Ecosystems and the Biosphere as Complex Adaptive Systems:

Scaling, collective phenomena and governance

Simon Levin, Princeton University

InternationalZoomTheoretical Ecology2023

members.home.nl/pamali/schilderen

With thanks to

ASU Arizona State University

C3.ai

NSF

GRAND CHALLENGES
ENERGY DEVELOPMENT HEALTH

CICS
Cooperative Institute for Climate Science

The Simons Foundation

CIMES

DARPA
Bridging the Gap
Powered by Ideas

National Institutes of Health

Google

Google

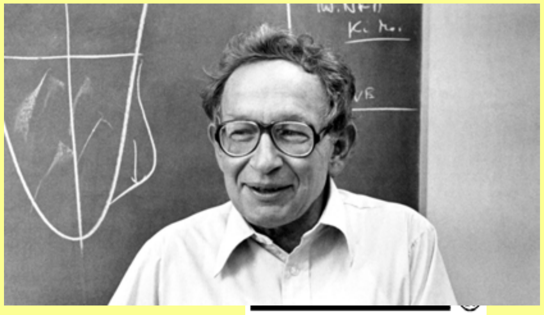
U.S. Department of Homeland Security

The Andrew W. Mellon Foundation

John Templeton Foundation

JSMF

MORE IS DIFFERENT



More Is Different

P. W. Anderson

Science, New Series, Vol. 177, No. 4047. (Aug. 4, 1972), pp. 393-396.

Stable URL:
http://links.jstor.org/sici?sici=0036-8075%2819720804%293%3A177%3A4047%3C393%3AMID%3E2.0.CO%3B2-N

Science is currently published by American Association for the Advancement of Science.

1972

Anderson

- "The ability to reduce everything to simple fundamental laws does not imply the ability to start from those laws and reconstruct the universe"

Francois Jacob, 1977, Science

Institut Pasteur

10 June 1977, Volume 196, Number 4295 **SCIENCE**

Must analyze complex objects at all levels

Evolution and Tinkering

François Jacob

Some of the 16th-century books devoted to zoology and botany are illustrated by superb drawings of the various animals that populate the earth. Certain contain detailed descriptions of such creatures as dogs with fish heads, men with chicken legs, or even women without heads. The notion of monsters that blend the characteristics of different species is not itself surprising: everyone has imagined or sketched such hybrids. What is disconcerting today is that in the 16th century these creatures belonged, not to the world of fantasies, but to the real world. Many people had seen them

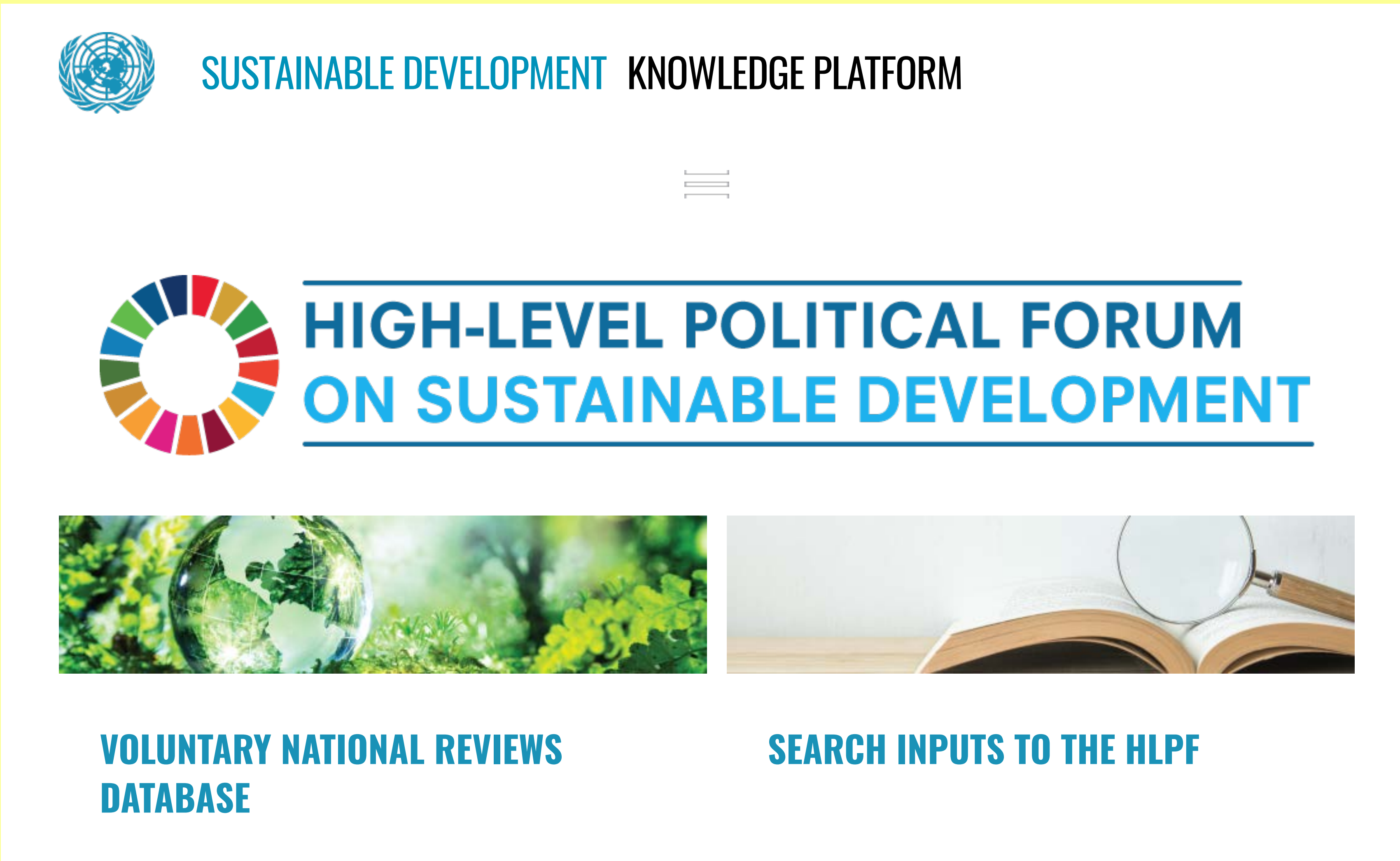
The interest in these monsters is that they show how a culture handles the possible and marks its limits. It is a requirement of the human brain to put order in the universe. It seems fair to say that all cultures have more or less succeeded in providing their members with a unified and coherent view of the world and of the forces that run it. One may disagree with the explanatory systems offered by myths or magic, but one cannot deny them unity and coherence. In fact, they are often charged with too much unity and coherence because of their capacity to explain anything by the same simple

terest. To produce a valuable observation, one has first to have an idea of what to observe, a preconception of what is possible. Scientific advances often come from uncovering a hitherto unseen aspect of things as a result, not so much of using some new instrument, but rather of looking at objects from a different angle. This look is necessarily guided by a certain idea of what the so-called reality might be. It always involves a certain conception about the unknown, that is, about what lies beyond that which one has logical or experimental reasons to believe. In the words of Peter Medawar, scientific investigation begins by the "invention of a possible world or of a tiny fraction of that world" (*2*). So also begins mythical thought. But it stops there. Having constructed what it considers as the only possible world, it easily fits reality into its scheme. For scientific thought, instead, imagination is only a part of the game. At every step, it has to meet with experimentation and criticism. The best world is the one that exists and has proven to work already for a long time. Science attempts to confront the possible with the actual.

From Jacob 1977

The second point concerns predictability. Is it possible to make predictions at one level on the basis of what is known at a simpler one? Only to a very limited extent. The properties of a system can be explained by the properties of its components. They cannot be deduced from them. Starting from fundamental laws of physics, there is no way of reconstructing the universe. This means that a

Sustainability of the biosphere is the ultimate global challenge for consilience research



EOWilson had a mixed relationship with math

- Consilience
- Collaborated with Oster, Tarnita, Nowak, others
- But WSJ article
- And "*logical positivism…* is more commonly studied in philosophy, as dinosaur fossils are studied in paleontology laboratories, to understand the causes of extinction."

But I will argue that math is the unifying discipline for consilience, because it helps us to grapple with

- Complex adaptive systems and emergence
- And to relate reductionistic and holistic perspectives in
- Understanding
  - Scaling
  - Emergence
  - Pattern formation
  - Critical transitions
  - Conflicts between interests of individuals and collective good

I want to explore the role of mathematical theory in addressing the fundamental issue of our time,

…achieving a sustainable future
for our children and grandchildren

Carole Levin

Ecosystems and the Biosphere are Complex Adaptive Systems

Heterogeneous collections of individual units (agents) that interact locally, and evolve based on the outcomes of those interactions.

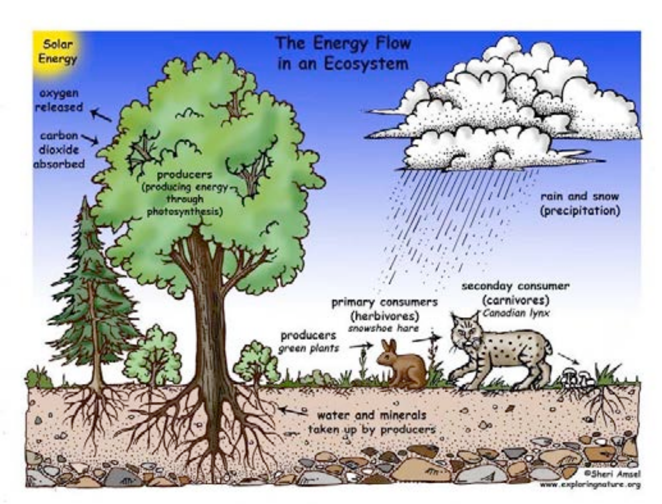
NOAA

So too are the socio-economic systems with which they are interlinked

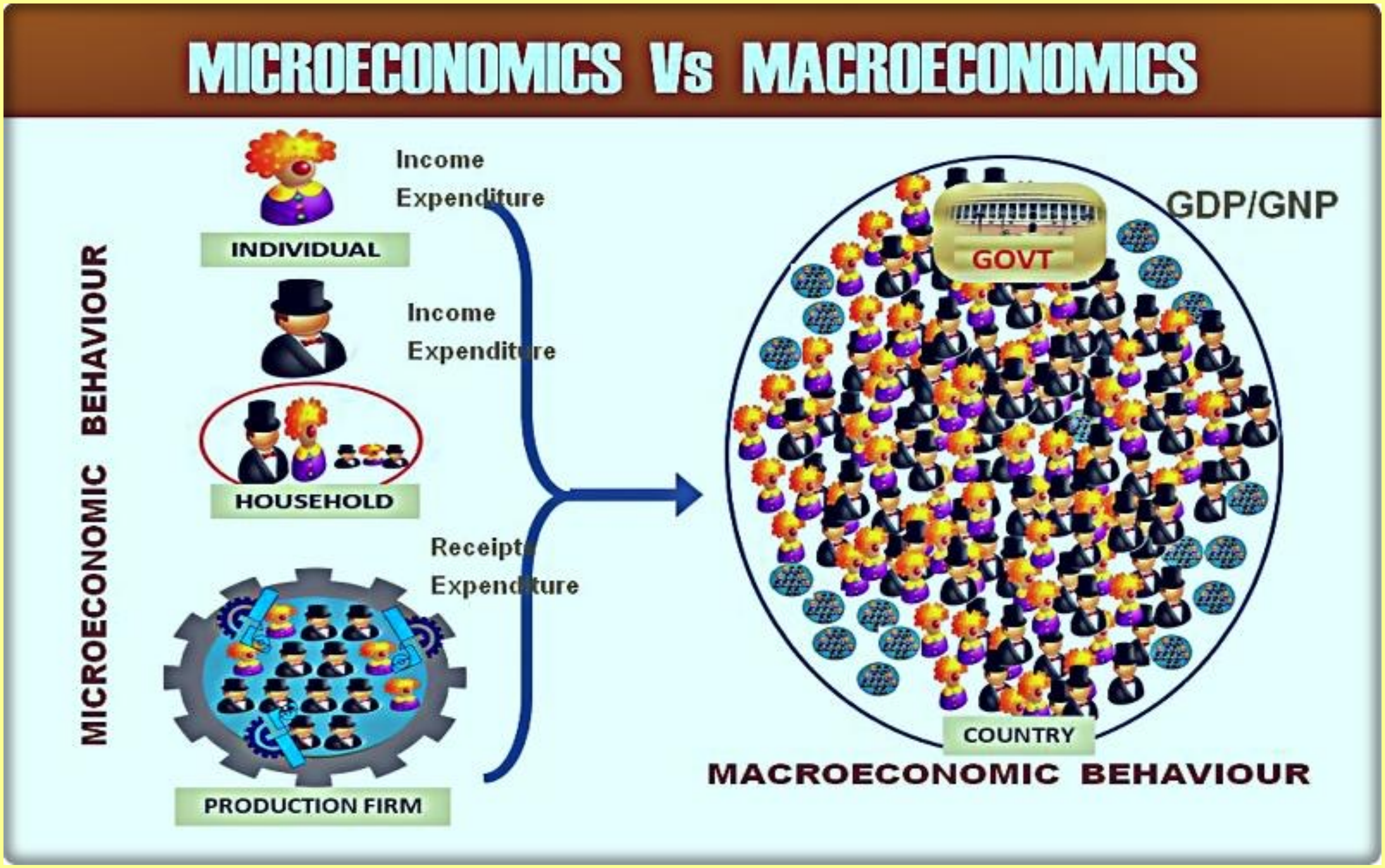
www.suite101.com

The fundamental macroscopic properties of the biosphere are emergent from lower-level interactions

- Species-abundance distributions
- Energy flow
- Nutrient cycling
- Ecosystem services



Just as emergence typifies problems in economics



https://businessandfinance.expertscolumn.com/

This implies a need to relate phenomena across scales, from

- cells to organisms to collectives to ecosystems to coupled social-ecological-technological systems

and to ask

- How robust are the properties of systems?
- How does robustness of macroscopic properties relate to dynamics on finer scales?
- Are systems at critical points?
- How do we manage the Commons across scales and conflicts of interest?

From a mathematical viewpoint

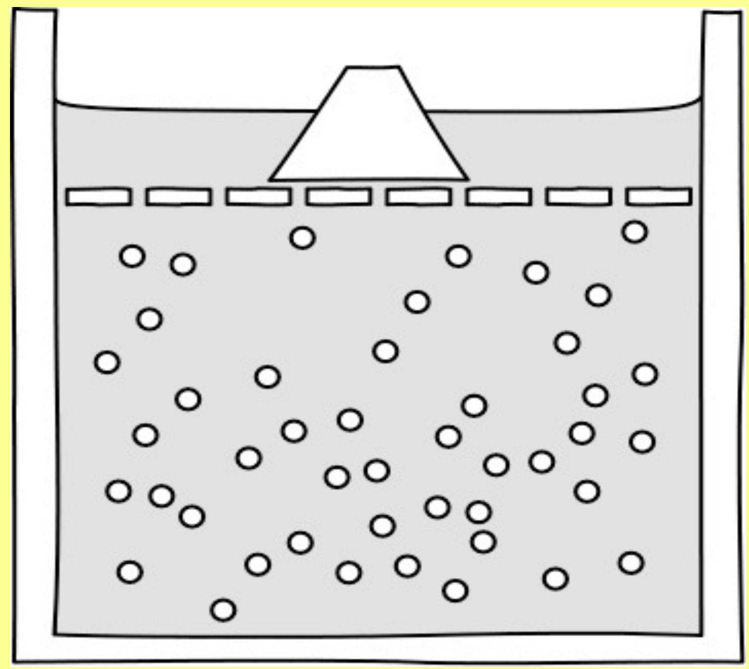
- Emergence and pattern formation
- Robustness and critical transitions
- Cooperation and collective intelligence

From a mathematical viewpoint

- Emergence and pattern formation

Sustainability must focus on macroscopic features, while recognizing that control of those rests at lower levels of organization

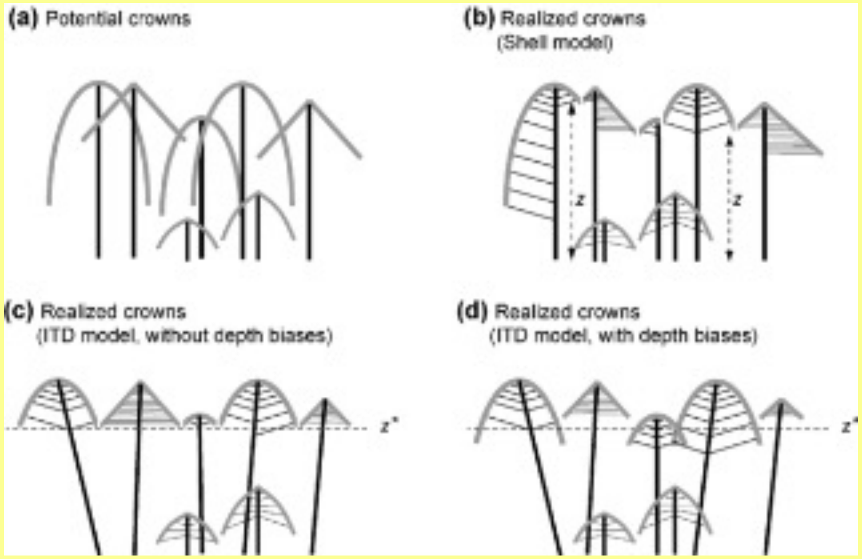
https://i1.wp.com/www.nopackagedeals.com/wp-content/uploads/2016/11/teapot.jpg?resize=300%2C199



www.pitt.edu/~jdnorton

Forest growth models can scale from individual to ecosystem

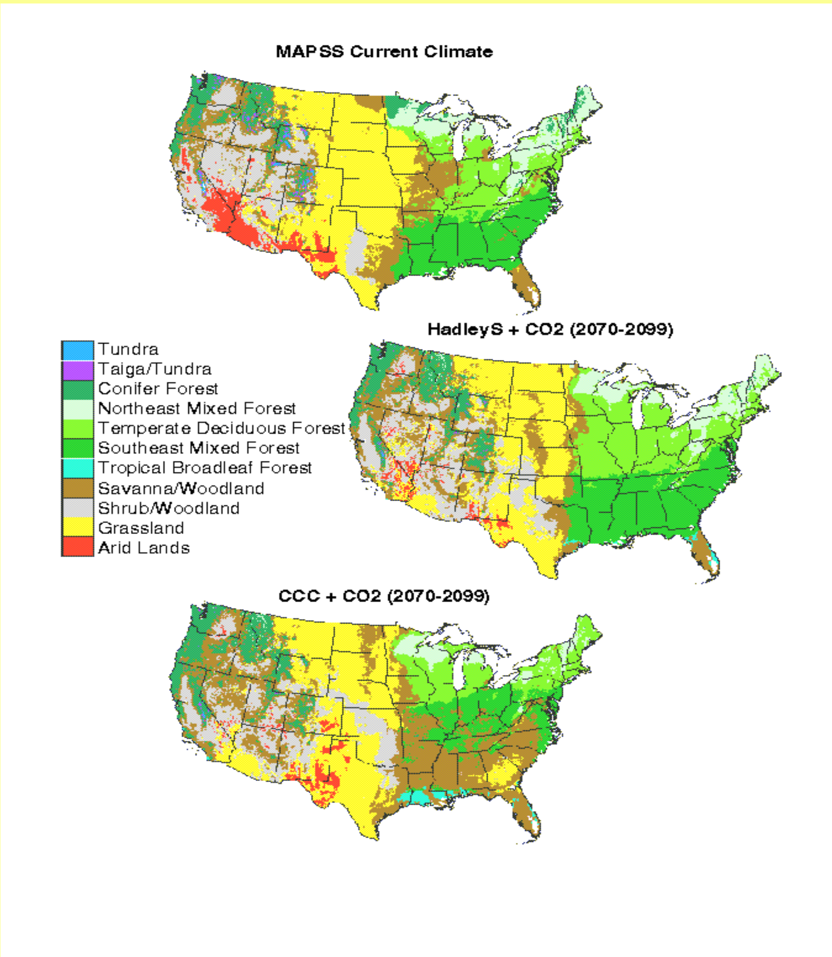
(Pacala, Botkin, Shugart, others)

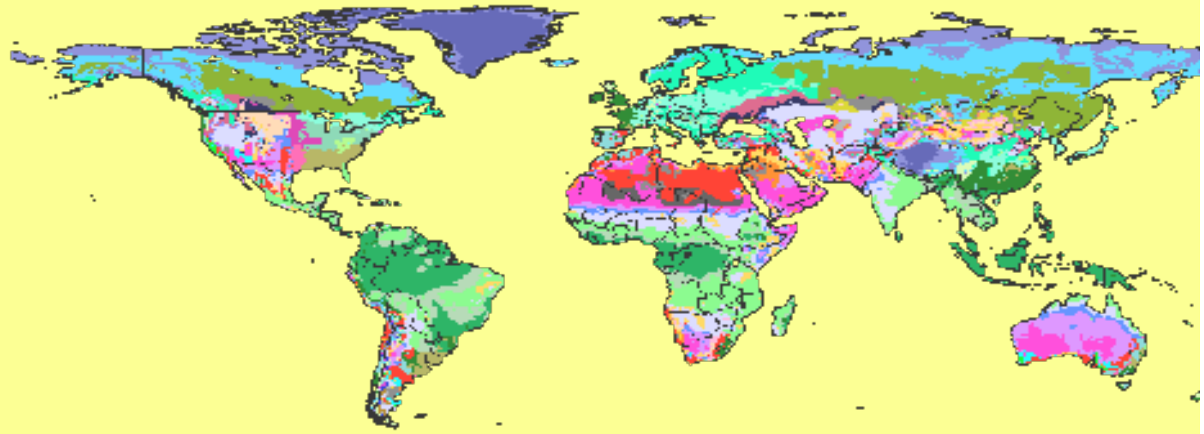


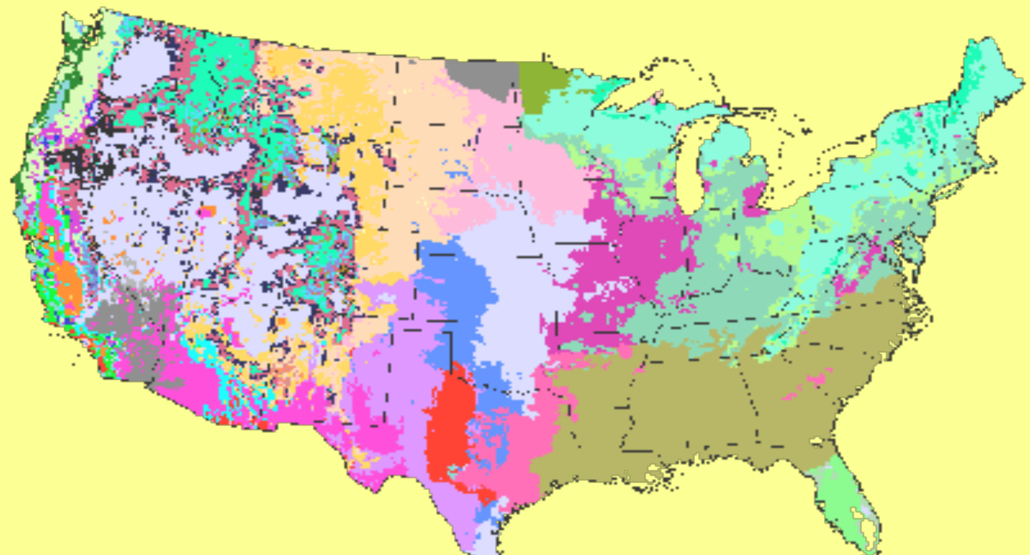
Drew W. Purves, Jeremy W. Lichstein, Stephen W. Pacala 2007 PLOSOne

Deutschman, DH, SA Levin, C Devine and LA Buttel. 1997. Science **277**:1688.

Vegetation models have been successful in explaining global patterns, though not individual species abundances







MAPSS

http://www.fs.fed.us/pnw/mdr/mapss/

Ocean dynamics: The MIT-DARWIN Model

u and **K** from ECCO2 GCM — Phyto growth — Remineralization & other sources

$$\frac{\partial N_i}{\partial t} = -\nabla \cdot (\mathbf{u}\, N_i) + \nabla \cdot (K\, \nabla N_i) - \sum_j \mu_j P_j R_{ij} + S_{N_i}$$

Growth — Mortality — Grazing — Sinking

$$\frac{\partial P_j}{\partial t} = -\nabla \cdot (\mathbf{u} P_j) + \nabla \cdot (K \nabla P_j) + \mu_j P_j - m_j^P P_j - \sum_k g_{jk} \frac{P_j Z_{k,i=1}}{P_j + k_j^P} - \frac{w_j^P \partial P_j}{\partial z}$$

$$\frac{\partial Z_{ki}}{\partial t} = -\nabla \cdot (\mathbf{u}\, Z_{ki}) + \nabla \cdot (K\, \nabla Z_{ki}) - m_k^Z Z_{ki} + \sum_k g_{jk} \frac{P_j R_{ij}}{P_j + k_j^P}$$

N/P/Z= nutrients/phytoplankton/zooplankton

C Wunsch & P Heimbach, *Physica D* **230**,197 (2007)

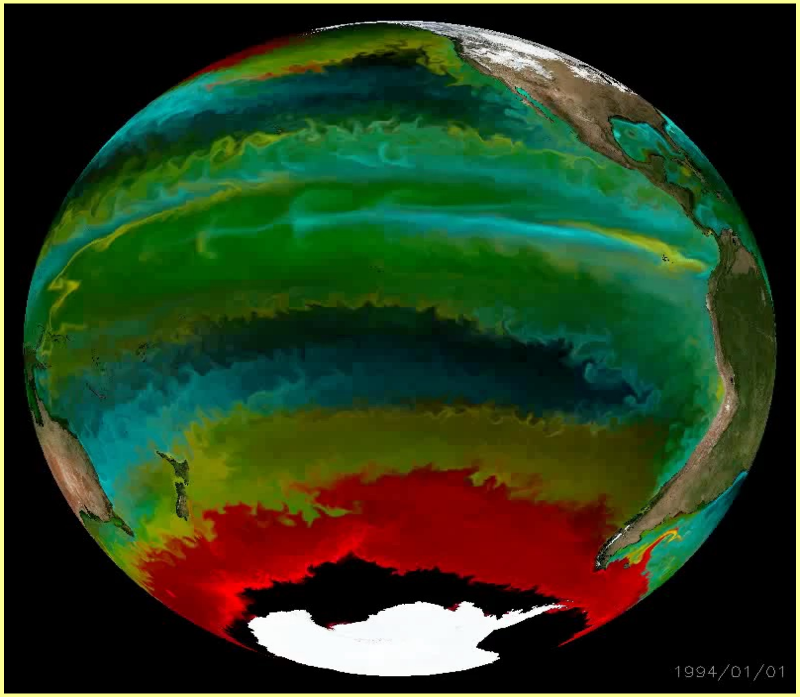
MJ Follows *et al*, *Science* **315**, 1843 (2007)

Ecotypes, not species, are predictable

Follows, Dutkiewicz, Chisholm,

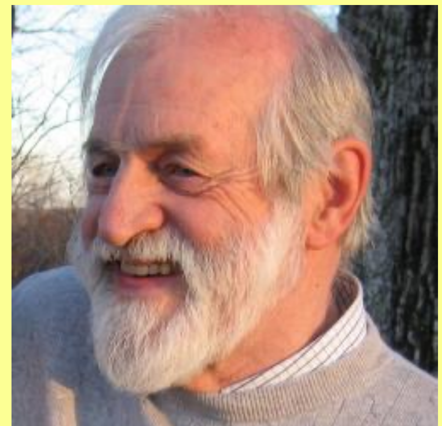
…

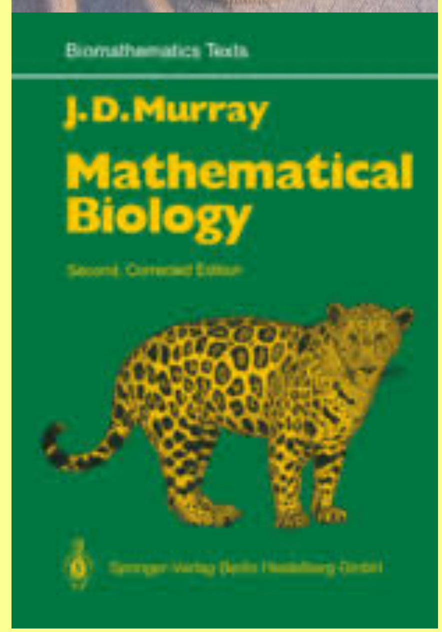
- Prochlorococcus
- Synechococcus
- Diatoms
- Large eukaryotes



Courtesy Follows and Dutkiewicz

Pattern formation has been one of the central themes of mathematical biology





Alan Turing posited the existence of two interacting chemicals (morphogens) in a homogeneous space

Alan Turing (1912-1954)

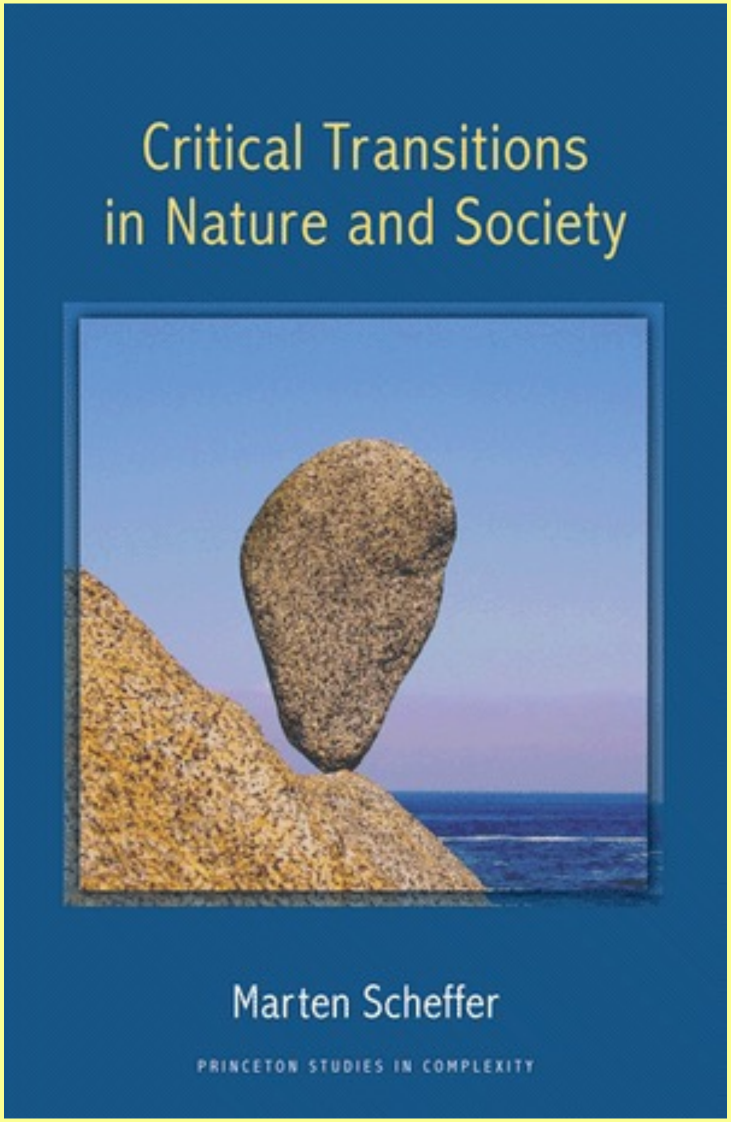
http://www.schmoozd.com

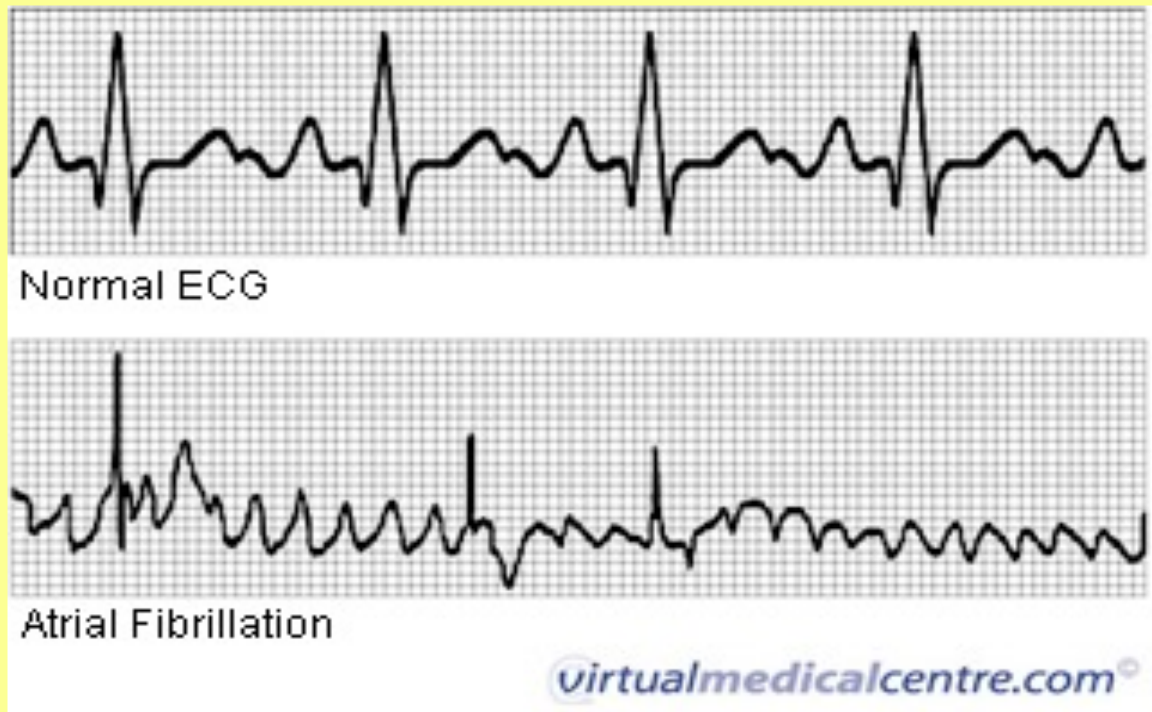
But pattern can be fragile

- Emergence and pattern formation
- Robustness and critical transitions

Stock markets crash…and recover

Such transitions are widespread





Can we read the tea leaves?
Are there early-warning signals?

https://www.twinings.co.uk

REVIEW

Anticipating Critical Transitions

Marten Scheffer,[1,2*] Stephen R. Carpenter,[3] Timothy M. Lenton,[4] Jordi Bascompte,[5] William Brock,[6] Vasilis Dakos,[1,5] Johan van de Koppel,[7,8] Ingrid A. van de Leemput,[1] Simon A. Levin,[9] Egbert H. van Nes,[1] Mercedes Pascual,[10,11] John Vandermeer[10]

Tipping points in complex systems may imply risks of unwanted collapse, but also opportunities for positive change. Our capacity to navigate such risks and opportunities can be boosted by combining emerging insights from two unconnected fields of research. One line of work is revealing fundamental architectural features that may cause ecological networks, financial markets, and other complex systems to have tipping points. Another field of research is uncovering generic empirical indicators of the proximity to such critical thresholds. Although sudden shifts in complex systems will inevitably continue to surprise us, work at the crossroads of these emerging fields offers new approaches for anticipating critical transitions.

About 12,000 years ago, the Earth suddenly shifted from a long, harsh glacial episode into the benign and stable Holocene climate that allowed human civilization to develop. On smaller and faster scales, ecosystems occasionally flip to contrasting states. Unlike gradual trends, such sharp shifts are largely unpredictable (*1*–*3*). Nonetheless, science is now carving into this realm of unpredictability in fundamental ways. Although the complexity of systems such as societies and ecological networks prohibits accurate mechanistic modeling, certain features turn out to be generic markers of the fragility that may typically precede a large class of abrupt changes. Two distinct approaches have led to these insights. On the one hand, analyses across networks and other systems with many components have revealed that particular aspects of their structure determine whether they are likely to have critical thresholds where they may change abruptly; on the other hand, recent findings suggest that certain generic indicators may be used to detect if a system is close to such a "tipping point." We highlight key findings but also challenges in these emerging research areas and discuss how exciting opportunities arise from the combination of these so far disconnected fields of work.

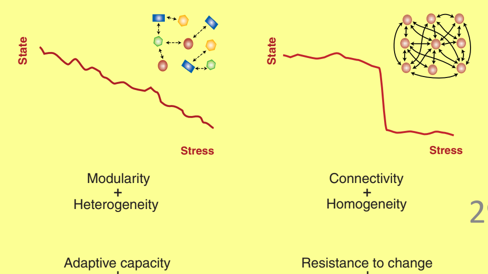
[1]Department of Environmental Sciences, Wageningen University, Post Office Box 47, NL-6700 AA Wageningen, Netherlands. [2]South American Institute for Resilience and Sustainability Studies (SARAS), Maldonado, Uruguay. [3]Center for Limnology, University of Wisconsin, 680 North Park Street, Madison, WI 53706, USA. [4]College of Life and Environmental Sciences, University of Exeter, Hatherly Laboratories, Prince of Wales Road, Exeter EX4 4PS, UK. [5]Integrative Ecology Group, Estación Biológica de Doñana, Consejo Superior de Investigaciones Científicas, E-41092 Sevilla, Spain. [6]Department of Economics, University of Wisconsin, 1180 Observatory Drive, Madison, WI

The Architecture of Fragility

Sharp regime shifts that punctuate the usual fluctuations around trends in ecosystems or societies may often be simply the result of an unpredictable external shock. However, another possibility is that such a shift represents a so-called critical transition (*3*, *4*). The likelihood of such transitions may gradually increase as a system approaches a "tipping point" [i.e., a catastrophic bifurcation (*5*)], where a minor trigger can invoke a self-propagating shift to a contrasting state. One of the big questions in complex systems science is what causes some systems to have such tipping points. The basic ingredient for a tipping point is a positive feedback that, once a critical point is passed, propels change toward an alternative state (*6*). Although this principle is well understood for simple isolated systems, it is more challenging to fathom how heterogeneous structurally complex systems such as networks of species, habitats, or societal structures might respond to changing conditions and perturbations. A broad range of studies suggests that two major features are crucial for the overall response of such systems (*7*): (i) the heterogeneity of the components and (ii) their connectivity (Fig. 1). How these properties affect the stability depends on the nature of the interactions in the network.

Domino effects. One broad class of networks includes those where units (or "nodes") can flip between alternative stable states and where the probability of being in one state is promoted by having neighbors in that state. One may think, for instance, of networks of populations (extinct or not), or ecosystems (with alternative stable states), or banks (solvent or not). In such networks, heterogeneity in the response of individual nodes and a low level of connectivity may cause the network as a whole to change gradually—rather than abruptly—in response to environmental change. This is because the relatively isolated and different nodes will each shift at another level of an environmental driver (*8*). By contrast, homogeneity (nodes being more similar) and a highly connected network may provide resistance to change until a threshold for a systemic critical transition is reached where all nodes shift in synchrony (*8*, *9*).

This situation implies a trade-off between local and systemic resilience. Strong connectivity



Current caveats

Theor Ecol (2013) 6:255–264
DOI 10.1007/s12080-013-0192-6

ORIGINAL PAPER

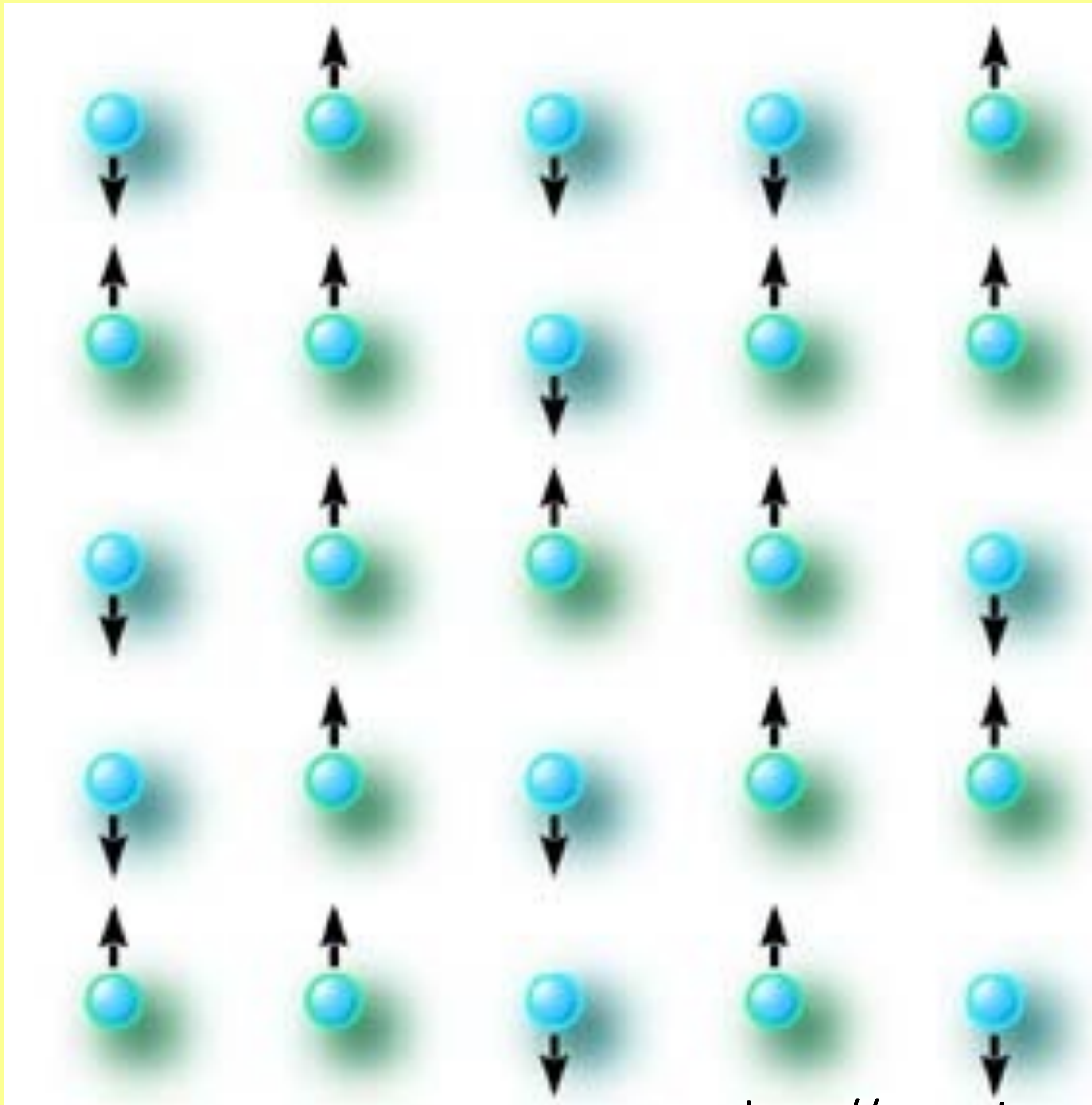
Early warning signals: the charted and uncharted territories

Carl Boettiger · Noam Ross · Alan Hastings

Received: 19 March 2013 / Accepted: 23 May 2013 / Published online: 21 June 2013

Abstract The realization that complex systems such as ecological communities can collapse or shift regimes suddenly and without rapid external forcing poses a serious challenge to our understanding and management of the natural world. The potential to identify early warning signals that would allow researchers and managers to predict such events before they happen has therefore been an invaluable discovery that offers a way forward in spite of such seemingly unpredictable behavior. Research into early warning signals has demonstrated that it is possible to define and detect such early warning signals in advance of a transition in certain contexts. Here, we describe the pattern emerging as research continues to explore just how far we can generalize these results. A core of examples emerges that shares three properties: the phenomenon of rapid regime shifts, a pattern of 'critical slowing down' that can be used to detect the approaching shift, and a mechanism of bifurcation driving the sudden change. As research has expanded beyond these core examples, it is becoming clear that not all systems that show regime shifts exhibit critical slowing down, or vice versa. Even when systems exhibit critical slowing down, statistical detection is a challenge. We review the literature that explores these edge cases and highlight the need for (a) new early warning behaviors that can be used in cases where rapid shifts do not exhibit critical slowing down; (b) the development of methods to identify which behavior might be an appropriate signal when encountering a novel system, bearing in mind that a positive indication for some systems is a negative indication in others; and (c) sta-

In physical systems, phase transitions provide a model



Ising Model

http://www.icmp.lviv.ua/ising/galam.html

- But many of the early-warning indicators suggested are characteristic of second-order phase transitions, though the transitions appear to be more like first-order
- Maybe these are not the right analogies

We have been trying to resolve this paradox

Phase Transitions and the Theory of Early Warning Indicators for Critical Transitions

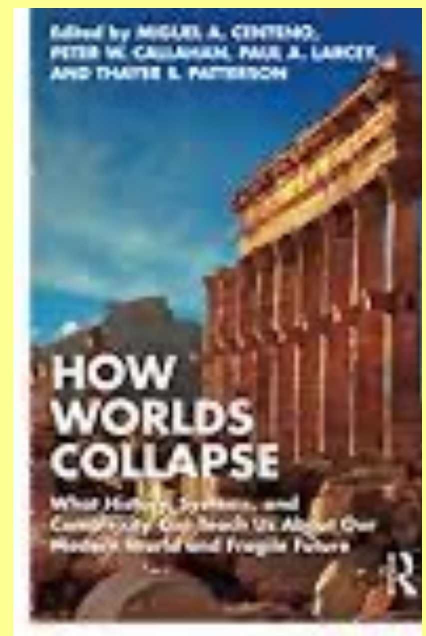
George I. Hagstrom and Simon A. Levin
Department of Ecology and Evolutionary Biology
Princeton University

Abstract

Critical transitions, or large changes in the state of a system after a small change in the system's external conditions or parameters, commonly occur in a wide variety of disciplines, from the biological and social sciences to physics. Statistical physics first confronted the problem of emergent phenomena such as critical transitions in the 1800s and 1900s, culminating in the theory of phase transitions. However, although phase transitions show a strong resemblance to critical transitions, the theoretical connections between the two sets of phenomena are tenuous at best, and it would be advantageous to make them more concrete in order to take advantage of the theoretical methods developed by physicists to study phase transitions. Here we attempt to explicitly connect the theory of critical transitions to phase transitions in physics. We initially find something paradoxical, that many critical transitions closely resemble first-order phase transitions, but that many of the early warning indicators developed to anticipate critical transitions, such as critical slowing down or increasing spatial correlations, occur instead in second-order phase transitions. We attempt to reconcile these disparities by making the connection with other phenomena associated with first-order phase transitions, such as spinodal instabilities and metastable states.

1 Introduction

Revolutions and economic collapses are some of the most dramatic and impactful historical events. They can occur with breathtaking speed such as the fall of Socialist governments in Eastern Europe in 1989[14] or the Black Monday stock market crash[20], and they often defy the expectations of both the general public and experts, who did not foresee such sudden changes[13]. Although exogenous shocks can play a role in triggering large-scale social or economic



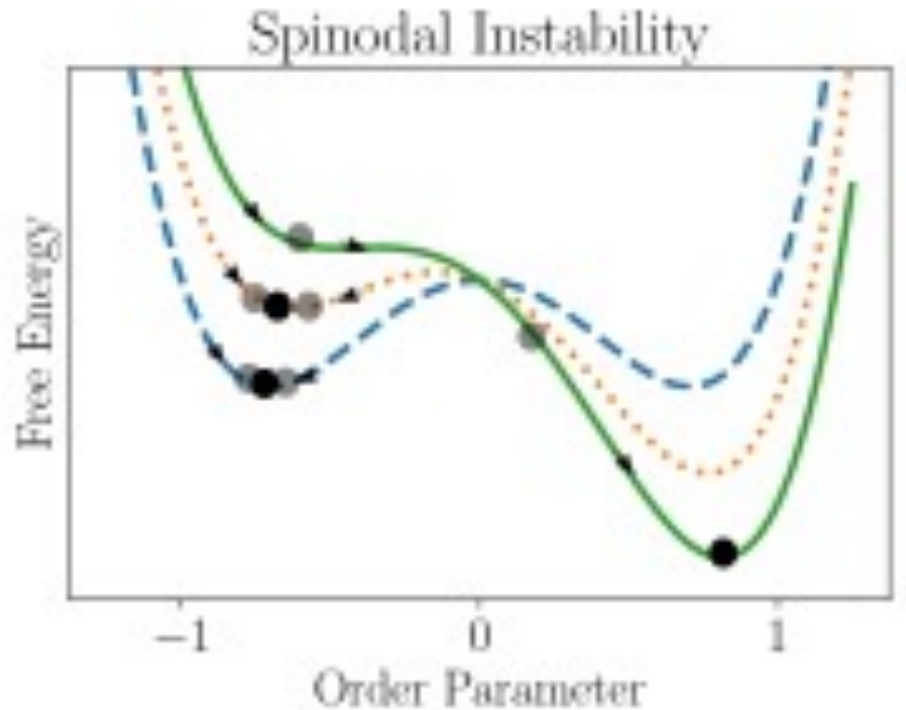
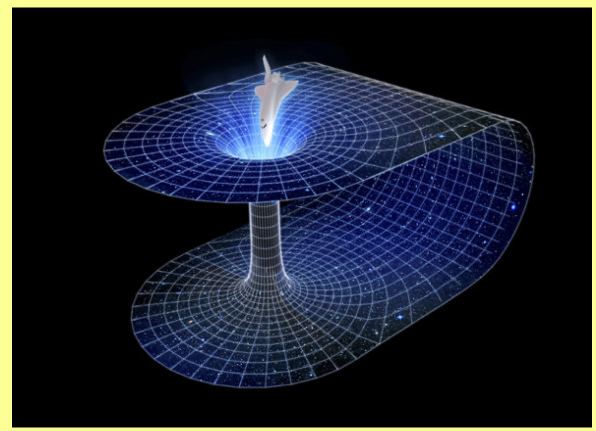


Figure 2: Spinodal Instability triggered by changing external field. As the field increases, the system undergoes a first-order phase transition but the system may remain trapped in a metastable state. At a certain critical value of the field, this metastable state loses stability and the system shifts to the lowest free-energy state. Approaching the spinodal point, relaxation times, susceptibilities, and correlation functions may diverge, though with different critical exponents than during a second-order phase transition.

Dimensional Reduction as an Early Warning Indicator of Transition

- Correlations in financial markets
- Housing market variations



James Watson and George Hagstrom

https://www.express.co.uk/news/science/819741/Wormholes-in-Milky-Way-galaxy-interstellar

The importance of critical transitions in ecological systems raises management challenges

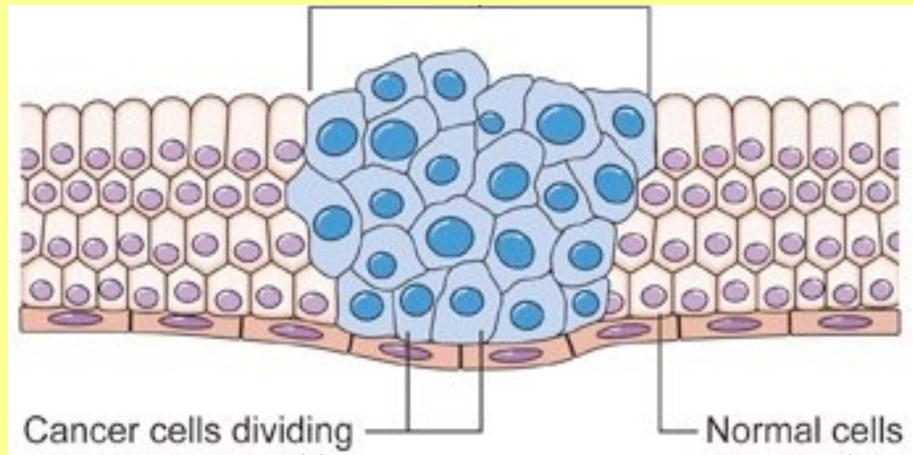
Source unknown

From a mathematical viewpoint

- Emergence and pattern formation
- Robustness and critical transitions
- Cooperation and collective intelligence

Public goods problems are widespread in socio-economic and ecological contexts

Patrick Semansky/AP



http://www.cancerresearchuk.org/

The Commons solution (Hardin, Ostrom)

"Mutual coercion, mutually agreed upon"

http://www.physics.ohio-state.edu/~wilkins

http://www.guardian.co.uk

How do such social norms become established

- What is the role of leadership?
- How is consensus achieved in democratic societies, under incomplete information?
- What is the role of the unopinionated?

Science (16 Dec 2011)

Achieving consensus in animal groups

REPORTS

Uninformed Individuals Promote Democratic Consensus in Animal Groups

Iain D. Couzin,[1]* Christos C. Ioannou,[1]† Güven Demirel,[2] Thilo Gross,[2]‡ Colin J. Torney,[1] Andrew Hartnett,[1] Larissa Conradt,[3]§ Simon A. Levin,[1] Naomi E. Leonard[4]

Conflicting interests among group members are common when making collective decisions, yet failure to achieve consensus can be costly. Under these circumstances individuals may be susceptible to manipulation by a strongly opinionated, or extremist, minority. It has previously been argued, for humans and animals, that social groups containing individuals who are uninformed, or exhibit weak preferences, are particularly vulnerable to such manipulative agents. Here, we use theory and experiment to demonstrate that, for a wide range of conditions, a strongly opinionated minority can dictate group choice, but the presence of uninformed individuals spontaneously inhibits this process, returning control to the numerical majority. Our results emphasize the role of uninformed individuals in achieving democratic consensus amid internal group conflict and informational constraints.

Social organisms must often achieve a consensus to obtain the benefits of group living and to avoid the costs of indecision (*1*–*12*). In some societies, notably those of eusocial insects, making consensus decisions is often a unitary, conflict-free process because the close relatedness among individuals means that they typically share preferences (*11*). However, in other social animals, such as schooling fish, flocking birds, herding ungulates, and humans, individual group members may be of low relatedness; thus, self-interest can play an important role in group

Consequently, for both human societies (*1*, *2*, *6*, *9*, *10*, *14*) and group-living animals (*6*, *13*), it has been argued that group decisions can be subject to manipulation by a self-interested and opinionated minority. In particular, previous work suggests that groups containing individuals who are uninformed, or naïve, about the decision being made are particularly vulnerable to such manipulation (*2*, *9*, *10*, *13*). Under this view, uninformed individuals destabilize the capacity for collective intelligence in groups (*10*, *14*), with poorly informed individuals potentially facilitat-

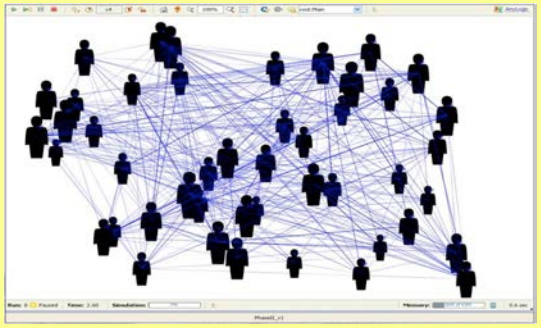
that uninformed individuals (defined as those who lack a preference or are uninformed about the features on which the collective decision is being made) play a central role in achieving democratic consensus.

We use a spatially explicit computational model of animal groups (*15*) that makes minimal assumptions regarding the capabilities of individual group members; they are assumed to avoid collisions with others and otherwise exhibit the capacity to be attracted toward, and to align direction of travel with, near neighbors (*5*, *16*). We investigate the case of consensus decision-making regarding a choice to move to one of two discrete targets in space (thus, the options are mutually exclusive).

The direction and strength of an individual's preference are encoded in a vector term $\vec{\omega}$ (directed toward the individual's preferred target). Higher scalar values of ω (equivalent to the length of the $\vec{\omega}$ vector, $\omega \equiv |\vec{\omega}|$) represent a greater conviction in, or strength of, individual preference to move in the direction of the target and, thus, also represent greater intransigence to social influence (*5*).We explore the case where there are two subpopulations within the group—N_1 and N_2, respectively—that have different preferred targets. Because we are interested in determining whether a minority can exploit a majority, we set $N_1 > N_2$ for the simulation. The strengths of the preference of the numerical majority and minority are represented by their respective ω values,

Similar conclusions emerge from multiple angles

- Experimental studies with fish
- Simulation and analytical models of movement
- Models of human collective decision-making



http://www.sie.arizona.edu/human-decision-making-and-social-behavior

Young-Jun Son, Leon Zhao, Keith Provan and Brian McGough

Unopinionated individuals aid consensus

http://motherjones.com/kevin-drum

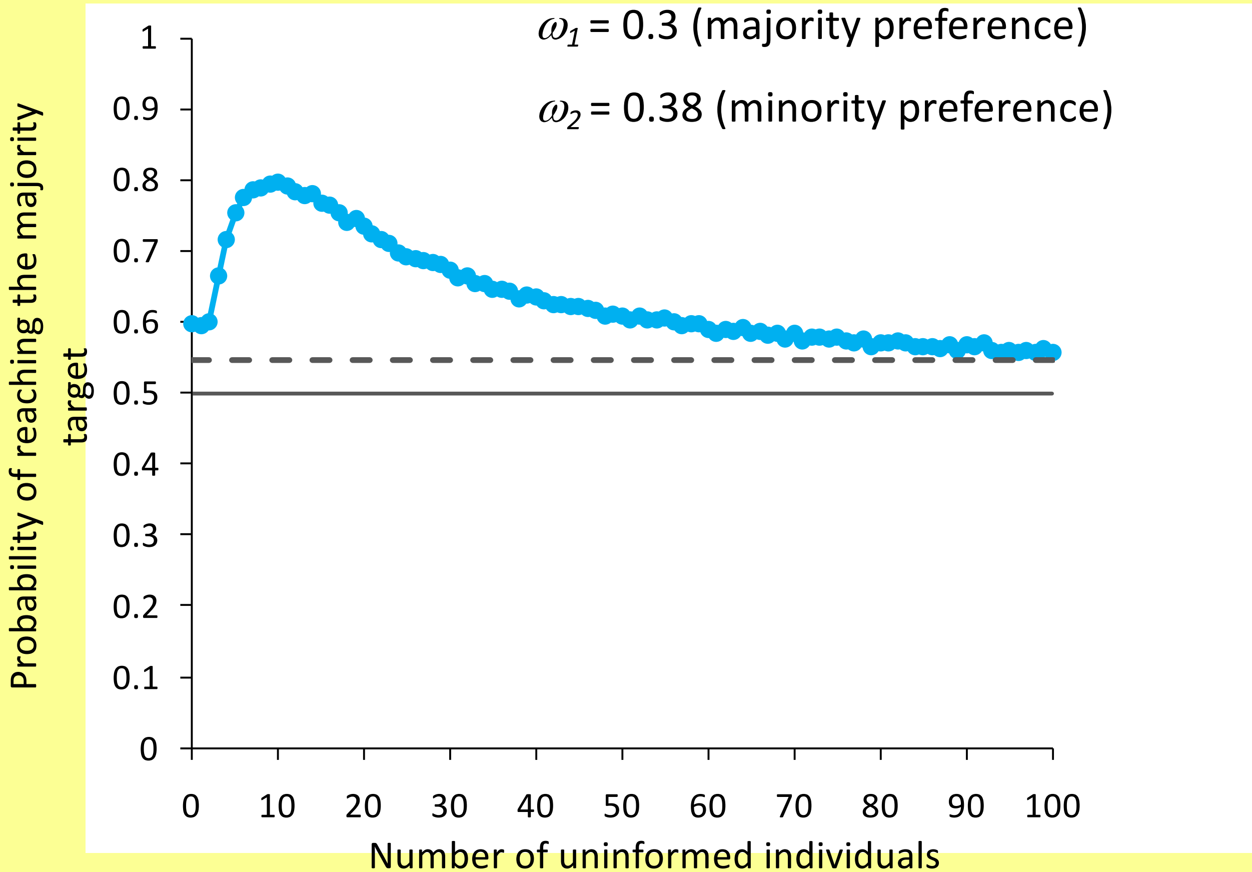
Collective decision-making

PRINCETON UNIVERSITY

The importance of uninformed individuals

targets model

Majority (N_1) = 6
Minority (N_2) = 5



Optimal number of uninformed

Conclusions

- Public goods and common pool resource problems represent fundamental challenges in economics and in evolutionary biology
- Collective action can emerge from local interactions
- Multiple scales: Collective decisions can impose "mutual coercion, mutually agreed upon"
- Linking these is key to understanding the management of the Commons

We need cooperation and collective intelligence

COLLECTIVE INTELLIGENCE

Perspective

Collective Intelligence
August-September 2022: 1–18

DOI: 10.1177/26339137221083293
journals.sagepub.com/home/col
SAGE

Collective intelligence as a public good

Naomi Ehrich Leonard
Department of Mechanical & Aerospace Engineering, Princeton University, USA

Simon A Levin
Department of Ecology & Evolutionary Biology, Princeton University, USA

Abstract

We discuss measures of collective intelligence in evolved and designed self-organizing ensembles, defining collective intelligence in terms of the benefits to be gained through the exchange of information and other resources, as well as through coordination or cooperation, in the interests of a public good. These benefits can be numerous, from estimating a hard-to-observe cue to efficiently searching for resource. The measures should also account for costs to individuals, such as in attention or energy, and trade-offs for the ensemble, such as the flexibility to respond to an important change in the environment versus stability that is robust to unimportant variability. When there is a tension between the interests of the individual and those of the group, game-theoretic considerations may affect the level of collective intelligence that can be achieved. Models of individual rules that yield collective dynamics with multi-stable solutions provide a means to examine and shape collective intelligence in evolved and designed systems.

However, political polarization is on the increase and threatens democratic governance

PewResearchCenter

FOR RELEASE JUNE 12, 2014

Political Polarization in the American Public

How Increasing Ideological Uniformity and Partisan Antipathy Affect Politics, Compromise and Everyday Life

FOR FURTHER INFORMATION ON THIS REPORT:

Michael Dimock, Vice President, Research
Carroll Doherty, Director of Political Research
Jocelyn Kiley, Associate Director
Russ Oates, Communications Manager

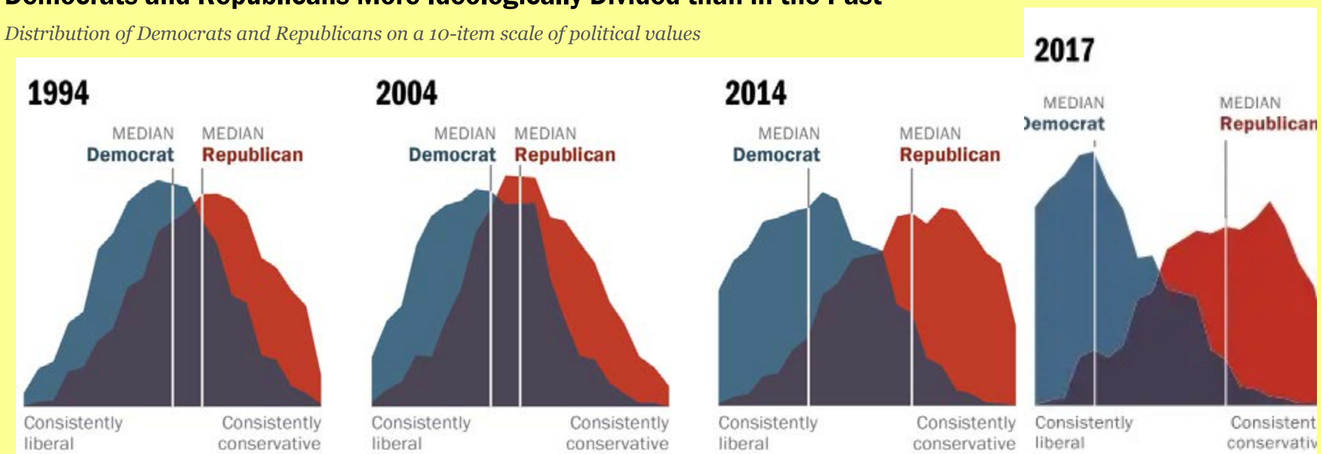
From Pew Report 2014

Overview

Republicans and Democrats are more divided along ideological lines – and partisan antipathy is deeper and more extensive – than at any point in the last two decades. These trends manifest themselves in myriad ways, both in politics and in everyday life. And a new survey of 10,000 adults nationwide finds that these divisions are greatest among those who are the most engaged and active in the political process.

Democrats and Republicans More Ideologically Divided than in the Past

Distribution of Democrats and Republicans on a 10-item scale of political values



Source: 2014 Political Polarization in the American Public

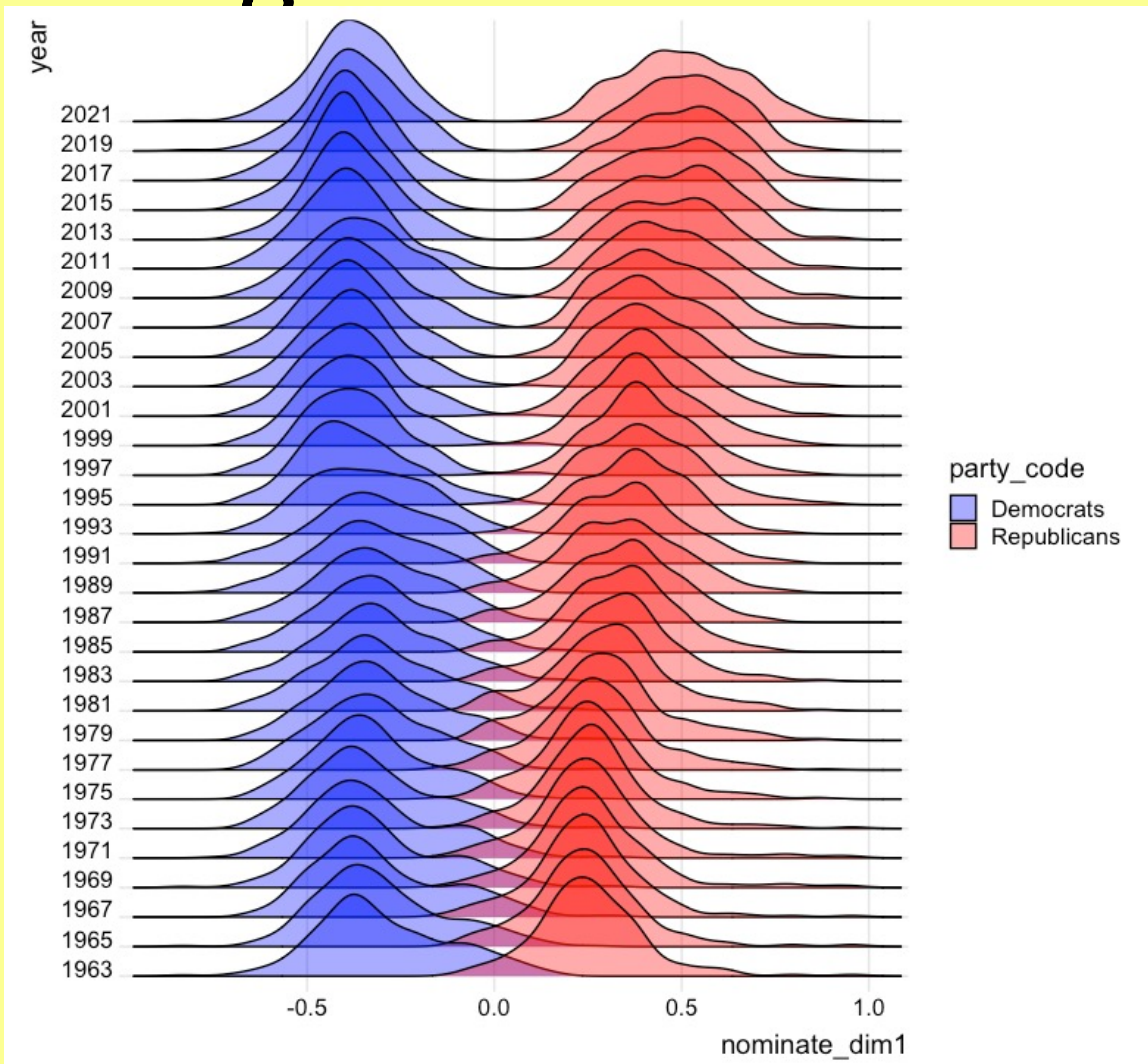
Notes: Ideological consistency based on a scale of 10 political values questions (see Appendix A).The blue area in this chart represents the ideological distribution of Democrats; the red area of Republicans. The overlap of these two distributions is shaded purple. Republicans include Republican-leaning independents; Democrats include Democratic-leaning independents (see Appendix B). See the online edition of this report for an animated version of this graphic.

PEW RESEARCH CENTER

The overall share of Americans who express consistently conservative or consistently liberal opinions has doubled over the past two decades from 10% to 21%. And ideological thinking is now much more closely aligned with partisanship than in the past. As a result, ideological overlap between the two parties has diminished: Today, 92% of Republicans are to the right of the median Democrat, and 94% of Democrats are to the left of the median Republican.

Partisan animosity has increased substantially over the same period. In each party, the share with a highly negative view of the opposing party has more than doubled since 1994. Most of these

Congressional votes



Courtesy, Yph Lelkes; Left -right ideology

SPECIAL FEATURE: INTRODUCTION

The dynamics of political polarization

Simon A. Levin[a,1], Helen V. Milner[b], and Charles Perrings[c]

A number of trends in national and international politics greatly affect our capacity to achieve the cooperation that will be necessary to address the challenges facing society over the coming decades. These involve the interplay among partisanship and party loyalties within countries, populism, and polarization within and among nations. The trends are widespread and seem to be reshaping politics across the globe. They are inherently systems-level phenomena, involving interactions among multiple component parts and the emergence of broader-scale features; yet, they have been inadequately explored from that perspective.

To make progress in understanding these issues, political-science research stands to benefit from insights from other disciplines, including evolutionary biology, systems science, and the disciplines concerned with the fair and efficient provision of public goods of all kinds, but especially those affecting the shared environment and public health. These other disciplines, in turn, stand to gain equally from the perspective developed in political science. In viewing political systems as complex adaptive systems, we can gain a new understanding of the forces that shape current trends, and how that knowledge might affect governance strategies going forward. Extreme polarization is a dangerous phenomenon that requires greater scientific attention to address effectively.

This Special Feature of PNAS draws on this relatively new interdisciplinary field, featuring original joint research from collaborating political scientists and complex systems theorists. Each paper is a true partnership among the different disciplines and illus-

The main goal of the Special Feature is to deepen our understanding of the dynamics of political polarization and related trends, and especially the interplay among these processes at multiple scales, from the local to the international. The papers cover many different aspects of this issue and do so from different systems-level perspectives, providing a broad view of the problem. The papers explore the impact of information flow networks, the diverse nature of national governance systems, the role of the media, and the dynamics of party sorting. They pose a number of key questions. Do the dynamics of such systems follow a natural progression of polarization and collapse, similar to Schumpeter's economic theories (1)? How do migration, globalization, and new technologies, such as the internet, affect the trends? Does an extension of Duverger's Law (2) foreshadow a natural tendency toward polarization in nations with two-party systems, like that in the United States, undercutting Madison's dream (3)? Duverger's Law argues that a system like that of the United States, based on a plurality rule on a single ballot, will lead to a two-party system, while Madison hoped for a system that would "break and control the violence of faction" (3).

The Special Feature arose from a series of workshops in which the issues were aired, collaborations were developed, and earlier versions of the papers received constructive feedback. It became clear from those discussions that even the definition of polarization has manifold aspects, that some degree of polarization is likely healthy in sharpening issue differences in any society, and that there have been historical fluctuations in polarization at all levels.

The nonlinear feedback dynamics of asymmetric political polarization

Naomi Ehrich Leonard[a,1,2], Keena Lipsitz[b,1,2], Anastasia Bizyaeva[a], Alessio Franci[c], Yphtach Lelkes[d]

[a]Department of Mechanical and Aerospace Engineering, Princeton University, Princeton, NJ 08544; [b]Department of Political Science, Queens College and The Graduate Center, City University of New York, Flushing, NY 11367; [c]Department of Mathematics, National Autonomous University of Mexico, 04510 Mexico City, Mexico; and [d]Annenberg School for Communication, University of Pennsylvania, Philadelphia, PA 19104

Edited by Robert Axelrod, University of Michigan, Ann Arbor, MI, and approved August 18, 2021 (received for review March 2, 2021)

Using a general model of opinion dynamics, we conduct a systematic investigation of key mechanisms driving elite polarization in the United States. We demonstrate that the self-reinforcing nature of elite-level processes can explain this polarization, with voter preferences accounting for its asymmetric nature. Our analysis suggests that subtle differences in the frequency and amplitude with which public opinion shifts left and right over time may have a differential effect on the self-reinforcing processes of elites, causing Republicans to polarize more quickly than Democrats. We find that as self-reinforcement approaches a critical threshold, polarization speeds up. Republicans appear to have crossed that threshold while Democrats are currently approaching it.

political polarization | nonlinear dynamics | political elites | public opinion | bifurcations

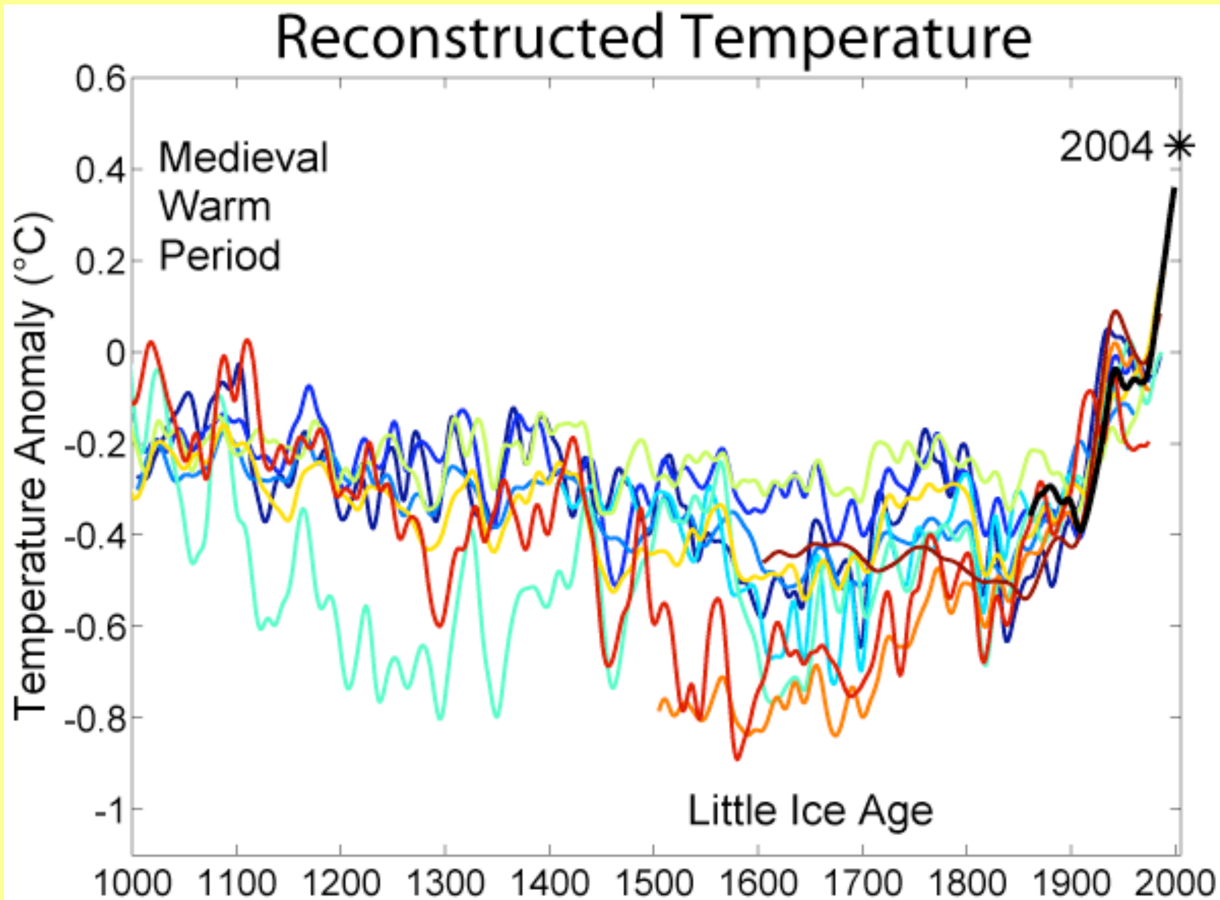
American policymakers are more polarized today than any time since the end of the Civil War. After a period of bipartisanship following World War II, Republican and Democratic political elites, typically defined as legislators and other elected officials, diverged dramatically. The resulting polarization threatens the long-term stability of America and "has triggered the epidemic of norm breaking that now challenges our democracy" (ref. 1, p. 204).

Despite clear evidence of its existence, explanations for polarization, such as changes to the media environment, interest group influence, and institutional factors, are often presented in a positive feedback mechanism, which, by definition, yields a pattern of increasing returns (4). Positive feedback amplifies variations in ideological position while negative feedback attenuates variations in ideological position. As positive feedback grows, it can reach a critical threshold at which point amplifying and attenuating effects are balanced. When positive feedback, in the form of party self-reinforcement or reflexive partisanship, crosses that threshold, then ideological positions can rapidly become extreme. Second, we find that elite-level self-reinforcement can explain polarization in the United States. The asymmetry in the polarization comes from asymmetry in self-reinforcement driven by the dynamics of policy mood—an aggregate measure of the public's ideology—wherein voters shift more frequently and for a longer duration to the right than to the left. Third, we rule out reflexive partisanship as a dominant mechanism since it does not explain asymmetric polarization even when driven by policy mood. The fact that reflexive partisanship is a mutual response undermines its asymmetric effect. Relatedly, we also demonstrate that the breakdown in norms of bipartisanship, i.e., the inverse of reflexive partisanship, cannot account for the rise of asymmetric polarization. Fourth, we rule out the (null) hypothesis that elites are merely responding to policy mood without a positive feedback mechanism.

Significance

Political polarization threatens democracy in America. This

Scientific consensus is strong on many core environmental issues

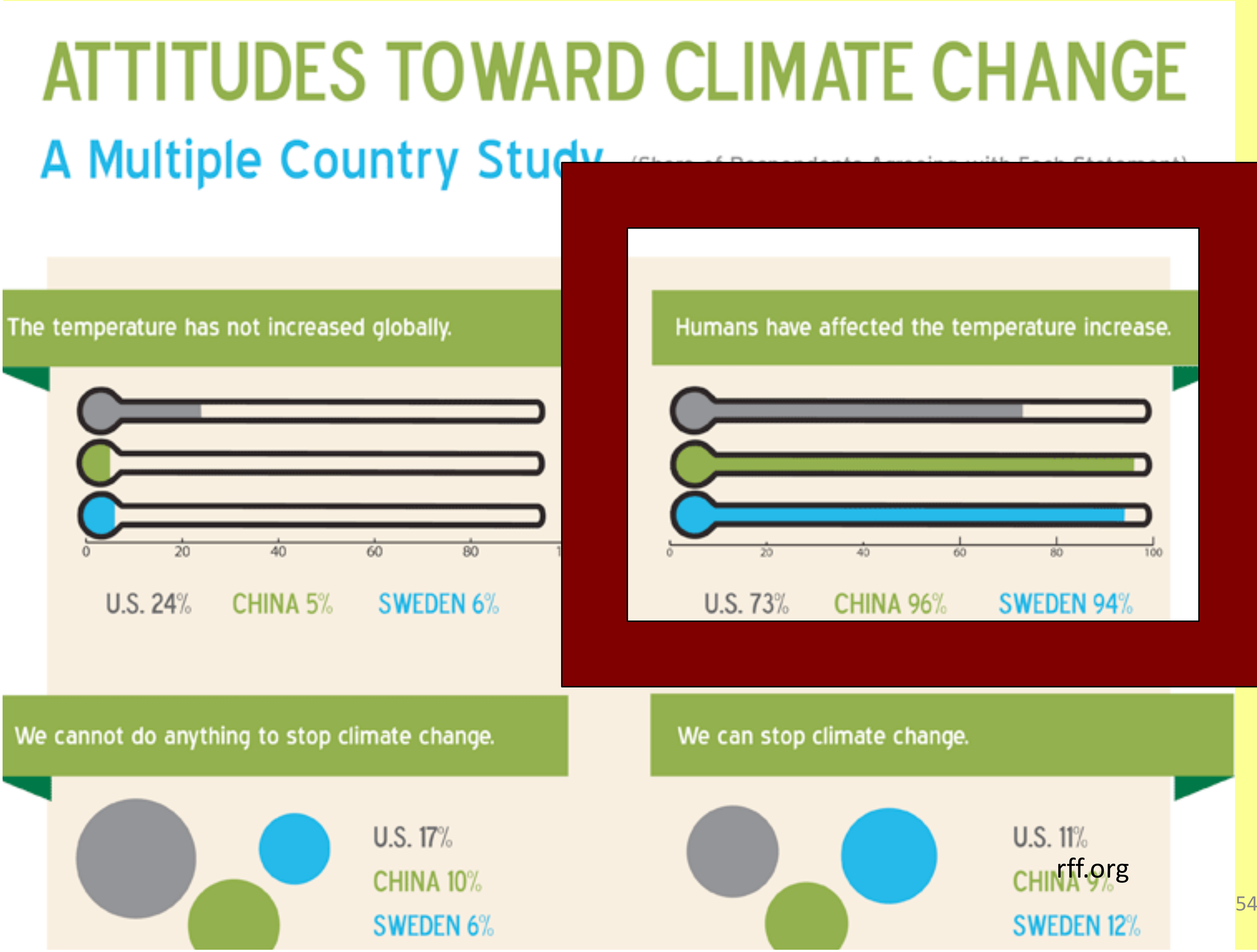


Robert Rohde, for [Global Warming Art]

But adequate action to address them has been lacking

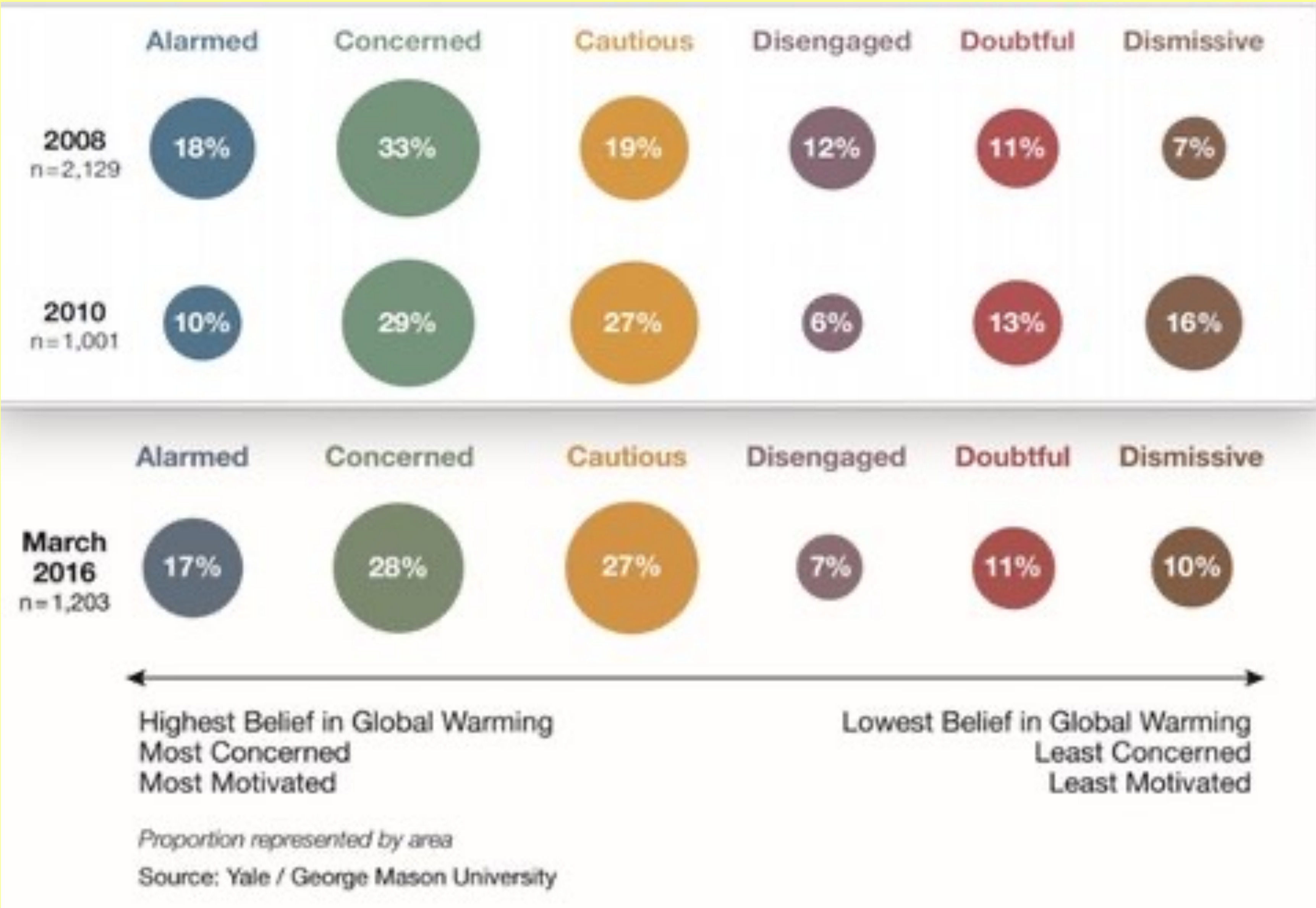
- Primary limitations to solutions not scientific knowledge, but rather
- Willingness of people and governments to commit to the common good
- And to cooperate in finding solutions that benefit all

www.edie.net

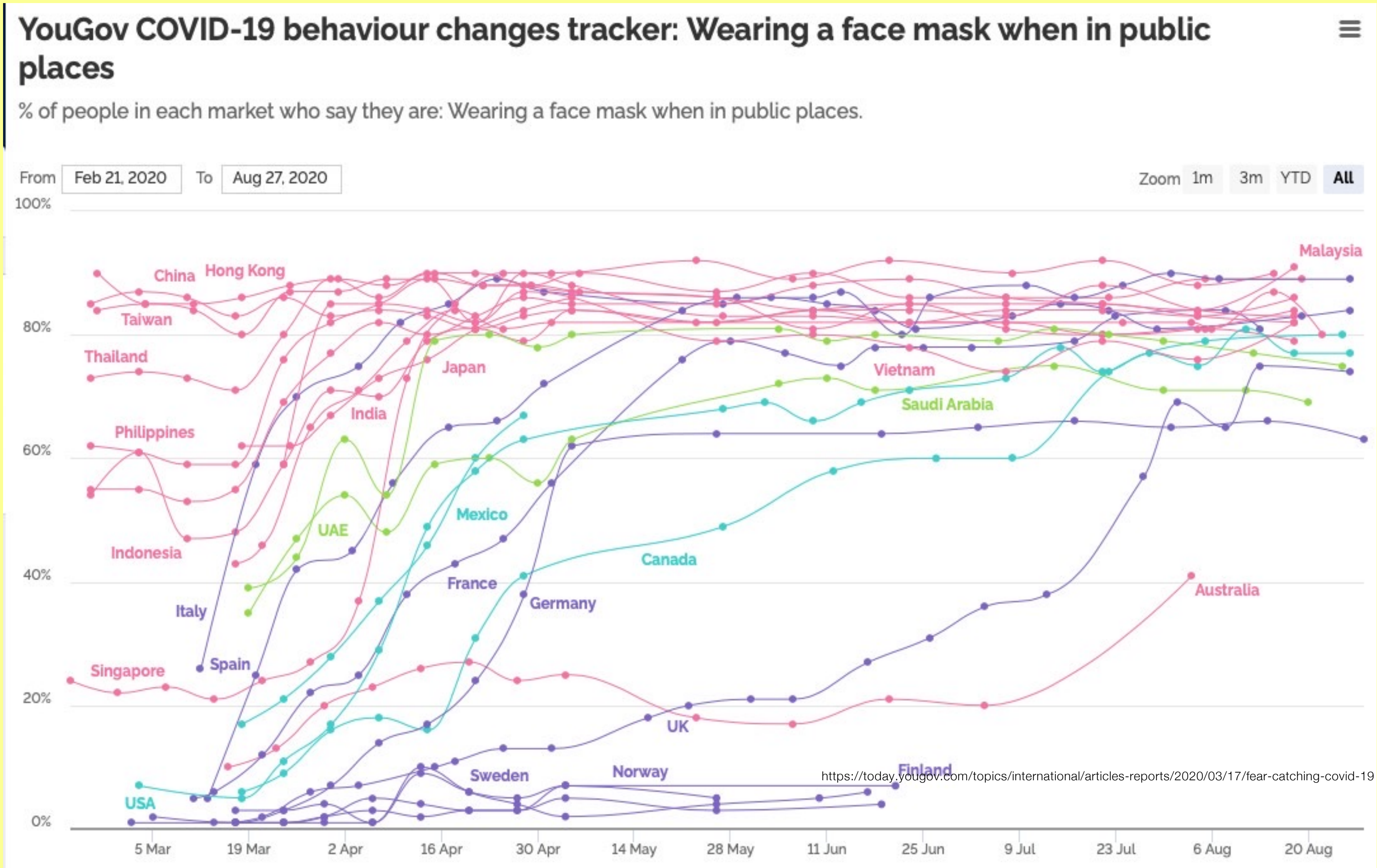

ATTITUDES TOWARD CLIMATE CHANGE
A Multiple Country Study
The temperature has not increased globally.
0 20 40 60 80
U.S. 24% CHINA 5% SWEDEN 6%
Humans have affected the temperature increase.
0 20 40 60 80 100
U.S. 73% CHINA 96% SWEDEN 94%
We cannot do anything to stop climate change.
U.S. 17%
CHINA 10%
SWEDEN 6%
We can stop climate change.
U.S. 11%
CHINA 9%
SWEDEN 12%

RFF

rff.org


Alarmed
Concerned
Cautious
Disengaged
Doubtful
Dismissive
2008
n=2,129
18%
33%
19%
12%
11%
7%
2010
n=1,001
10%
29%
27%
6%
13%
16%
Alarmed
Concerned
Cautious
Disengaged
Doubtful
Dismissive
March
2016
n=1,203
17%
28%
27%
7%
11%
10%
Highest Belief in Global Warming
Most Concerned
Most Motivated
Lowest Belief in Global Warming
Least Concerned
Least Motivated
Proportion represented by area
Source: Yale / George Mason University

Cultural and Political Influences are Crucial



Current work with Luojun Yang, Joergen Weibull, Kaushik Basu, Avinash Dixit, others

Social norms are key

INSIGHTS

COLLECTIVE ACTION

Social norms as solutions

Policies may influence large-scale behavioral tipping

By **Karine Nyborg, John M. Anderies, Astrid Dannenberg, Therese Lindahl, Caroline Schill, Maja Schlüter, W. Neil Adger, Kenneth J. Arrow, Scott Barrett, Stephen Carpenter, F. Stuart Chapin III, Anne-Sophie Crépin, Gretchen Daily, Paul Ehrlich, Carl Folke, Wander Jager, Nils Kautsky, Simon A. Levin, Ole Jacob Madsen, Stephen Polasky, Marten Scheffer, Brian Walker, Elke U. Weber, James Wilen, Anastasios Xepapadeas, Aart de Zeeuw**

Climate change, biodiversity loss, antibiotic resistance, and other global challenges pose major collective action problems: A group benefits from a certain action, but no individual has sufficient incentive to act alone. Formal institutions, e.g., laws and treaties, have helped address issues like ozone depletion, lead pollution, and acid rain. However, cooperation (*1*). Solutions can be specific to context (e.g., small-scale irrigated rice paddies in Nepal) and local in nature. Yet social norms can affect behavior on larger scales, e.g., cessation of smoking in public places (*2*, *3*), abandonment of foot-binding in China (*4*), and changed fertility norms (*4*)—all striking large-scale transformations of social (dis)approval and behavior.

to understanding social norm changes (*6*). Here, we try to integrate these views.

IS THERE A TIPPING POINT?

For vicious and virtuous behavioral cycles to arise, people must be more willing to choose a behavior the more widespread it is. The tipping point is where a vicious cycle turns into a virtuous one, or vice versa. Social, economic, and technical factors often invoke a need for people to coordinate their behavior. Striking cases are provided by network externalities, in which a good's value to the individual increases with the frequency of others consuming that same type of good. For example, if few own electric cars, charging stations are rare and few will buy electric cars; if most cars are electric, gas stations are rare, and few buy gas-fueled cars.

Similar coordination benefits occur in social life. Diet variation across countries cannot be fully explained by prices, incomes, and nutrition content (*7*); it appears that other forces, like norms, are involved. Differing diets make cooking shared meals cumbersome. If people tend to prefer the foods they are used to, sticking to the most common diet is convenient. The availability and quality of particular foods in stores and restaurants may increase with demand. Hence, if a less meat-intensive diet became the norm, individuals might conform partly owing to social pressure or a wish to be environmentally friendly; but a primary motive may simply be to enjoy pleasant and convenient joint meals.

When behavior is easily observable (e.g., smoking), social sanctioning can create tipping points. If norm followers sanction norm violators, the social sanctioning of violators increases as the share of followers grows (*2*). Other mechanisms inducing people to act like others include conditional cooperation—an often observed willingness to cooperate more when others cooperate

Social norms can change rapidly

- Attitudes towards
  - Foot binding
  - Smoking in public places
  - Racial equality
  - Gender equality
  - Climate change
  - Pandemic?

http://message.snopes.com

Open access, freely available online

Essay

The Evolution of Norms

Paul R. Ehrlich, Simon A. Levin*

Over the past century and a half, we have made enormous progress in assembling a coherent picture of genetic evolution—that is, changes in the pools of genetic information possessed by populations, the genetic differentiation of populations (speciation) (see summaries in [1,2]), and the application of that understanding to the physical evolution of *Homo sapiens* and its forebears ([3]; e.g., [4,5]). But human beings, in addition to being products of biological evolution, are—vastly more than any other organisms—also products of a process of "cultural evolution." Cultural evolution consists of changes in the nongenetic information stored in brains, stories, songs, books, computer disks, and the like. Despite some important first steps, no integrated picture of the process of cultural evolution that has the explanatory power of the theory of genetic evolution has yet emerged.

Much of the effort to examine cultural evolution has focused on interactions of the genetic and cultural processes (e.g., [6], see also references in [7]). This focus, however, provides a sometimes misleading perspective, since most of the behavior of our species that is of interest to policy makers is a product of the portion of cultural evolution [8] that occurs so rapidly that genetic change is irrelevant. There is a long-recognized need both to understand the process of human cultural evolution per se and to find ways of altering its course (an operation in which institutions as diverse as schools, prisons, and governments have long been engaged). In a world threatened by weapons of mass destruction and escalating environmental deterioration, the need to change our behavior to avoid a global collapse [9] has become urgent. A clear understanding of how cultural changes interact with individual actions is central to informing democratically and humanely guided efforts to influence cultural evolution. While most of the effort to understand that evolution has come from the social sciences, biologists have also struggled with the issue (e.g., p. 285 of [10], [11–16], and p. 62 of [17]). We argue that biologists and social scientists need one another and must collectively direct more of their attention to understanding how social norms develop and change. Therefore, we offer this review of the challenge in order to emphasize its multidisciplinary dimensions and thereby to recruit a broader mixture of scientists into a more integrated effort to develop a theory of change in social norms—and, eventually, cultural evolution as a whole.

What Are the Relevant Units of Culture?

Norms (within this paper understood to include conventions or customs) are representative or typical patterns and rules of behavior in a human group [18], often supported by legal or other sanctions. Those sanctions, norms in themselves, have been called "metanorms" when failure to enforce them is punished [17,19,20]. In our (liberal) usage, norms are standard or ideal behaviors "typical" of groups. Whether these indeed represent the average behaviors of individuals in the groups is an open question, and depends on levels of conformity. Conformity or nonconformity with these norms are attributes of individuals, and, of course, heterogeneity in those attributes is important to how norms evolve. Norms and metanorms provide a cultural "stickiness" (p. 10 of [21]) or viscosity that can help sustain adaptive behavior and retard detrimental changes, but that equally can inhibit the introduction and spread of beneficial ones. It is in altering normative attitudes that changes can be implemented.

Here, we review the daunting problem of understanding how norms change, discuss some basic issues, argue that progress will depend on the development of a comprehensive quantitative theory of the initiation and spread of norms (and ultimately all elements of culture), and introduce some preliminary models that examine the spread of norms in space or on social networks. Most models of complex systems are meant to extract signal from noise, suppressing extraneous detail and thereby allowing an examination of the influence of the dominant forces that drive the dynamics of pattern and process. To this end, models necessarily introduce some extreme simplifying assumptions.

Early attempts to model cultural evolution have searched for parallels of the population genetic models used to analyze genetic evolution. A popular analogy, both tempting and facile, has been that there are cultural analogues of genes, termed "memes" [22,23], which function as replicable cultural units. Memes can be ideas, behaviors, patterns, units of information, and so on. But the differences between genes and memes makes the analogy inappropriate, and "memetics" has not led to real understanding of cultural evolution. Genes are relatively stable, mutating rarely, and those changes that do occur usually result in nonfunctional products. In contrast, memes are extremely mutable, often transforming considerably with each transmission. Among humans, genes can only pass unidirectionally from

Essays articulate a specific perspective on a topic of broad interest to scientists.

Citation: Ehrlich PR, Levin SA (2005) The evolution of norms. PLoS Biol 3(6): e194.

Paul R. Ehrlich is with the Department of Biological Sciences, Stanford University (Stanford, California, United States of America). Simon A. Levin is with the Department of Ecology and Evolutionary Biology, Princeton University (Princeton, New Jersey, United States of America).

*To whom correspondence should be addressed. E-mail: slevin@princeton.edu

DOI: 10.1371/journal.pbio.0030194

Ostrom: Climate change

ANNALS OF ECONOMICS AND FINANCE **15-1**, 97–134 (2014)

A Polycentric Approach for Coping with Climate Change

Elinor Ostrom

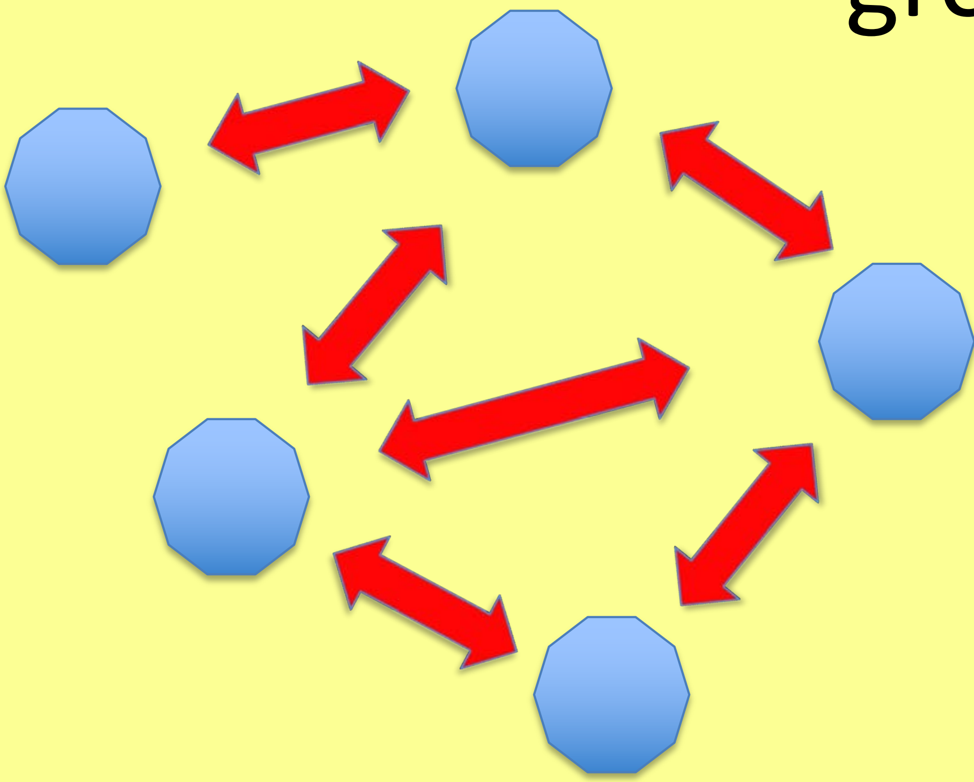
Indiana University

This paper proposes an alternative approach to addressing the complex problems of climate change caused by greenhouse gas emissions. The author, who won the 2009 Nobel Prize in Economic Sciences, argues that single policies adopted only at a global scale are unlikely to generate sufficient trust among citizens and firms so that collective action can take place in a comprehensive and transparent manner that will effectively reduce global warming. Furthermore, simply recommending a single governmental unit to solve global collective action problems is inherently weak because of free-rider problems. For example, the Carbon Development Mechanism (CDM) can be 'gamed' in

Tilman-Dixit- Levin

Theoretical Ecology

Prosociality and multiple groups



Localized Pro-Social Preferences, Public Goods and Common-Pool Resources

Andrew Tilman, Avinash Dixit, and Simon Levin

June 11, 2018

Abstract

The presence of pro-social preferences is thought to reduce significantly the difficulty of solving our societal collective action problems such as providing public goods (or reducing public bads). However, pro-sociality is often limited to members of an in-group. We present a general theoretical model where society is split into subgroups and people care more about the welfare of others within their own subgroup than they do about others. Additionally, individual contributions to the public good spill over and benefit members in each group to some degree. We then consider special cases of our general model under which we can examine the consequences of localized pro-sociality for the economic outcomes of society as a whole. We find that relative public-good provision can be either a concave or a convex function of the level of pro-sociality. The former arises when public and private efforts are poor substitutes, and in that case even low levels of pro-sociality can lead to public-goods provision near the social optimum.

1 Introduction and motivation

As the world becomes more interconnected, we increasingly are faced with problems of the Commons and their governance (Hardin, 1968; Ostrom, 1990; Levin, 1999). Individuals and nations withdraw water, fish and other resources from a finite pool; overuse of antibiotics erodes their effectiveness (Smith et al., 2005); and the emission of pollutants and greenhouse gases fouls the atmosphere. In most such situations, individual incentives are insufficient to restrain usage of finite resources and sustain public goods in the Commons; governments must find ways to change the incentive structure to overcome the tendency to overexploit. The task may be easier in smaller societies, where pro-social preferences may play a greater

Tilman-Dixit-Levin: Multiple groups

Individual utility:

$$v_{gi} = y(x_{gi}, Z_g) - (k/2)(x_{gi} + z_{gi})^2 + \gamma_g \sum_{k \neq i} y(x_{gk}, Z_g)$$

where

Z_g is the public pool in group g,
including leakage from other groups

ϒ is prosociality within group

x, z are private and public effort

Also consider fixed budget

- Prosociality facilitates cooperation
- Local prosociality with leakage of benefits can lead to global cooperation
- Prosociality can be selected for because it leave offspring with better life

The Puzzle of Prosociality*

Herbert Gintis

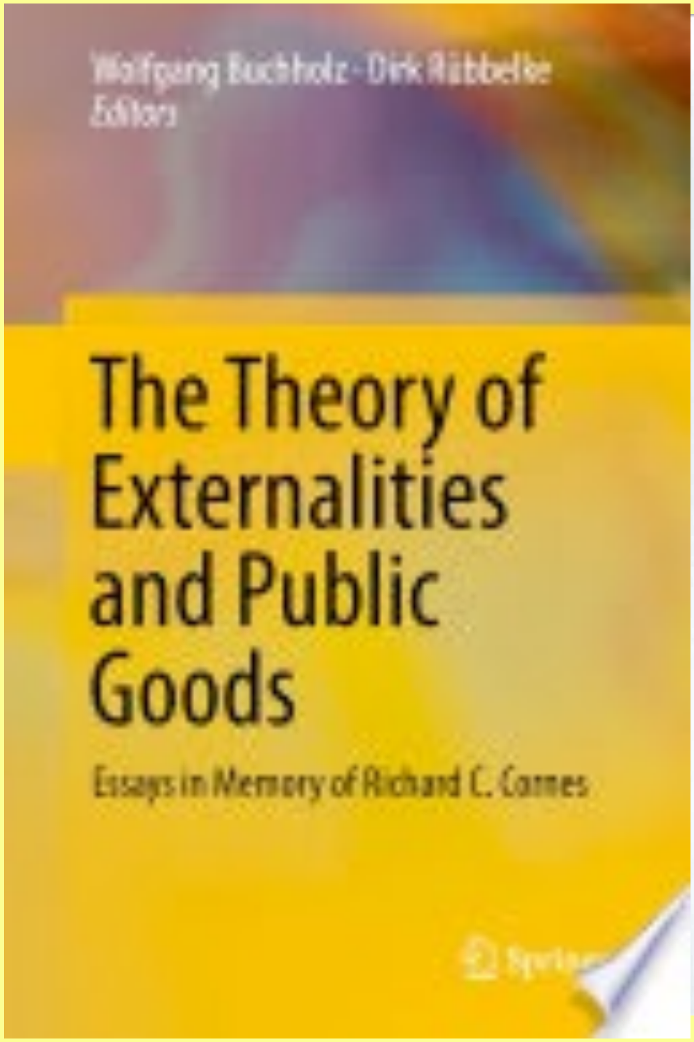
October 10, 2001

Abstract

How is cooperation among large numbers of unrelated individuals sustained? Cooperation generally requires *altruism*, where individuals take actions that are group-beneficial but personally costly. Why do selfish agents not drive out altruistic behavior? This is the *puzzle of prosociality*.

Altruism is supported by culture. Sociology treats culture as a set of norms that are transmitted by socialization institutions and internalized by individuals. Altruism, in this approach, is thus sustained by the internalization of norms. Biology treats culture as knowledge that is passed to children from parents (vertical transmission), from other prominent adults (oblique transmission), and from peers (horizontal transmission), such that individuals with higher payoffs have a higher level of biological fitness, leading norms to follow a dynamic of Darwinian selection. Altruism, in this approach, can be sustained only if group selection is feasible, which it rarely is. Economics uses evolutionary game theory to model culture as strategies deployed in social interaction that evolve according to a replicator dynamic, in which individuals shift from lower to higher payoff norms. In this approach, altruism cannot

Prosociality can emerge endogenously



Social Creation of Pro-social Preferences for Collective Action

Avinash Dixit and Simon Levin

1 Introduction and Motivation

Study of collective action to provide public goods was the focus of much of Richard Cornes' work. Attainment of aggregate efficiency in these situations has to overcome free riding by selfish participants. Most of the work in this area, including the classic book of Cornes and Sandler (1996), was grounded in economists' traditional assumption of exogenous and self-regarding preferences. Cornes's occasional excursions into other-regarding preferences involved goods with joint private and public characteristics (e.g. Cornes and Sandler 1996, Chap. 8), and intra-family altruism for transfers (e.g. Cornes and Silva 1999) or for public good provision (e.g. Cornes et al. 2012). Economics in recent years has increasingly recognized that people have pro-social preferences in larger social groups, and is beginning to recognize that preferences are not exogenous but are socially formed. In this paper we develop a model with these features, and examine to what extent such pro-socialness can be instilled and help solve collective action problems.

Pro-social preferences and other-regarding behaviors more generally are a fact of life, though it is often puzzling how they are sustained (Henrich et al. 2001; Gintis 2003; Fehr and Gintis 2007; Akcay et al. 2009; Henrich et al. 2010). The most plausible explanation will combine genetic and evolutionary pathways with socio-cultural processes to incentivize and reinforce pro-sociality. In this paper we focus on one such societal process. Our basic framework builds on earlier work by the first author (Dixit 2009). The framework is a general one, where individuals allocate their efforts or resources between their own interests and the public good. The analysis applies equally to investments that limit the damage to common pool

A. Dixit (✉) • S. Levin
Department of Ecology & Evolutionary Biology, Princeton University, Princeton, NJ 08544, USA
e-mail: dixitak@princeton.edu

 127
W. Buchholz, D. Rübbelke (eds.), *The Theory of Externalities and Public Goods*,
DOI 10.1007/978-3-319-49442-5_7

Conclusions

- At all levels, mathematical thinking can address the fundamental problems of complex adaptive systems
- Unifying disciplines, and transferring successes in one discipline to another
- This was Wilson's definition of consilience
- And NSF's definition of "convergence" research