciplinary efforts toward a better understanding of complex SESs.

I present an updated version of a multilevel, nested framework for analyzing outcomes achieved in SESs (*12*). Figure 1 provides an overview of the framework, showing the relationships among four first-level core subsystems of an SES that affect each other as well as linked social, economic, and political settings and related ecosystems. The subsystems are (i) resource systems (e.g., a designated protected park encompassing a specified territory containing forested areas, wildlife, and water systems); (ii) resource units (e.g., trees, shrubs, and plants contained in the park, types of wildlife, and amount and flow of water); (iii) governance systems (e.g., the government and other organizations that manage the park, the specific rules related to the use of the park, and how these rules are made); and (iv) users (e.g., individuals who use the park in diverse ways for sustenance, recreation, or commercial purposes). Each core subsystem is made up of multiple second-level variables (e.g., size of a resource system, mobility of a resource unit, level of governance, users' knowledge of the resource system) (Table 1), which are further composed of deeper-level variables .

This framework helps to identify relevant variables for studying a single focal SES, such as the lobster fishery on the Maine coast and the fishers who rely on it (*13*). It also provides a common set of variables for organizing studies of similar SESs such as the lakes in northern Wisconsin (e.g., why are the pollution levels in some lakes worse than in others?) (*14*), forests around the world (e.g., why do some locally managed forests thrive better than government-protected forests?) (*15*), or water institutions (e.g., what factors affect the likelihood that farmers will effectively manage irrigation systems?) (*16*). Without a framework to organize relevant variables identified in theories and empirical research, isolated knowledge acquired from studies of diverse resource systems in different countries by biophysical and social scientists is not likely to cumulate.

A framework is thus useful in providing a common set of potentially relevant variables and their subcomponents to use in the design of data collection instruments, the conduct of fieldwork, and the analysis of findings about the sustainability of complex SESs. It helps identify factors that may affect the likelihood of particular policies enhancing sustainability in one type and size of resource system and not in others. Table 1 lists the second-level variables identified in many empirical studies as affecting interactions and outcomes. The choice of relevant second or deeper levels of variables for analysis (from the large set of variables at multiple levels) depends on the particular questions under study, the type of SES, and the spatial and temporal scales of analysis.

To illustrate one use of the SES framework, I will focus on the question: When will the users of a resource invest time and energy to avert "a tragedy of the commons"? Garrett Hardin (*17*) earlier argued that users were trapped in accelerated overuse and would never invest time and energy to extract themselves. If that answer were supported by research, the SES framework would not be needed to analyze this question. Extensive empirical studies by scholars in diverse disciplines have found that the users of many (but not all) resources have invested in designing and implementing costly governance systems to increase the likelihood of sustaining them (*3*, *6*, *7*, *18*).

A theoretical answer to this question is that when expected benefits of managing a resource exceed the perceived costs of investing in better rules and norms for most users and their leaders, the probability of users' self-organizing is high (supporting online material text). Although joint benefits may be created, self-organizing to sustain a resource costs time, and effort can result in a loss of short-term economic gains. These costs, as well as the fear that some users will cheat on rules related to when, where, and how to harvest, can lead users to avoid costly changes and continue to overharvest (*6*). Accurate and reliable measures of users' perceived benefits and costs are difficult and costly to obtain, making it hard to test theories based on users' expected net benefits.

Multiple variables that have been observed and measured by field researchers are posited to affect the likelihood of users' engaging in collective action to self-organize. Ten second-level variables (indicated by asterisks in Table 1) are frequently identified as positively or negatively affecting the likelihood of users' self-organizing to manage a resource (*3*, *6*, *19*, *20*). To explain why these variables are potentially important for understanding sustainability and, in particular, for addressing the question of when self-organization activities will occur, I briefly discuss how they affect perceived benefits and costs.

Size of resource system (RS3). For land-related resource systems, such as forests, very large territories are unlikely to be self-organized given the high costs of defining boundaries (e.g., surrounding with markers or fences), monitoring use patterns, and gaining ecological knowledge. Very small territories do not generate substantial flows of valuable products. Thus, moderate territorial size is most conducive to self-organization (*15*). Fishers who consistently harvest from moderately sized coastal zones, lakes, or rivers are also more likely to organize (*13*) than fishers who travel the ocean in search of valuable fish (*5*).

Productivity of system (RS5). A resource system's current productivity has a curvilinear effect on self-organization across all sectors. If a water source or a fishery is already exhausted or apparently very abundant, users will not see a need to manage for the future. Users need to observe some

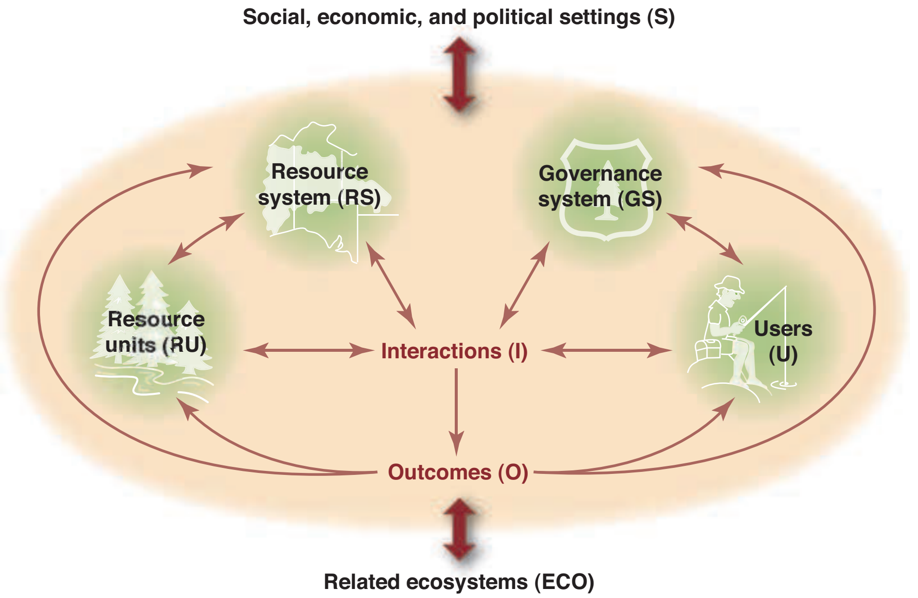

Fig. 1. The core subsystems in a framework for analyzing social-ecological systems.

scarcity before they invest in self-organization (*19*).

Predictability of system dynamics (RS7). System dynamics need to be sufficiently predictable that users can estimate what would happen if they were to establish particular harvesting rules or no-entry territories. Forests tend to be more predictable than water systems. Some fishery systems approach mathematical chaos and are particularly challenging for users or government officials (*21*). Unpredictability at a small scale may lead users of pastoral systems to organize at larger scales to increase overall predictability (*22*, *23*).

Resource unit mobility (RU1). Due to the costs of observing and managing a system, self-organization is less likely with mobile resource units, such as wildlife or water in an unregulated river, than with stationary units such as trees and plants or water in a lake (*24*).

Number of users (U1). The impact of group size on the transaction costs of self-organizing tends to be negative given the higher costs of getting users together and agreeing on changes (*19*, *20*). If the tasks of managing a resource, however, such as monitoring extensive community forests in India, are very costly, larger groups are more able to mobilize necessary labor and other resources (*25*). Thus, group size is always relevant, but its effect on self-organization depends on other SES variables and the types of management tasks envisioned.

Leadership (U5). When some users of any type of resource system have entrepreneurial skills and are respected as local leaders as a result of prior organization for other purposes, self-organization is more likely (*19*, *20*). The presence of college graduates and influential elders, for example, had a strong positive effect on the establishment of irrigation organization in a stratified sample of 48 irrigation systems in Karnataka and Rajasthan, India (*16*).

Norms/social capital (U6). Users of all types of resource systems who share moral and ethical standards regarding how to behave in groups they form, and thus the norms of reciprocity, and have sufficient trust in one another to keep agreements will face lower transaction costs in reaching agreements and lower costs of monitoring (*20*, *26*, *27*).

Knowledge of the SES (U7). When users share common knowledge of relevant SES attributes, how their actions affect each other, and rules used in other SESs, they will perceive lower costs of organizing (*7*). If the resource system regenerates slowly while the population grows rapidly, such as on Easter Island, users may not understand the carrying capacity of the resource, fail to organize, and destroy the resource (*28*).

Importance of resource to users (U8). In successful cases of self-organization, users are either dependent on the RS for a substantial portion of their livelihoods or attach high value to the sustainability of the resource. Otherwise, the costs of organizing and maintaining a self-governing system may not be worth the effort (*3*, *7*, *15*).

Collective-choice rules (GS6). When users, such as the Seri fishers in Mexico (*29*) and forest user groups in Nepal (*30*), have full autonomy at the collective-choice level to craft and enforce some of their own rules, they face lower transaction costs as well as lower costs in defending a resource against invasion by others (*5*).

Obtaining measures for these 10 variables is the first step in analyzing whether the users of one or more SESs would self-organize. Data analysis of these relationships is challenging, because the impact of any one variable depends on the values of other SES variables. As in most complex systems, the variables interact in a nonlinear fashion (*8*–*10*). Furthermore, although the long-term sustainability of SESs is initially dependent on users or a government to establish rules, these rules may not be sufficient over the long run (*7*, *18*).

If the initial set of rules established by the users, or by a government, are not congruent with local conditions, long-term sustainability may not be achieved (*8*, *9*, *18*). Studies of irrigation systems (*16*, *26*), forests (*25*, *31*), and coastal fisheries (*13*) suggest that long-term sustainability depends on rules matching the attributes of the resource system, resource units, and users. Rules forbidding the harvest of pregnant female fish are easy to monitor and enforce in the case of lobster, where eggs are visibly attached to the belly, and have been important in sustaining lobster fisheries (*13*). However, monitoring and enforcing these rules have proven more difficult in the case of gravid fish, where the presence of internal eggs is harder to assess.

Comparative studies of rules used in long-surviving resource systems governed by traditional societies document the wide diversity of rules used across sectors and regions of the world (*21*). Simple blueprint policies do not work. For example, the total allowable catch quotas established by the Canadian government for the west coast of Canada led to widespread dumping of unwanted fish, misrepresentation of catches, and the closure of the groundfishery in 1995 (*32*). To

Table 1. Examples of second-level variables under first-level core subsystems (S, RS, GS, RU, U, I, O and ECO) in a framework for analyzing social-ecological systems. The framework does not list variables in an order of importance, because their importance varies in different studies. [Adapted from (*12*)]

Social, economic, and political settings (S)	
S1 Economic development. S2 Demographic trends. S3 Political stability. S4 Government resource policies. S5 Market incentives. S6 Media organization.	
Resource systems (RS)	*Governance systems (GS)*
RS1 Sector (e.g., water, forests, pasture, fish)	GS1 Government organizations
RS2 Clarity of system boundaries	GS2 Nongovernment organizations
RS3 Size of resource system*	GS3 Network structure
RS4 Human-constructed facilities	GS4 Property-rights systems
RS5 Productivity of system*	GS5 Operational rules
RS6 Equilibrium properties	GS6 Collective-choice rules*
RS7 Predictability of system dynamics*	GS7 Constitutional rules
RS8 Storage characteristics	GS8 Monitoring and sanctioning processes
RS9 Location	
Resource units (RU)	*Users (U)*
RU1 Resource unit mobility*	U1 Number of users*
RU2 Growth or replacement rate	U2 Socioeconomic attributes of users
RU3 Interaction among resource units	U3 History of use
RU4 Economic value	U4 Location
RU5 Number of units	U5 Leadership/entrepreneurship*
RU6 Distinctive markings	U6 Norms/social capital*
RU7 Spatial and temporal distribution	U7 Knowledge of SES/mental models*
	U8 Importance of resource*
	U9 Technology used
Interactions (I) → outcomes (O)	
I1 Harvesting levels of diverse users	O1 Social performance measures (e.g., efficiency, equity, accountability, sustainability)
I2 Information sharing among users	O2 Ecological performance measures (e.g., overharvested, resilience, bio-diversity, sustainability)
I3 Deliberation processes	O3 Externalities to other SESs
I4 Conflicts among users	
I5 Investment activities	
I6 Lobbying activities	
I7 Self-organizing activities	
I8 Networking activities	
Related ecosystems (ECO)	
ECO1 Climate patterns. ECO2 Pollution patterns. ECO3 Flows into and out of focal SES.	

*Subset of variables found to be associated with self-organization.

remedy this initial failure, the government reopened the fishery but divided the coastal area into more than 50 sectors, assigned transferable quotas, and required that all ships have neutral observers onboard to record all catches (*32*).

Furthermore, the long-term sustainability of rules devised at a focal SES level depends on monitoring and enforcement as well their not being overruled by larger government policies. The long-term effectiveness of rules has been shown in recent studies of forests in multiple countries to depend on users' willingness to monitor one another's harvesting practices (*15*, *31*, *33*, *34*). Larger-scale governance systems may either facilitate or destroy governance systems at a focal SES level. The colonial powers in Africa, Asia, and Latin America, for example, did not recognize local resource institutions that had been developed over centuries and imposed their own rules, which frequently led to overuse if not destruction (*3*, *7*, *23*).

Efforts are currently under way to revise and further develop the SES framework presented here with the goal of establishing comparable databases to enhance the gathering of research findings about processes affecting the sustainability of forests, pastures, coastal zones, and water systems around the world. Research across disciplines and questions will thus cumulate more rapidly and increase the knowledge needed to enhance the sustainability of complex SESs. Quantitative and qualitative data about the core set of SES variables across resource systems are needed to enable scholars to build and test theoretical models of heterogeneous costs and benefits between governments, communities, and individuals and to lead to improved policies.

References and Notes

1. E. Pennisi, *Science* **302**, 1646 (2003).
2. R. B. Norgaard, *Conserv. Biol.* **22**, 862 (2008).
3. National Research Council, *The Drama of the Commons* (National Academies Press, Washington, DC, 2002).
4. L. Pritchett, M. Woolcock, *World Dev.* **32**, 191 (2004).
5. F. Berkes *et al.*, *Science* **311**, 1557 (2006).
6. E. Ostrom, R. Gardner, J. Walker, *Rules, Games, and Common-Pool Resources* (Univ. of Michigan Press, Ann Arbor, MI, 1994).
7. F. Berkes, C. Folke, Eds., *Linking Social and Ecological Systems* (Cambridge Univ. Press, Cambridge, 1998).
8. M. A. Janssen, *Complexity and Ecosystem Management* (Edward Elgar, Cheltenham, UK, 2002).
9. J. Norberg, G. Cumming, Eds., *Complexity Theory for a Sustainable Future* (Columbia Univ. Press, New York, 2008).
10. S. A. Levin, *Ecology* **73**, 1943 (1992).
11. R. Axelrod, M. D. Cohen, *Harnessing Complexity* (Free Press, New York, 2001).
12. E. Ostrom, *Proc. Natl. Acad. Sci. U.S.A.* **104**, 15181 (2007).
13. J. Wilson, L. Yan, C. Wilson, *Proc. Natl. Acad. Sci. U.S.A.* **104**, 15212 (2007).
14. W. A. Brock, S. R. Carpenter, *Proc. Natl. Acad. Sci. U.S.A.* **104**, 15206 (2007).
15. A. Chhatre, A. Agrawal, *Proc. Natl. Acad. Sci. U.S.A.* **105**, 13286 (2008).
16. R. Meinzen-Dick, *Proc. Natl. Acad. Sci. U.S.A.* **104**, 15200 (2007).
17. G. Hardin, *Science* **162**, 1243 (1968).
18. T. Dietz, E. Ostrom, P. Stern, *Science* **302**, 1907 (2003).
19. R. Wade, *Village Republics: Economic Conditions for Collective Action in South India* (ICS, San Francisco, CA, 1994).
20. J.-M. Baland, J.-P. Platteau, *Halting Degradation of Natural Resources* (Oxford Univ. Press, New York, 2000).
21. J. M. Acheson, J. A. Wilson, R. S. Steneck, in *Linking Social and Ecological Systems*, F. Berkes, C. Folke, Eds. (Cambridge Univ. Press, Cambridge, 1998), pp. 390–413.
22. P. N. Wilson, G. D. Thompson, *Econ. Dev. Cult. Change* **41**, 299 (1993).
23. E. Mwangi, *Socioeconomic Change and Land Use in Africa* (Palgrave MacMillan, New York, 2007).
24. E. Schlager, W. Blomquist, S. Y. Tang, *Land Econ.* **70**, 294 (1994).
25. A. Agrawal, in *People and Forests: Communities, Institutions, and Governance*, C. C. Gibson, M. A. McKean, E. Ostrom, Eds. (MIT Press, Cambridge, MA, 2000), pp. 57–86.
26. P. B. Trawick, *Hum. Ecol.* **29**, 1 (2001).
27. E. Ostrom, *Understanding Institutional Diversity* (Princeton Univ. Press, Princeton, NJ, 2005).
28. J. A. Brander, M. S. Taylor, *Am. Econ. Rev.* **88**, 119 (1998).
29. X. Basurto, *J. Soc. Nat. Resour.* **18**, 643 (2005).
30. H. Nagendra, *Proc. Natl. Acad. Sci. U.S.A.* **104**, 15218 (2007).
31. E. Ostrom, H. Nagendra, *Proc. Natl. Acad. Sci. U.S.A.* **103**, 19224 (2006).
32. C. W. Clark, *The Worldwide Crisis in Fisheries: Economic Models and Human Behavior* (Cambridge Univ. Press, Cambridge, 2006).
33. G. C. Gibson, J. T. Williams, E. Ostrom, *World Dev.* **33**, 273 (2005).
34. E. Coleman, B. Steed, *Ecol. Econ.* **68**, 2106 (2009).
35. Supported in part by NSF grants BCS-0624178 and BCS-0601320. I thank T. K. Ahn, R. Axtell, X. Basurto, J. Broderick, E. Coleman, C. Eavey, B. Fischer, C. A. González, E. Jameson, B. de Leon, D. Porter, M. Schlueter, D. Sprinz, and J. Walker for comments and suggestions.

10.1126/science.1172133

PERSPECTIVE

Economic Networks: The New Challenges

Frank Schweitzer,[1]* Giorgio Fagiolo,[2] Didier Sornette,[1,3] Fernando Vega-Redondo,[4,5] Alessandro Vespignani,[6,7] Douglas R. White[8]

The current economic crisis illustrates a critical need for new and fundamental understanding of the structure and dynamics of economic networks. Economic systems are increasingly built on interdependencies, implemented through trans-national credit and investment networks, trade relations, or supply chains that have proven difficult to predict and control. We need, therefore, an approach that stresses the systemic complexity of economic networks and that can be used to revise and extend established paradigms in economic theory. This will facilitate the design of policies that reduce conflicts between individual interests and global efficiency, as well as reduce the risk of global failure by making economic networks more robust.

The economy, as any other complex system, reflects a dynamic interaction of a large number of different agents, not just a few key players. The resulting systemic behavior, observable on the aggregate level, often shows consequences that are hard to predict, as illustrated by the current crisis, which cannot be simply explained by the failure of a few major agents. Thus, we need a more fundamental insight into the system's dynamics and how they can be traced back to the structural properties of the underlying interaction network.

Research examining economic networks has been studied from two perspectives; one view comes from economics and sociology; the other originated in research on complex systems in physics and computer science. In both, nodes represent the different individual agents, which can represent firms, banks, or even countries, and where links between the nodes represent their mutual interactions, be it trade, ownership, R&D alliances, or credit-debt relationships. Different agents may have different behaviors under the same conditions and have strategic interactions (*1*). These evolving interactions can be represented by network dynamics that are bound in space and time and can change with the environment and coevolve with the agents (*2*). Networks are formed or devolve on the basis of the addition or deletion of either agents or the links between them.

The socioeconomic perspective has emphasized understanding how the strategic behavior of the interacting agents is influenced by—and reciprocally shapes—relatively simple network architectures. One common example is that of a star-spoke network, like a very centralized or-

[1]ETH Zurich, D-MTEC, Kreuzplatz 5, 8032 Zurich, Switzerland. [2]Laboratorio di Economia e Management (LEM), Scuola Superiore Sant'Anna, Piazza Martiri della Liberta 33, 56127 Pisa, Italy. [3]Swiss Finance Institute, c/o University of Geneva, 40 Boulevard Du Pont d'Arve, 1211 Geneva 4, Switzerland. [4]Economics Department, European University Institute, Via della Piazzuola 43, 50133 Firenze, Italy. [5]Instituto Valenciano de Investigaciones Economicas, Calle Guardia Civil, 22 esc. 2 no 1, 46020 Valencia, Spain. [6]School of Informatics and Pervasive Technology Institute, Indiana University, 919 East 10th Street, Bloomington, IN 47408, USA. [7]Institute for Scientific Interchange, 10133 Torino, Italy. [8]Institute of Mathematical Behavioral Sciences, University of California, 3151 Social Science Plaza, Irvine, CA 92697, USA.

*To whom correspondence should be addressed. E-mail: fschweitzer@ethz.ch