The challenge of sustainability and the promise of mathematics

http://greencraft.co.uk/

Simon Levin
Moscow2013

The central problem facing societies is achieving a sustainable future

www.anualadearhitectura.ro

Sustainability means many things

- Financial markets and economic security

www.centralbanking.com/

Sustainability means many things

- Financial markets and economic security
- Energy and other natural resources

Mathematics of energy

- Energy exploration
- Increasing combustion efficiency
- Alternative energy
- Network management
- Climate consequences

Sustainability means many things

- Financial markets and economic security
- Energy and other natural resources
- Biological and cultural diversity

eoearth.org

Sustainability means many things

- Financial markets and economic security
- Energy and other natural resources
- Biological and cultural diversity
- Ecosystem services

www.serconline.org

Characteristic regularities in macroscopic patterns exist in all ecosystems

www.bio.unc.edu

www.yale.edu/yibs

www.csiro.au

These sustain ecosystem services

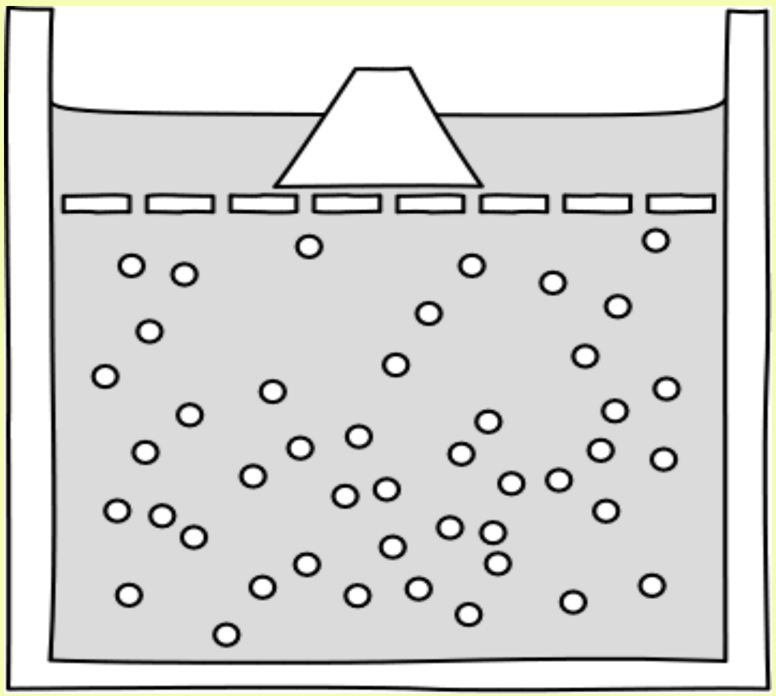
This implies a need to relate phenomena across scales, from

- cells to organisms to collectives to ecosystems

and to ask

- How robust are the properties of ecosystems?
- How does the robustness of macroscopic properties relate to ecological and evolutionary dynamics on finer scales?
- Are ecosystems at critical points?

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



Mathematical Challenges

- Can we develop a *statistical mechanics* of ecological communities, socio-economic systems and of the biosphere?
- Can we model the *emergence* of ecological pattern?
- Are there indicators of impending *critical transitions* between states?
- Can mathematics help with *governance* to achieve sustainability in these multi-scale systems?

Forest growth simulators

Botkin, Shugart, Pacala,…

Deutschman, DH, SA Levin, C Devine and LA Buttel. 1997.

Scaling from trees to forests: analysis of a complex simulation model. Science **277**:1688.

Simplification approaches

- Coarse graining
- Lagrangian to Eulerian transitions
- Moment closure schemes
- Equation-free methods

At what scale is prediction possible?
Ecotypes, not species, are predictable

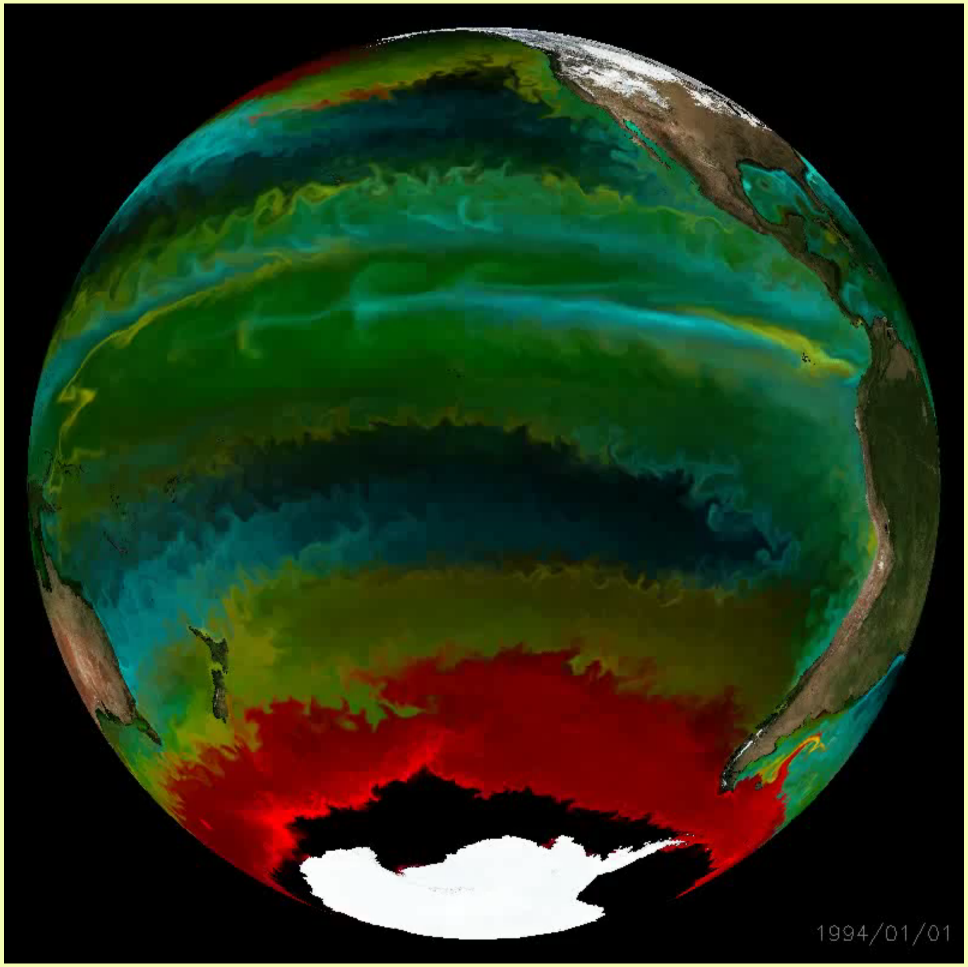
Darwin model: Follows, Dutkiewicz, Chisholm, …

Prochlorococcus

Synechococcus

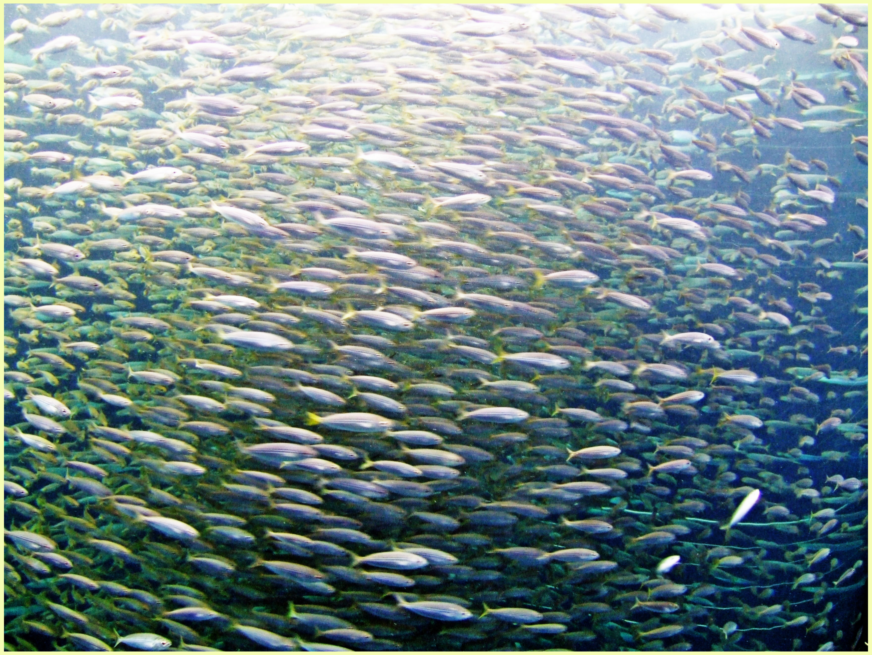
Diatoms

Large eukaryotes



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.



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

2008

Vol 451|21 February 2008

NEWS & VIEWS

COMPLEX SYSTEMS

Ecology for bankers

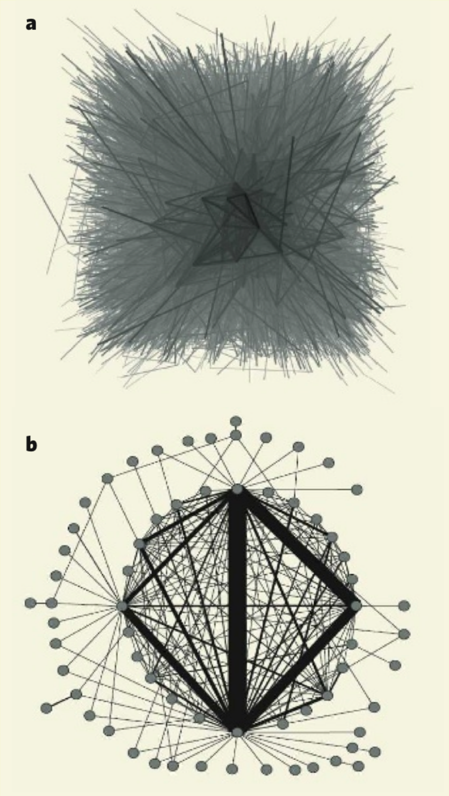
Robert M. May, Simon A. Levin and George Sugihara

There is common ground in analysing financial systems and ecosystems, especially in the need to identify conditions that dispose a system to be knocked from seeming stability into another, less happy state.

'Tipping points', 'thresholds and breakpoints', 'regime shifts' — all are terms that describe the flip of a complex dynamical system from one state to another. For banking and other financial institutions, the Wall Street Crash of 1929 and the Great Depression epitomize such an event. These days, the increasingly complicated and globally interlinked financial markets are no less immune to such system-wide (systemic) threats. Who knows, for instance, how the present concern over sub-prime loans will pan out?

Well before this recent crisis emerged, the US National Academies/National Research Council and the Federal Reserve Bank of New York collaborated[1] on an initiative to "stimulate fresh thinking on systemic risk". The main event was a high-level conference held in May 2006, which brought together experts from various backgrounds to explore parallels between systemic risk in the financial sector and in selected domains in engineering, ecology and other fields of science. The resulting report[1] was published late last year and makes stimulating reading.

Catastrophic changes in the overall state of a system can ultimately derive from how it is organized — from feedback mechanisms within it, and from linkages that are latent and often



spent on studying systemic risk as compared with that spent on conventional risk management in individual firms? Second, how expensive is a systemic-risk event to a national or global economy (examples being the stock market crash of 1987, or the turmoil of 1998 associated with the Russian loan default, and the subsequent collapse of the hedge fund Long-Term Capital Management)? The answer to the first question is "comparatively very little"; to the second, "hugely expensive".

An analogous situation exists within fisheries management. For the past half-century, investments in fisheries science have focused on management on a species-by-species basis (analogous to single-firm risk analysis). Especially with collapses of some major fisheries, however, this approach is giving way to the view that such models may be fundamentally incomplete, and that the wider ecosystem and environmental context (by analogy, the full banking and market system) are required for informed decision-making. It is an example of a trend in many areas of applied science acknowledging the need for a larger-system perspective.

But to what extent can study of ecosystems inform the design of financial networks in, for instance, their robustness against perturbation? Ecosystems are robust by virtue of their

2008

COMPLEX SYSTEMS

Ecology for bankers

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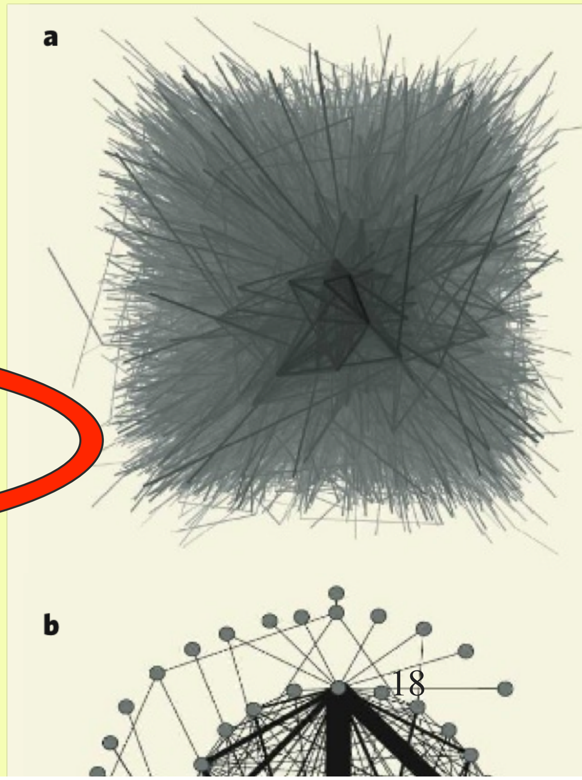
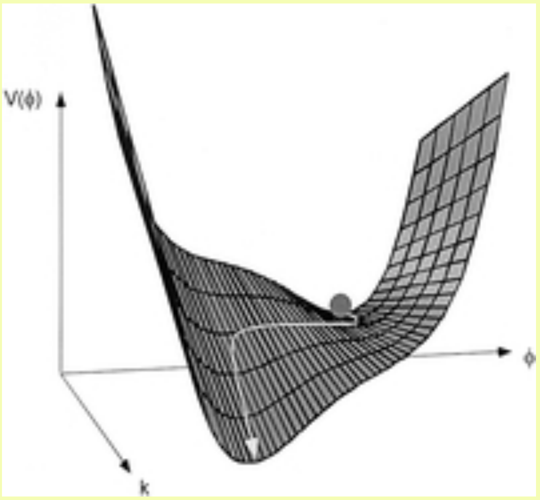


Many such transitions have characteristic early warning signals

- Critical slowing down
- Increasing variance
- Increasing autocorrelation
- Flickering between states



Bardy, B.; Oullier, O.; Bootsma, R. J.; Stoffregen, T. A.;J. Exp. Psych. Vol 28(3):499-514.

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.

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

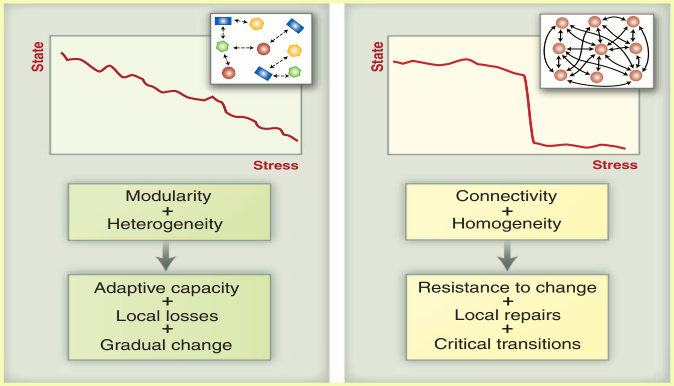
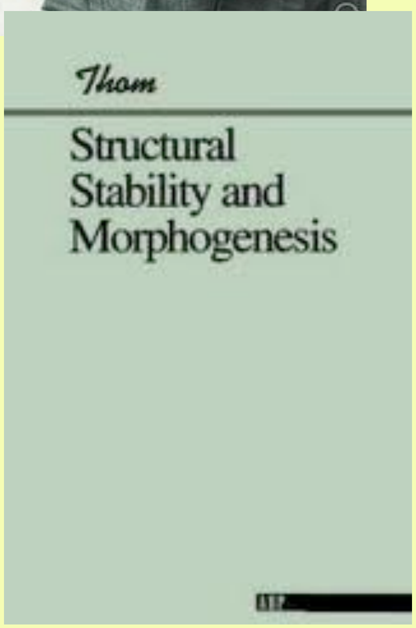


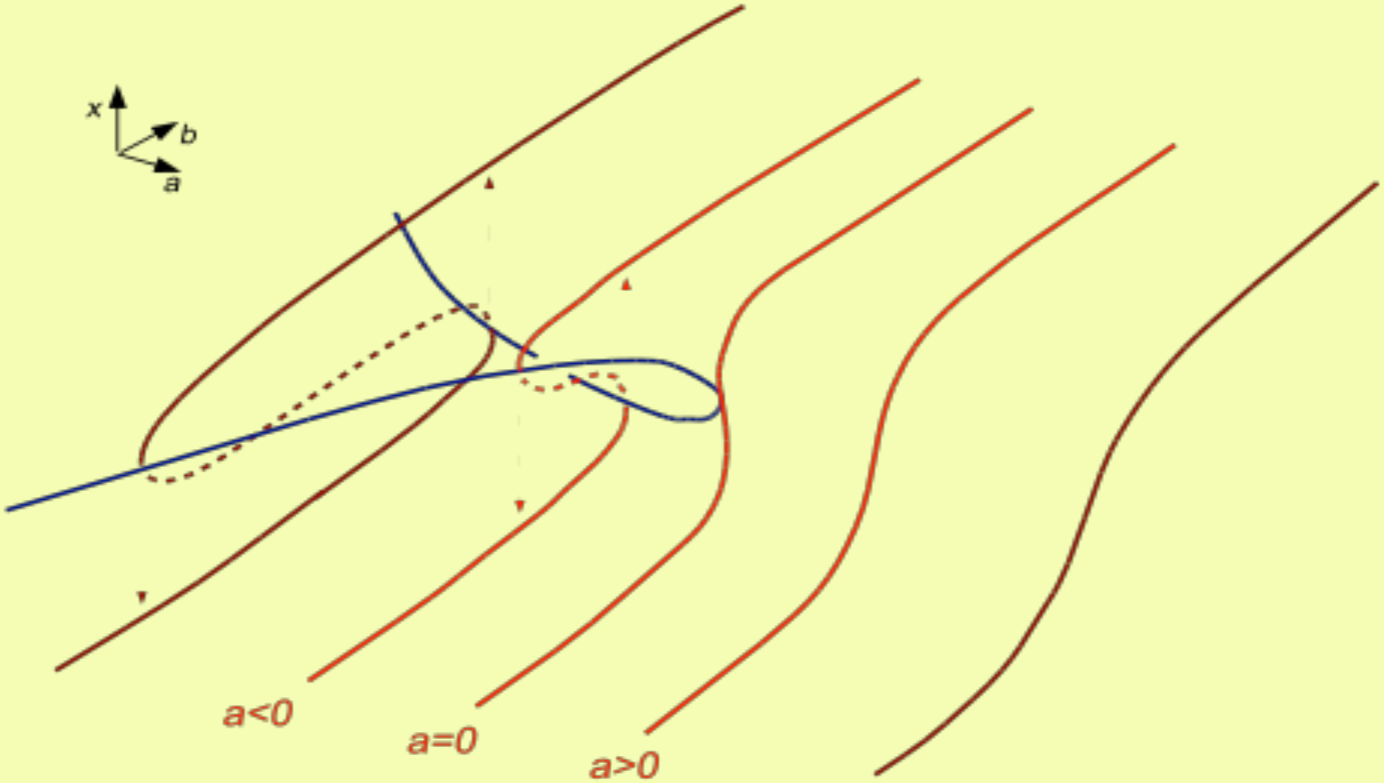
Fig. 1. The connectivity and homogeneity of the units affect the way in which distributed systems with local alternative states respond to changing conditions. Networks in which the components differ (are

[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 53706, USA. [7]Spatial Ecology Department, Royal Netherlands Institute for Sea Research (NIOZ), Post Office Box 140, 4400AC, Yerseke, Netherlands. [8]Community and Conservation Ecology Group, Centre for Ecological and Evolutionary Studies (CEES), University of Groningen, Post Office Box 11103, 9700 CC Groningen, Netherlands. [9]Department of Ecology and Evolutionary Biology, Princeton University, Princeton, NJ 08544–1003, USA. [10]University of Michigan and Howard Hughes Medical

Science, 2012

But caution is needed…mechanisms need to be identified

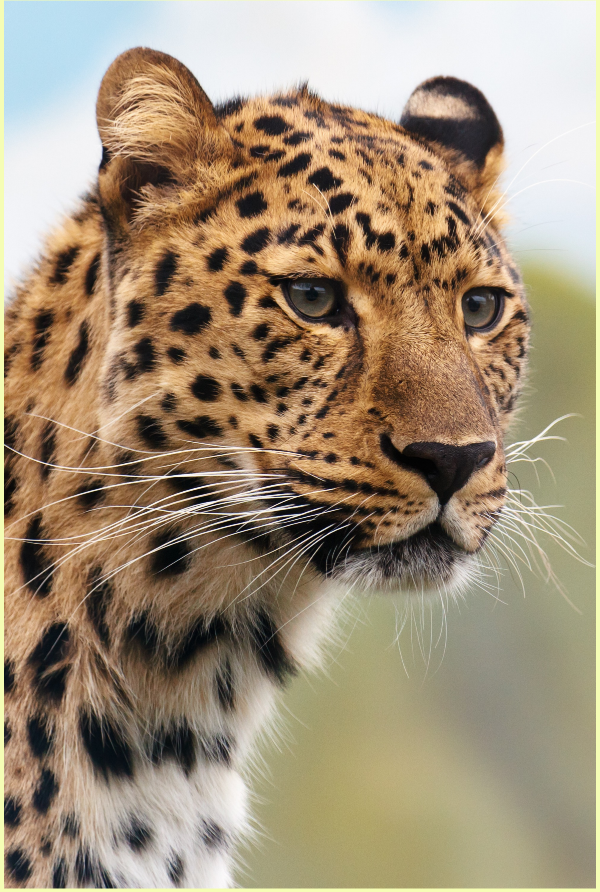


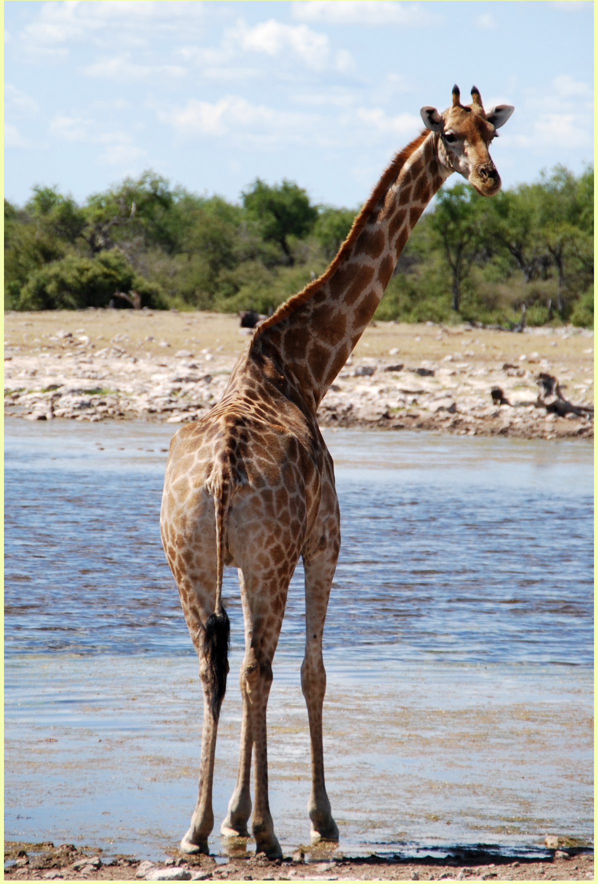


http://en.wikipedia.org/wiki/Catastrophe_theory
http://en.wikipedia.org/wiki/Ren%C3%A9_Thom

Pattern can arise endogenously or exogenously

Endogenous causes: Animal coat patterns and deeper problems in development





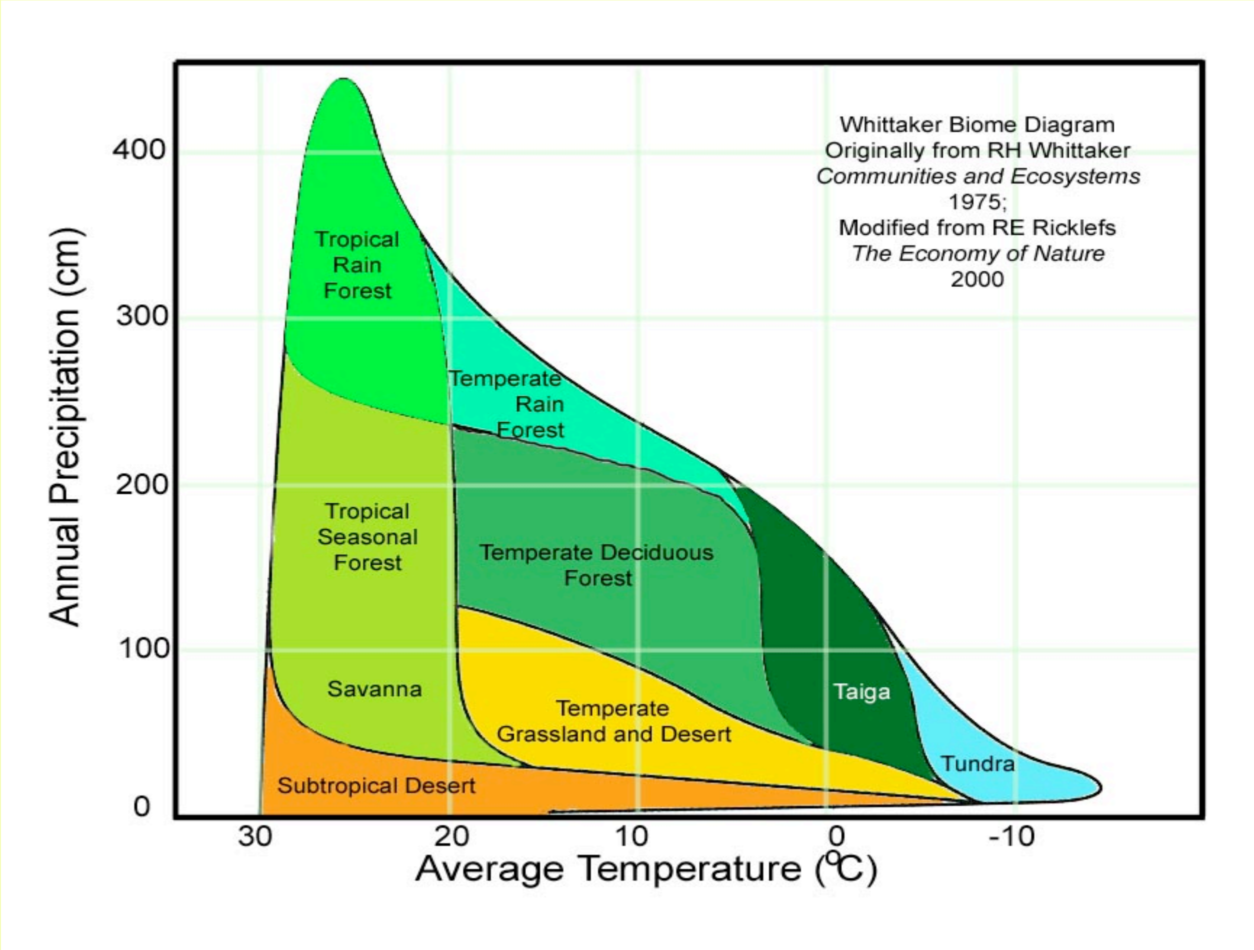
See Murray, 1988

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

Alan Turing (1912-1954)

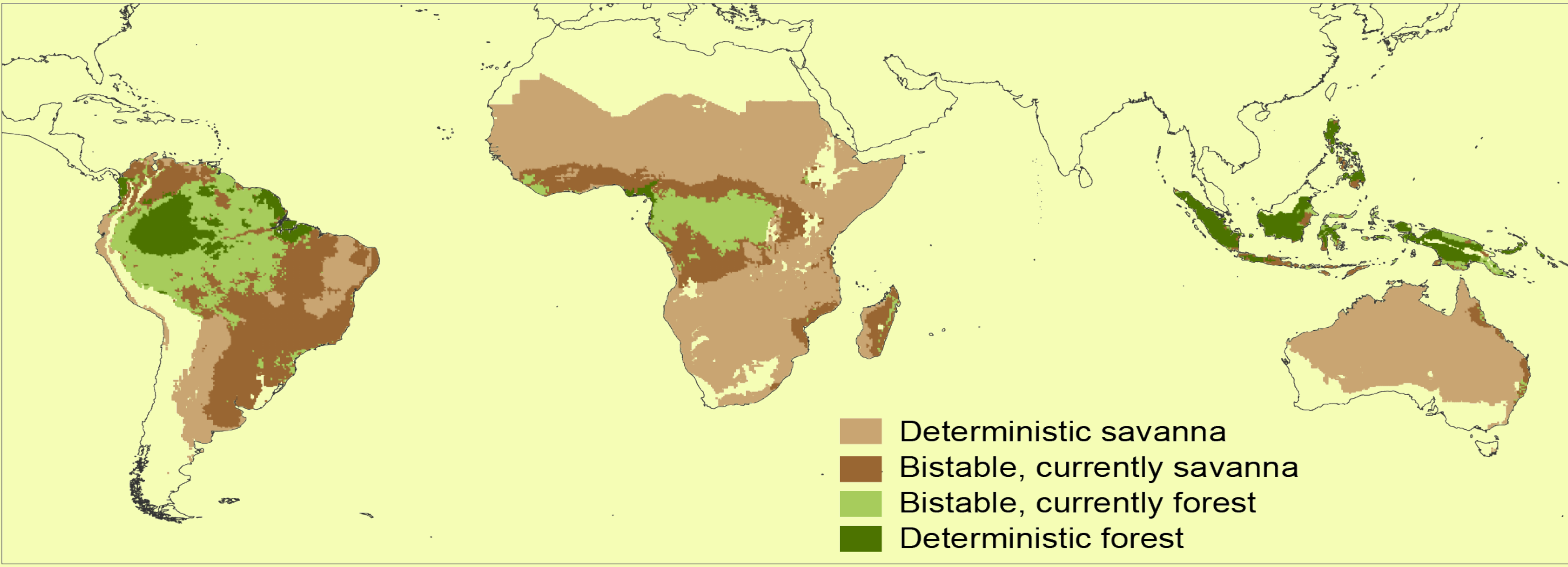
http://www.schmoozd.com

Much ecological pattern is exogenous: tracks environmental pattern



Savanna/Forest Distributions

But, there are limits to predictability: Alternative stable states
Bistability characterizes global distributions



Staver *et al.* 2011 (*Ecology* and *Science)*

Relatively simple models can capture this behavior

Grass $$\frac{dG}{dt} = \mu S + \nu T - \beta G T$$

Saplings $$\frac{dS}{dt} = \beta G T - \omega(G) S - \mu S$$

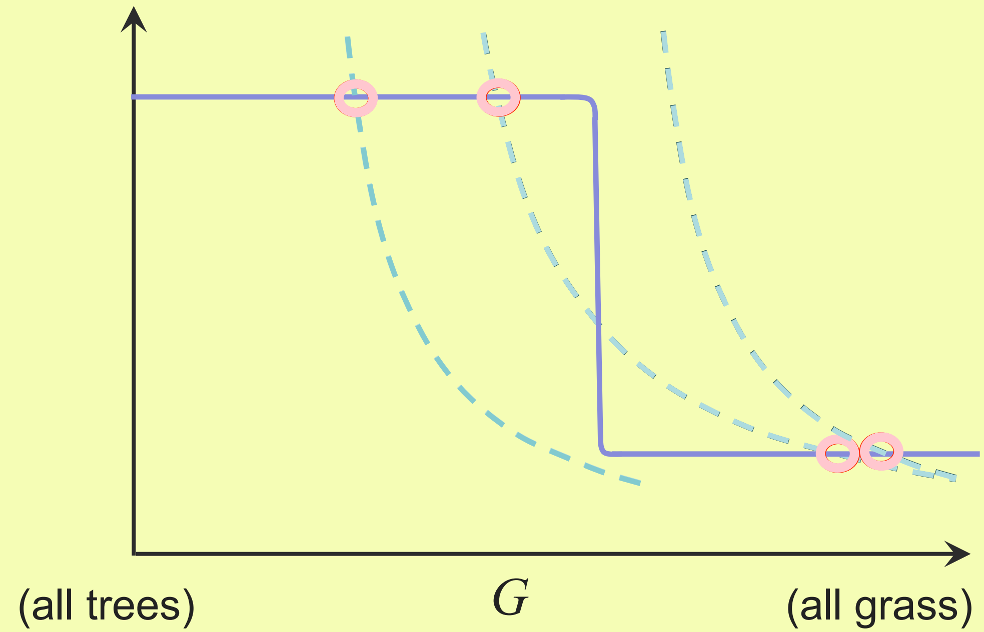
Trees $$\frac{dT}{dt} = \omega(G) S - \nu T$$

$$G + S + T = 1$$

$\omega(G)$ can be derived from a fire-percolation model

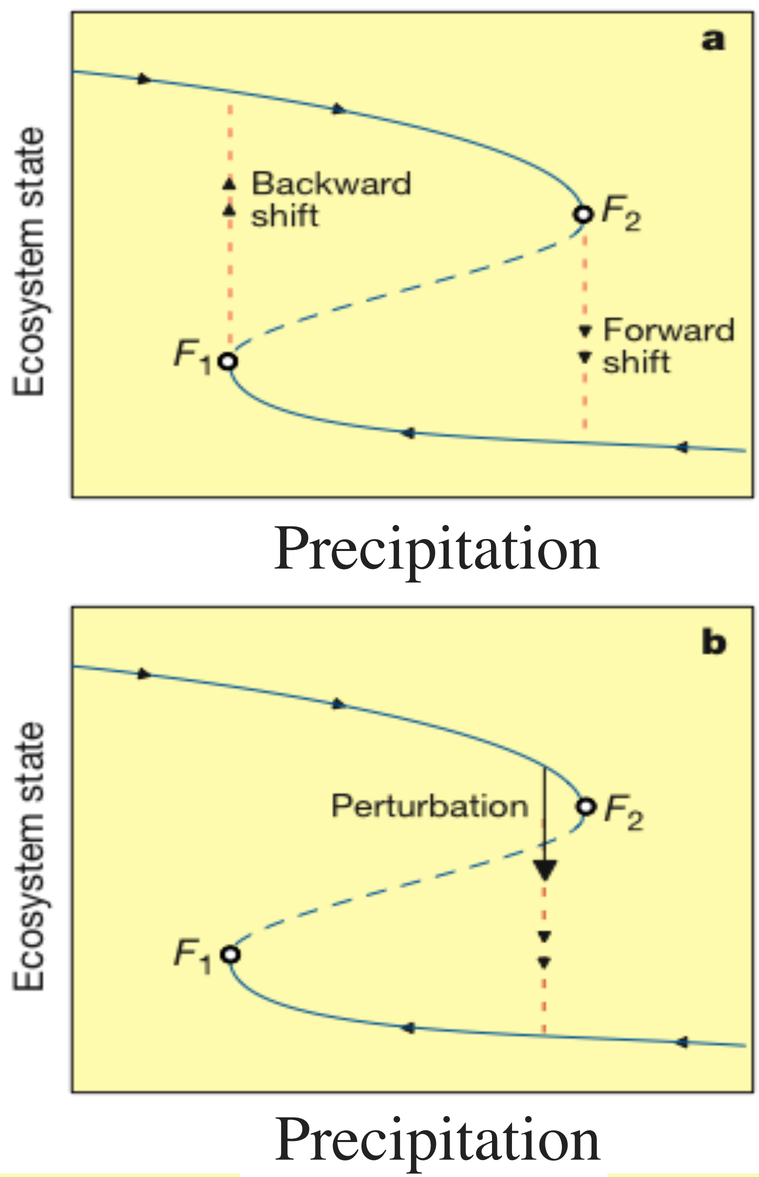
Staver *et al.* 2011 (*Ecology*) and Staver & Levin 2012 (Amer.Natur.)

$$\omega(\overline{G}) = \frac{\mu\nu}{\beta\overline{G} - \nu}$$



Staver *et al.* 2011 (*Ecology*) and Staver & Levin AmerNatur 2012)

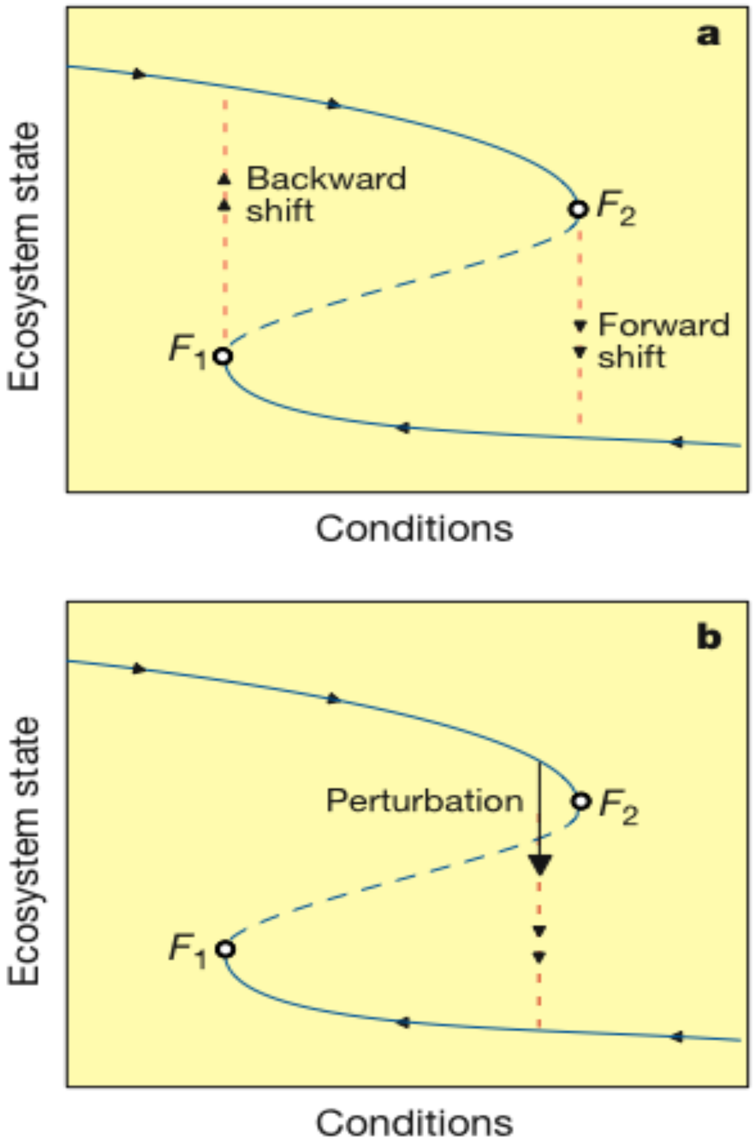
Savanna/Forest Distributions



Modified very slightly from Scheffer *et al.* 2003, Nature

- Responses to changes in rainfall status will be rapid, threshold transitions
- Changes will not be linear or easy to reverse

Results of dynamic mathematical model



Scheffer et al. 2003

- Savannas represent a stable alternative to forest, with long-term temporal persistence maintained by fire
- Shallow lakes show similar behavior
- So too do other systems, like pathogen systems

Are there critical biosphere thresholds?

doi:10.1038/nature11018

Approaching a state shift in Earth's biosphere

Anthony D. Barnosky[1,2,3], Elizabeth A. Hadly[4], Jordi Bascompte[5], Eric L. Berlow[6], James H. Brown[7], Mikael Fortelius[8], Wayne M. Getz[9], John Harte[9,10], Alan Hastings[11], Pablo A. Marquet[12,13,14,15], Neo D. Martinez[16], Arne Mooers[17], Peter Roopnarine[18], Geerat Vermeij[19], John W. Williams[20], Rosemary Gillespie[9], Justin Kitzes[9], Charles Marshall[1,2], Nicholas Matzke[1], David P. Mindell[21], Eloy Revilla[22] & Adam B. Smith[23]

Localized ecological systems are known to shift abruptly and irreversibly from one state to another when they are forced across critical thresholds. Here we review evidence that the global ecosystem as a whole can react in the same way and is approaching a planetary-scale critical transition as a result of human influence. The plausibility of a planetary-scale 'tipping point' highlights the need to improve biological forecasting by detecting early warning signs of critical transitions on global as well as local scales, and by detecting feedbacks that promote such transitions. It is also necessary to address root causes of how humans are forcing biological changes.

Mathematical Challenges

- Can we develop a *statistical mechanics* of ecological communities, socio-economic systems and of the biosphere?
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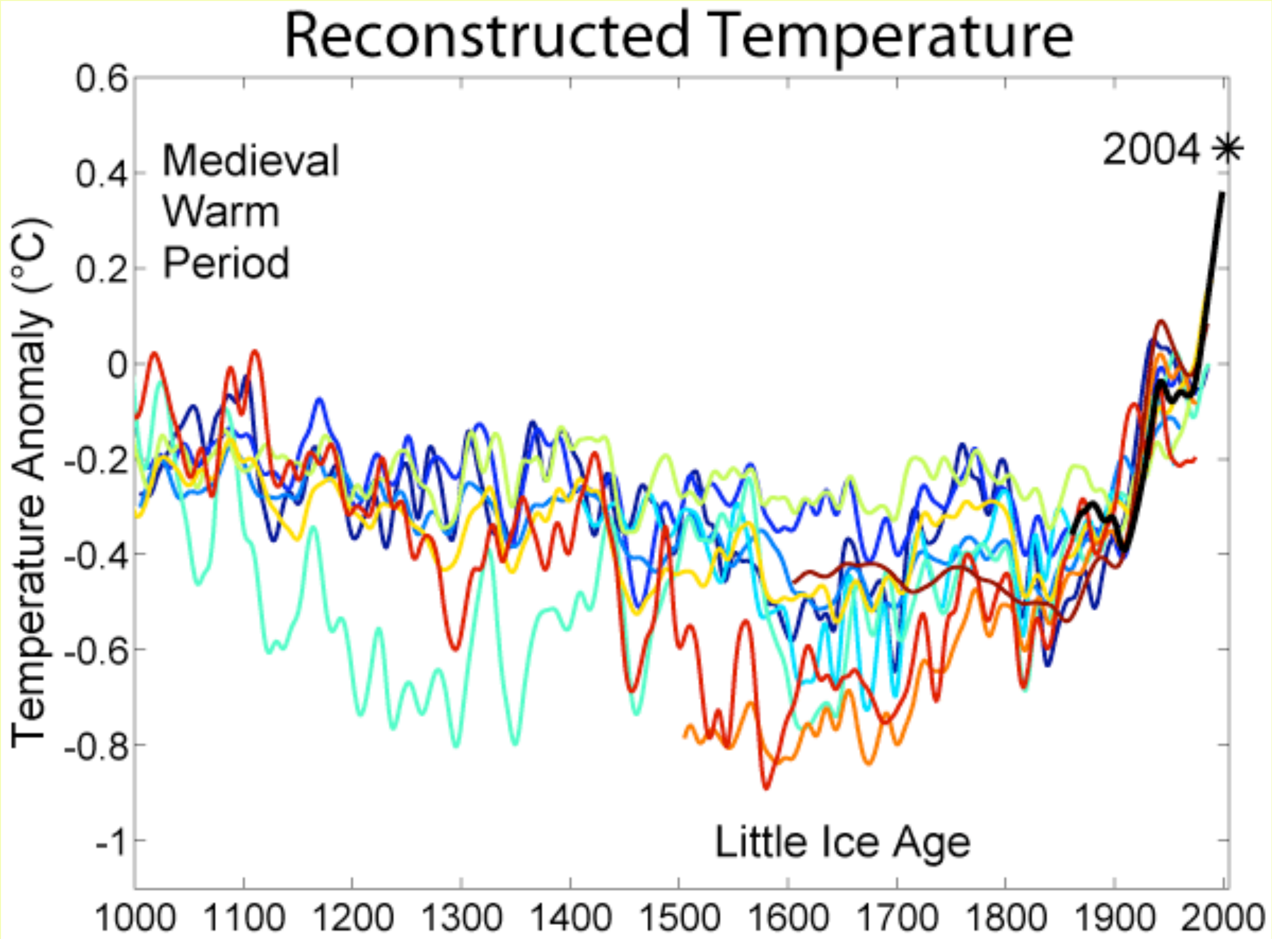
Mathematical Challenges

- Can mathematics help with *governance* to achieve sustainability in these multi-scale systems?
  - Optimal control theory
  - Voting theory
  - Collective motion and collective action
  - Game theory and negotiation

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

The central issues are issues of behavior and culture

- Intergenerational and intragenerational equity
- Public goods and common pool resources
- Cooperation in the Commons
- Social norms and institutions
- Leadership and developing consensus

Equity: We discount

- The future

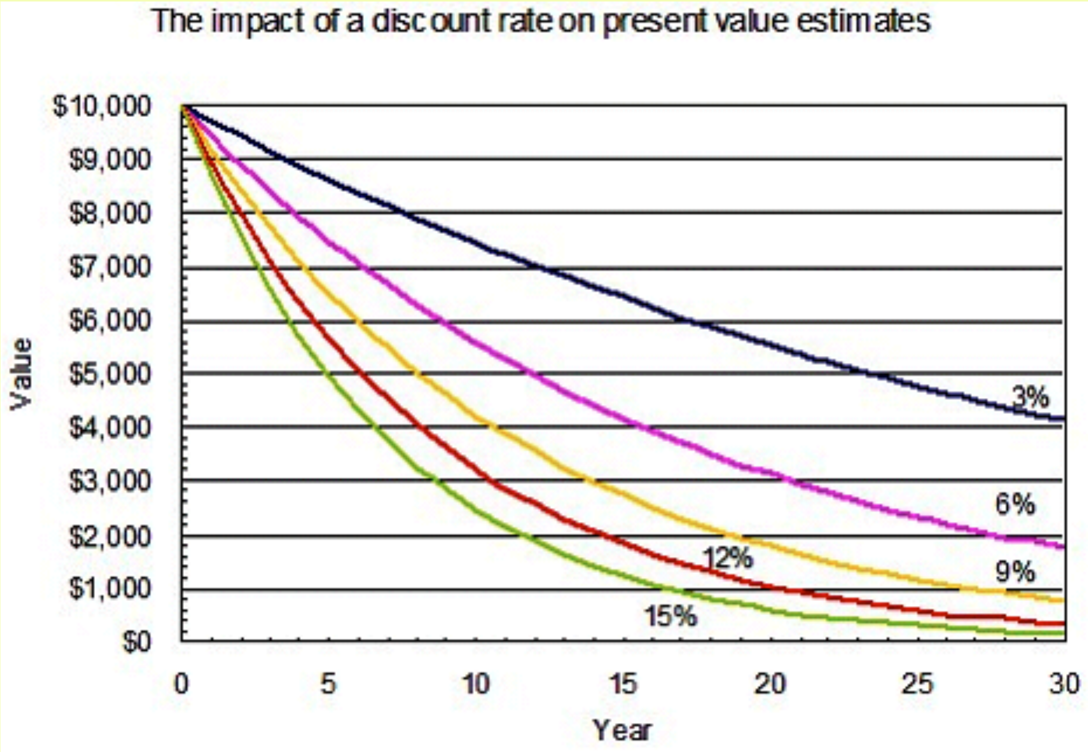
Equity:
We discount

- The future
- The interests of others

www.improvingyourworld.com

Intergenerational equity

- How should we discount the future?



www.dot.ca.gov/hq

Journal of Economic Perspectives—Volume 18, Number 3—Summer 2004—Pages 147–172

Are We Consuming Too Much?

Kenneth Arrow, Partha Dasgupta,
Lawrence Goulder, Gretchen Daily, Paul Ehrlich,
Geoffrey Heal, Simon Levin, Karl-Göran Mäler,
Stephen Schneider, David Starrett and
Brian Walker

Is humanity's use of Earth's resources endangering the economic possibilities open to our descendants? There is wide disagreement on the question. Many people worry about the growth in our use of natural resources over the past century. Some of this increase reflects the higher resource demands from a growing world population. But it also reflects the growth of per capita output and consumption. During the twentieth century, world population grew by a factor of four to more than 6 billion, and industrial output increased by a factor of 40. Per capita

■ *Kenneth Arrow is Professor of Economics Emeritus, Stanford University, Stanford, California. Partha Dasgupta is the Frank Ramsey Professor of Economics at the University of*

Intertemporal social welfare

$$V(t) = \int_t^{\infty} U[C(s)]e^{-\delta(s-t)}ds$$

Intergenerational resource transfers with random offspring numbers

Kenneth J. Arrow[a] and Simon A. Levin[b,1]

[a]Department of Economics, Stanford University, Stanford, CA 94305-6072; and [b]Department of Ecology and Evolutionary Biology, Princeton University, Princeton, NJ 08544-1003

Contributed by Kenneth J. Arrow, May 26, 2009 (sent for review March 29, 2009)

A problem common to biology and economics is the transfer of resources from parents to children. We consider the issue under the assumption that the number of offspring is unknown and can be represented as a random variable. There are 3 basic assumptions. The first assumption is that a given body of resources can be divided into consumption (yielding satisfaction) and transfer to children. The second assumption is that the parents' welfare includes a concern for the welfare of their children; this is recursive in the sense that the children's welfares include concern for their children and so forth. However, the welfare of a child from a given consumption is counted somewhat differently (generally less) than that of the parent (the welfare of a child is "discounted"). The third assumption is that resources transferred may grow (or decline). In economic language, investment, including that in education or nutrition, is productive. Under suitable restrictions, precise formulas for the resulting allocation of resources are found, demonstrating that, depending on the shape of the utility curve, uncertainty regarding the number of offspring may or may not favor increased consumption. The results imply that wealth (stock of resources)

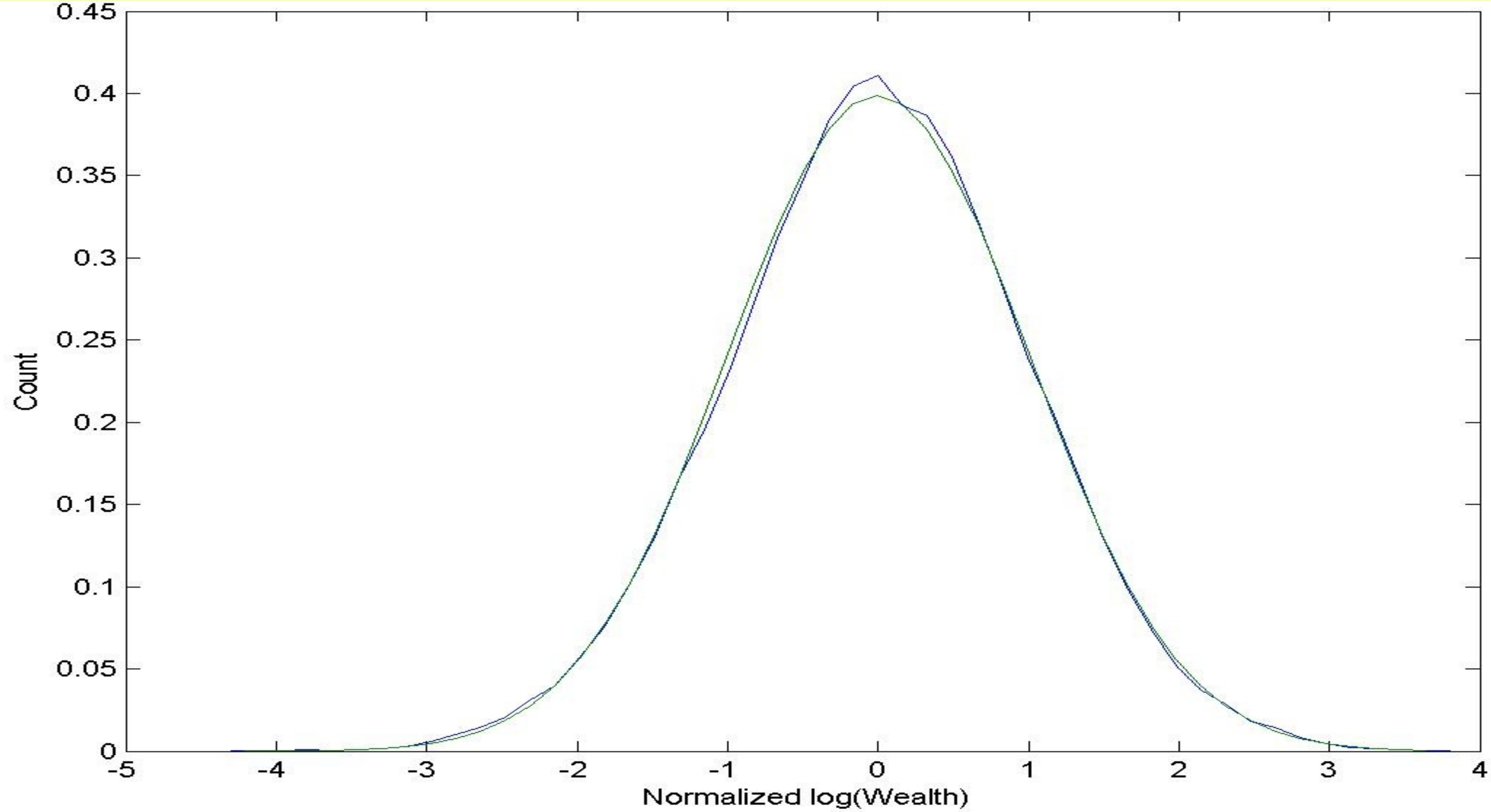
ping generations, offspring produced early in life are more valuable than those produced later because those offspring can also begin reproduction earlier. This is analogous to the classic investment problem in economics, in that population growth imposes a discount rate that affects when one should have offspring. The flip side is that early reproduction compromises the parent's ability to care for its children, and that increased number of offspring reduces the investment that can be made in each. Again, the best solution generally involves compromise and an intermediate optimum.

A particularly clear manifestation of this tradeoff involves the problem of clutch or litter size—how many offspring should an organism, say a bird, have in a particular litter? (11) Large litters mandate decreased investment in individuals, among other costs, but increase the number of lottery tickets in the evolutionary sweepstakes. This problem has relevance across the taxonomic spectrum, and especially from the production of seed by plants to the litter sizes of elephants and humans. Even for vertebrates, the evolutionary resolution shows great variation: The typical

ECONOMIC SCIENCES

Dynamic programming solution: Wealth converges to a log-normal distribution with spread determined by uncertainty

Arrow and Levin, PNAS



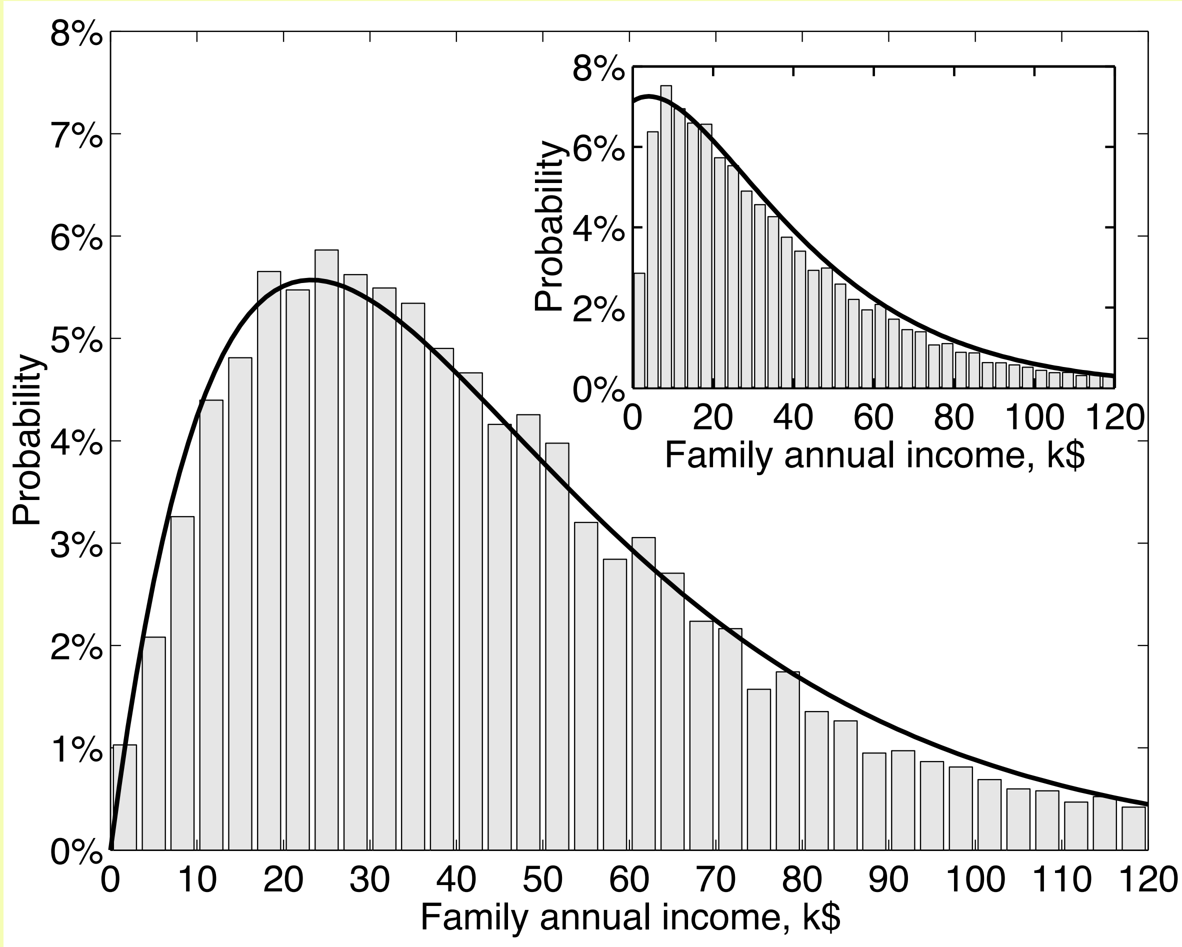
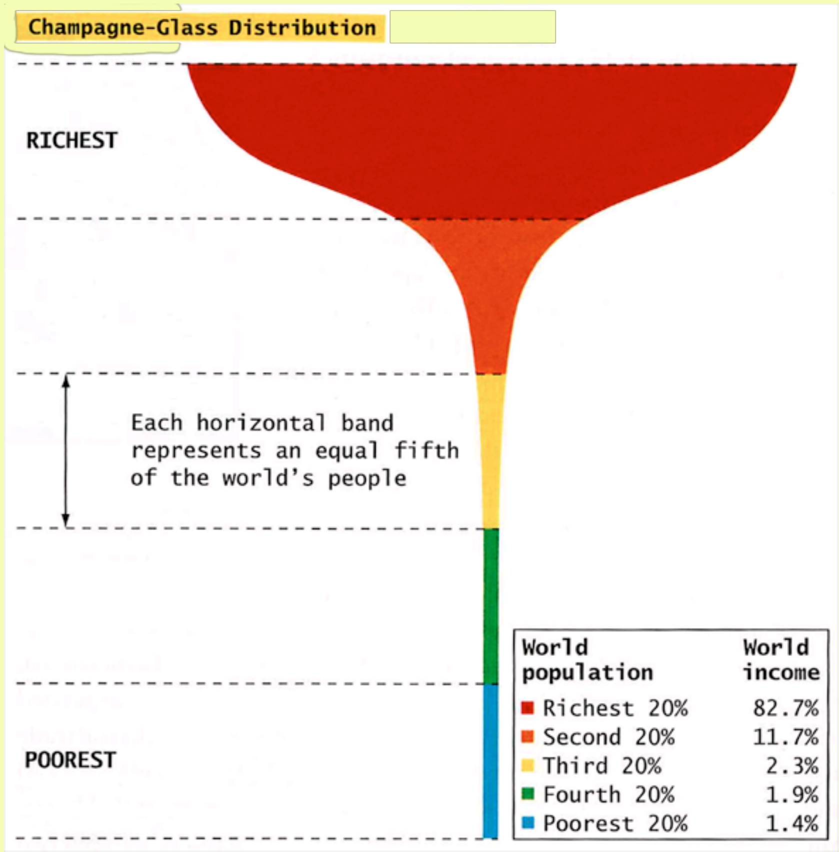


Fig. 4. Histogram: Probability distribution of income for families with two adults in 1996 [11]. Solid line: Fit to equation (5). Inset histogram: Probability distribution of income for all families in 1996 [11]. Inset solid line: $0.45P_1(r) + 0.55P_2(r)$.

Eur. Phys. J. B **20, 585{589 (2001) THE EUROPEAN PHYSICAL JOURNAL B**
Evidence for the exponential distribution of income in the USA
A. Dragulescu and V.M. Yakovenko

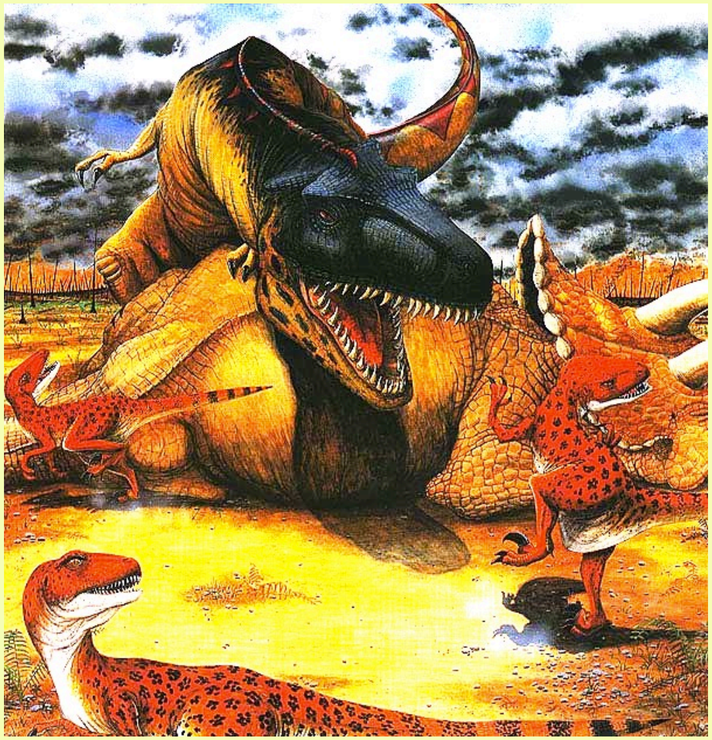
World distribution of wealth



Conley, D. (2008) You may ask yourself: An introduction to thinking like a sociologist. W.W. Norton and Company. p.392., after UNDP Human Developmnet report 1992. Oxford University Press.

Moreover, we live in a global commons, in which

- Individual agents act largely in their own self-interest



www.centerstage-musicals.com

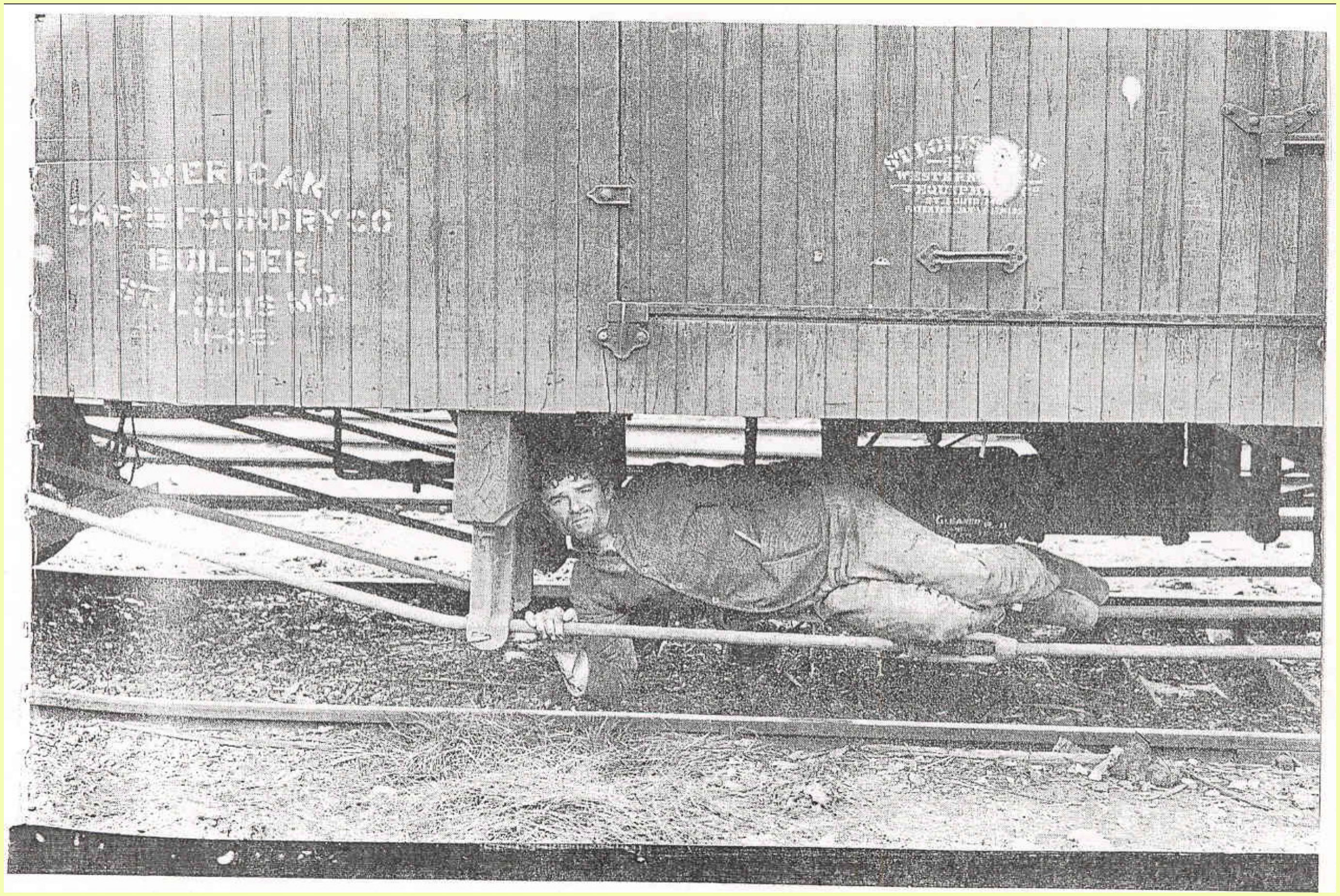
Moreover, we live in a global commons, in which

- Individual agents act largely in their own self-interest
- Social costs are not adequately accounted for

The challenge….achieving cooperation at the global level

un.org

The problem: Free-riders



www.americanpopularculture.com

For public goods,

The Tragedy of the Commons

Aelbert_Cuyp

William Forster Lloyd (1832)

The Commons solution (Hardin, Ostrom)

"Mutual coercion, mutually agreed upon"

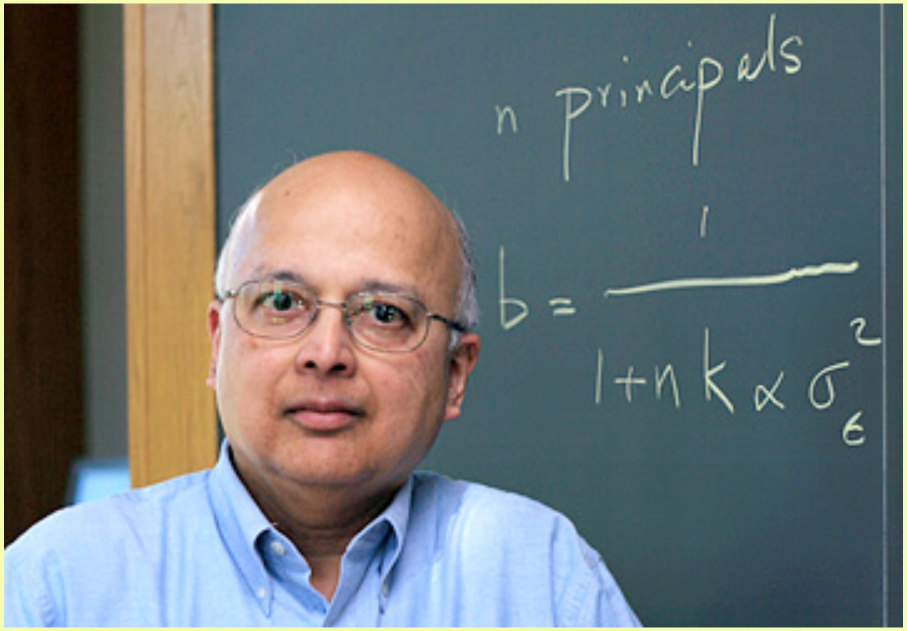
http://www.physics.ohio-state.edu/~wilkins

http://www.guardian.co.uk

Sustainability is about

- Learning to share
- Establishing enforceable cooperative agreements
- To achieve mutual benefit
- Insurance arrangements
- At levels from individuals to nations

Dixit and Levin: Prosociality and public goods



www.zam.it

Game theory and the Commons

Dixit-Levin: How much will individuals contribute to a public good? Game-theoretic perspective

x=private effort,
z=public effort,
γ=prosociality

Individual utility:

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

For example:

$$y(x_{gi}, Z_g) = x_{gi}{}^{\alpha} Z_g{}^{\beta}$$

Where

$$Z_g = \sum_h \lambda_{gh} n_h z_h$$

Pastoralism and sharing of grazing grounds

- With Avinash Dixit and Daniel Rubenstein

meshakenya.wordpress.com

Extension (with Dan Rubenstein)

- Pastoralism and sharing of grazing grounds in East Africa

http://www.ilri.org/ilrinews/

Basic framework

- Good years A_H, bad years A_L
- When one has a good year, and the other has a bad year, m cattle moved from bad to good
- Total welfare is

$$W = A_1(x_1 + m)^{\alpha} z_1^{\beta} + A_2(x_2 - m)^{\alpha} z_2^{\beta}$$

$$-(1/2)c(x_1 + z_1)^2 - (1/2)(x_2 + z_2)^2$$

Variety of mechanisms: Repeated game

- Social optimum: Choose transfers to maximize total welfare
- Self-enforcing? Depends on discount rate
- Arrangement is stable if discount rate is small enough relative to the benefits of cooperation

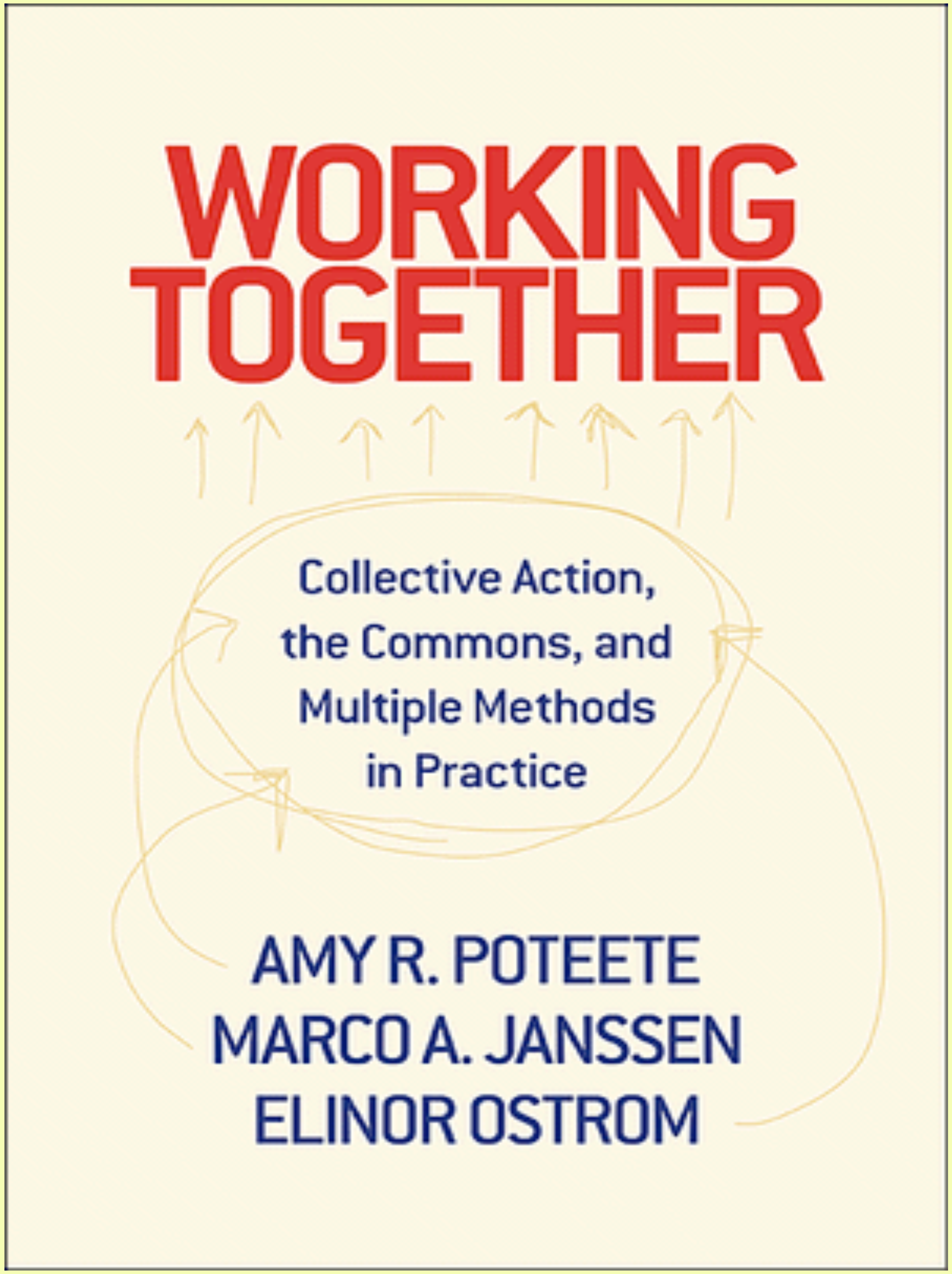
Variety of mechanisms: Repeated game

- Social optimum
- Self-enforcing?
- If not, second-best solutions to make them self-enforcing
  - Constrained optimization

Variety of mechanisms: Repeated game

- Social optimum
- Self-enforcing?
- If not, second-best solutions to make them self-enforcing
  - Constrained optimization
- Prosociality enhances
- Mechanism design given imperfect information (work with Erol Akcay)

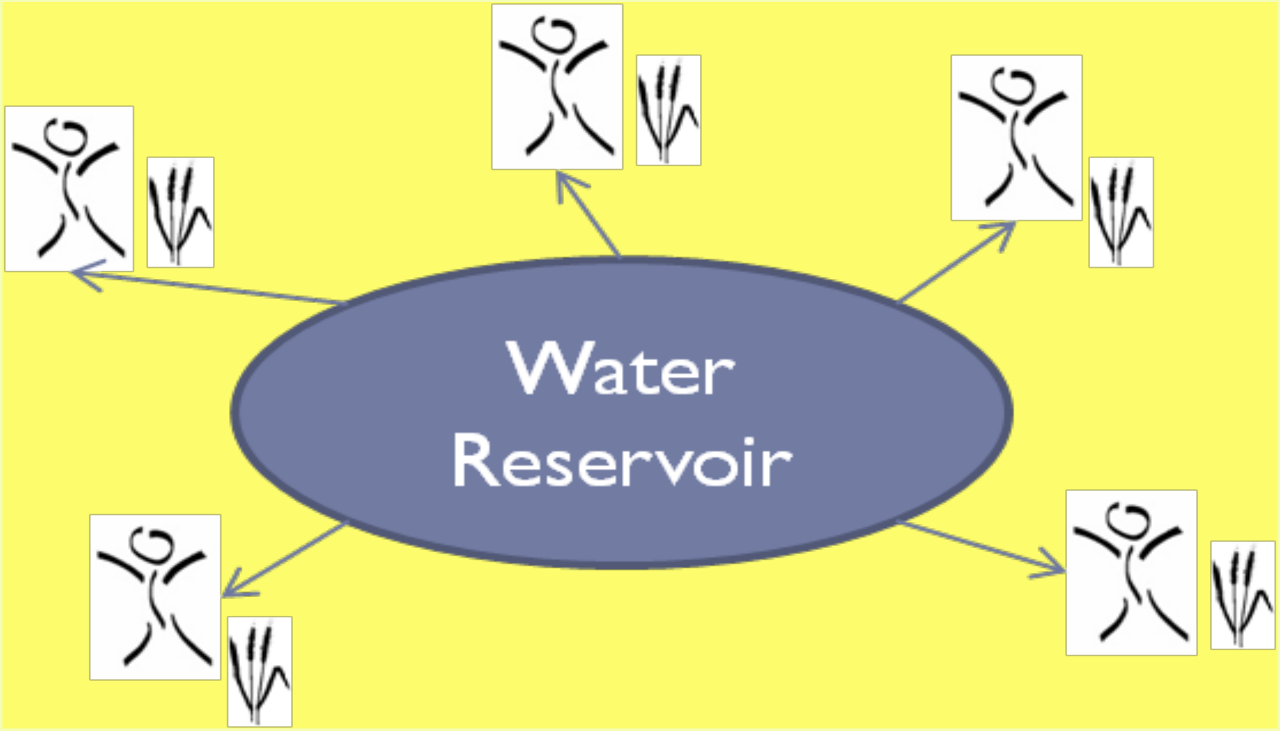
The pastoral insurance example is of interest in itself, but more broadly is a model for addressing (international) cooperation


WORKING TOGETHER
Collective Action, the Commons, and Multiple Methods in Practice
AMY R. POTEETE
MARCO A. JANSSEN
ELINOR OSTROM

Agent-based approaches: Coupling individual behaviors to environmental systems

with Alessandro Tavoni and Maja Schlüter

Cooperation can coevolve with a norm structure

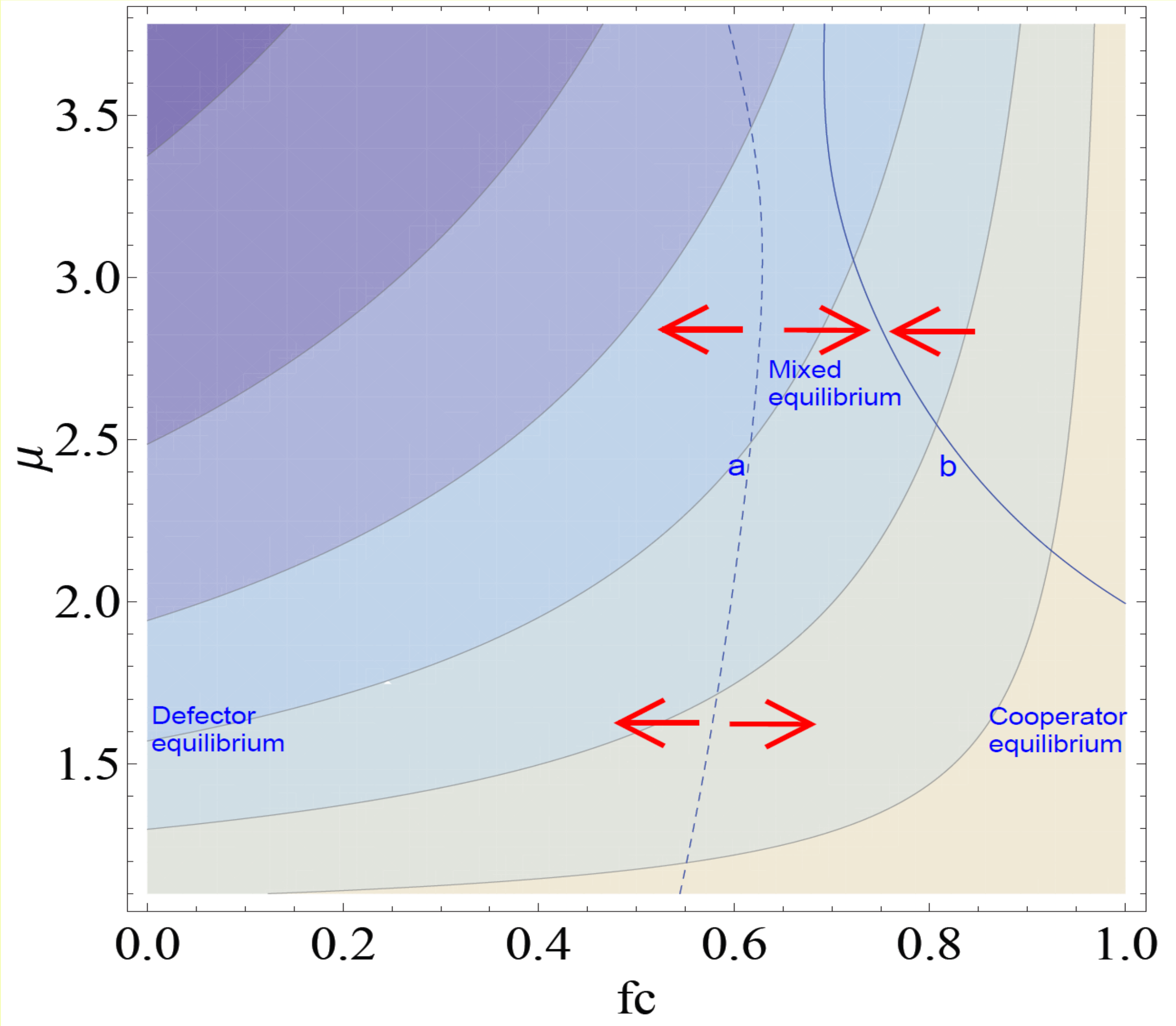


Tavoni, Schlueter, Levin
Journal of Theoretical Biology, 299 pp. 152-161

Equity-driven ostracism

- Community establishes normative standards for resource use
- Agents that withdraw more than socially accepted are ostracized and refused help -> reduction in utility
- Cooperation is possible if number of cooperators exceeds a critical value
- In general, uncertainty enhances cooperation …but there are exceptions
- This is a prototypical model for cooperation in the Global Commons

Selfishness



Frequency of cooperators

Theor Ecol
DOI 10.1007/s12080-013-0187-3

ORIGINAL PAPER

Regime shifts in a social-ecological system

Steven J. Lade · Alessandro Tavoni · Simon A. Levin · Maja Schlüter

Received: 15 February 2013 / Accepted: 29 April 2013

Abstract Ecological regime shifts are rarely purely ecological. Not only is the regime shift frequently triggered by human activity, but the responses of relevant actors to ecological dynamics are often crucial to the development and even existence of the regime shift. Here, we show that the dynamics of human behaviour in response to ecological changes can be crucial in determining the overall dynamics of the system. We find a social–ecological regime shift in a model of harvesters of a common-pool resource who avoid over-exploitation of the resource by social ostracism of non-complying harvesters. The regime shift, which can be triggered by several different drivers individually or also in combination, consists of a breakdown of the social norm, sudden collapse of co-operation and an over-exploitation of the resource. We use the approach of generalised modelling to study the robustness of the regime shift to uncertainty over the specific forms of model components such as the ostracism norm and the resource dynamics. Importantly, the regime shift in our model does not occur if the dynamics of harvester behaviour are not included in the model. Finally, we sketch some possible early warning signals for the social–ecological regime shifts we observe in the models.

Keywords Regime shifts · Tipping points · Early warning signals · Bifurcation · Generalised modelling · social–ecological system

Introduction

Many ecological systems can undergo large, sudden and long-lasting changes in structure and function (Scheffer et al. 2001). Such changes, often called regime shifts[1] or critical transitions (Scheffer et al. 2009), have been found in a range of ecological systems, including eutrophication of freshwater lakes, soil salinisation, degradation of coral reefs, collapse of fisheries and encroachment of bushland (Biggs et al. 2012a).

Most ecological systems, and especially those systems that are at risk of sudden non-linear changes such as regime shifts, are subject to influence by humans (Millennium Ecosystem Assessment 2005). Furthermore, humans not only influence the ecological system but also adapt

S. J. Lade (✉) · M. Schlüter
Stockholm Resilience Centre, Stockholm University,
Kräftriket 2B, 114 19 Stockholm, Sweden

How do such social norms become established?

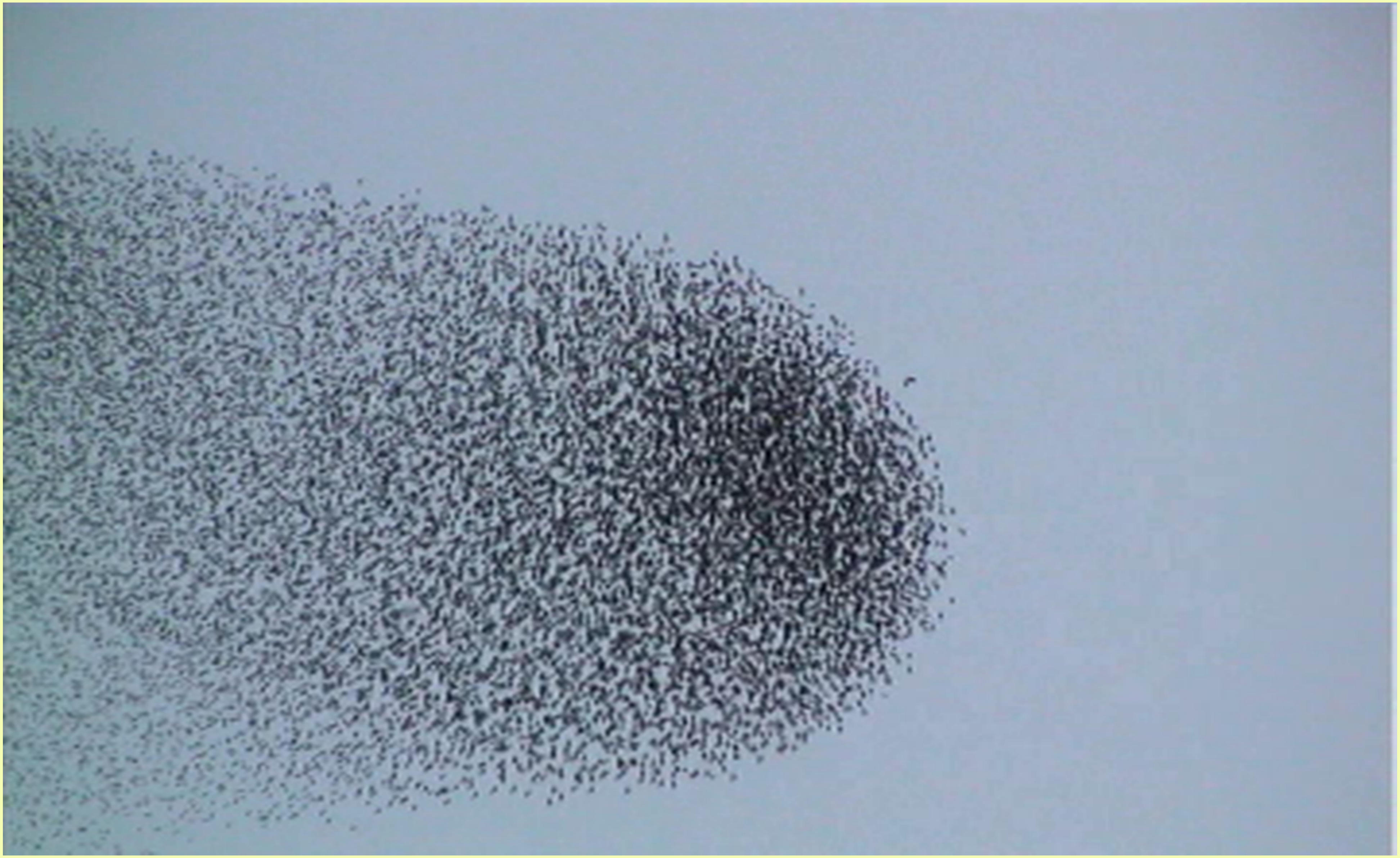
- What is the role of leadership?
- How is consensus achieved in democratic societies, under incomplete information?
- What is the role of the unopinionated?
- What are the implications for cooperation in achieving sustainability?
- Again, mathematics can help

Mathematical Challenges

- Can we develop a statistical mechanics of ecological communities, human societies and the biosphere?
- The dynamics of collective phenomena and collective decision-making

Claudio Carere

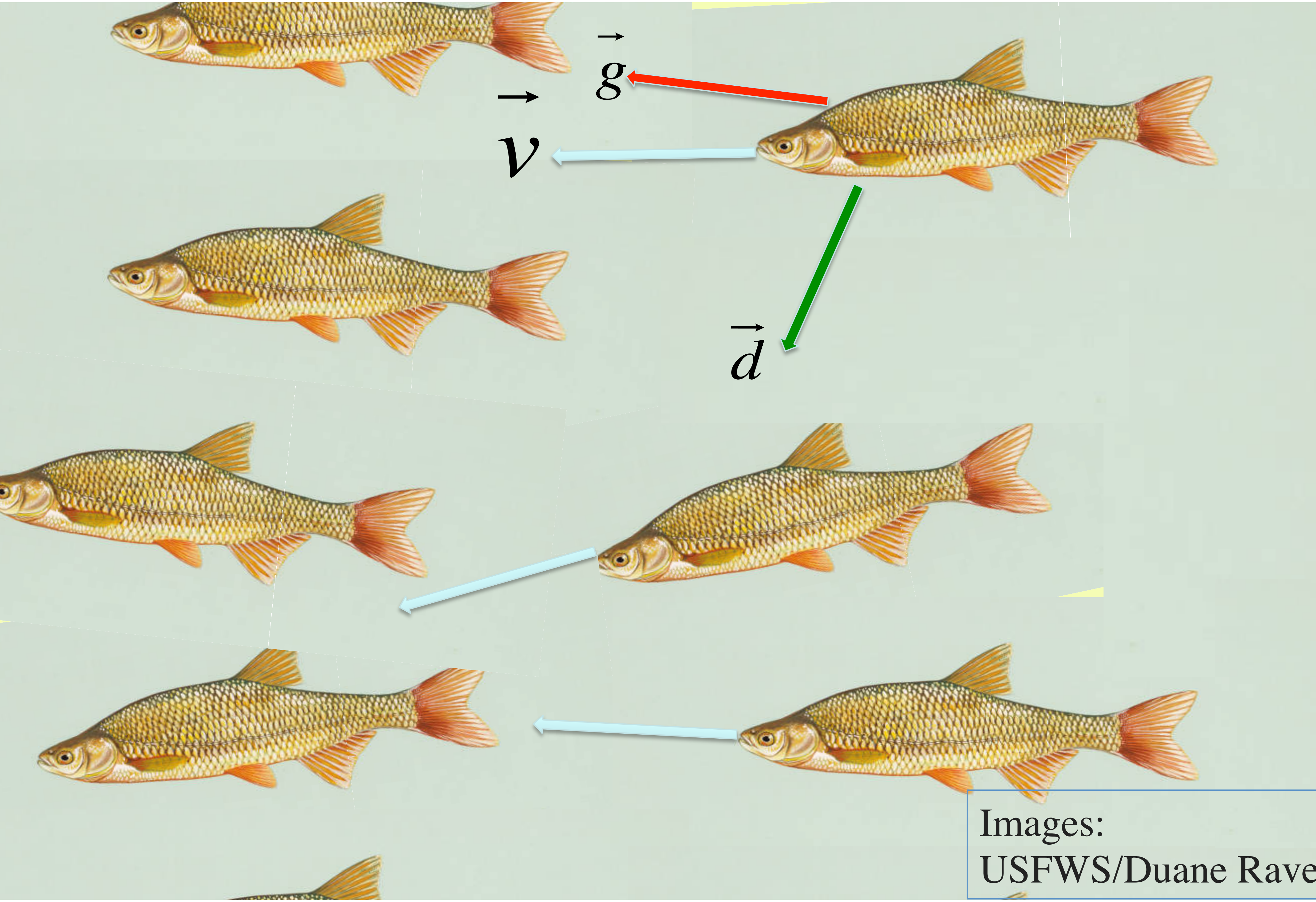
http://old.enciclopedia.com.pt/en/
articles.php?article_id=296



Claudio Carere

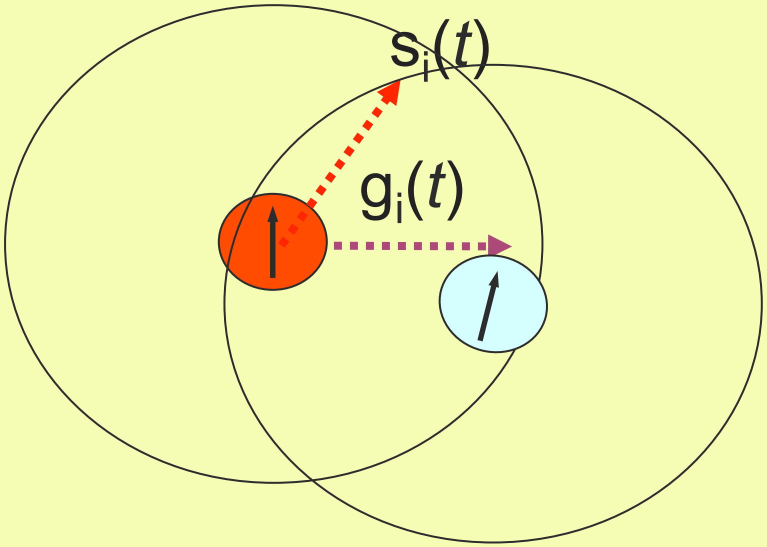
Role of leadership and collective decision-making

Couzin, Krause, Franks, Levin



Images:
USFWS/Duane Rave

So the direction chosen by informed individuals must reconcile these tendencies.



$$d_i(t+\Delta t) = \frac{s_i(t) + \omega\, g_i(t)}{|\, s_i(t) + \omega\, g_i(t) \,|}$$

Courtesy Iain Couzin

Collective decision-making

1 informed individuals in group of 100.

Courtesy Iain Couzin

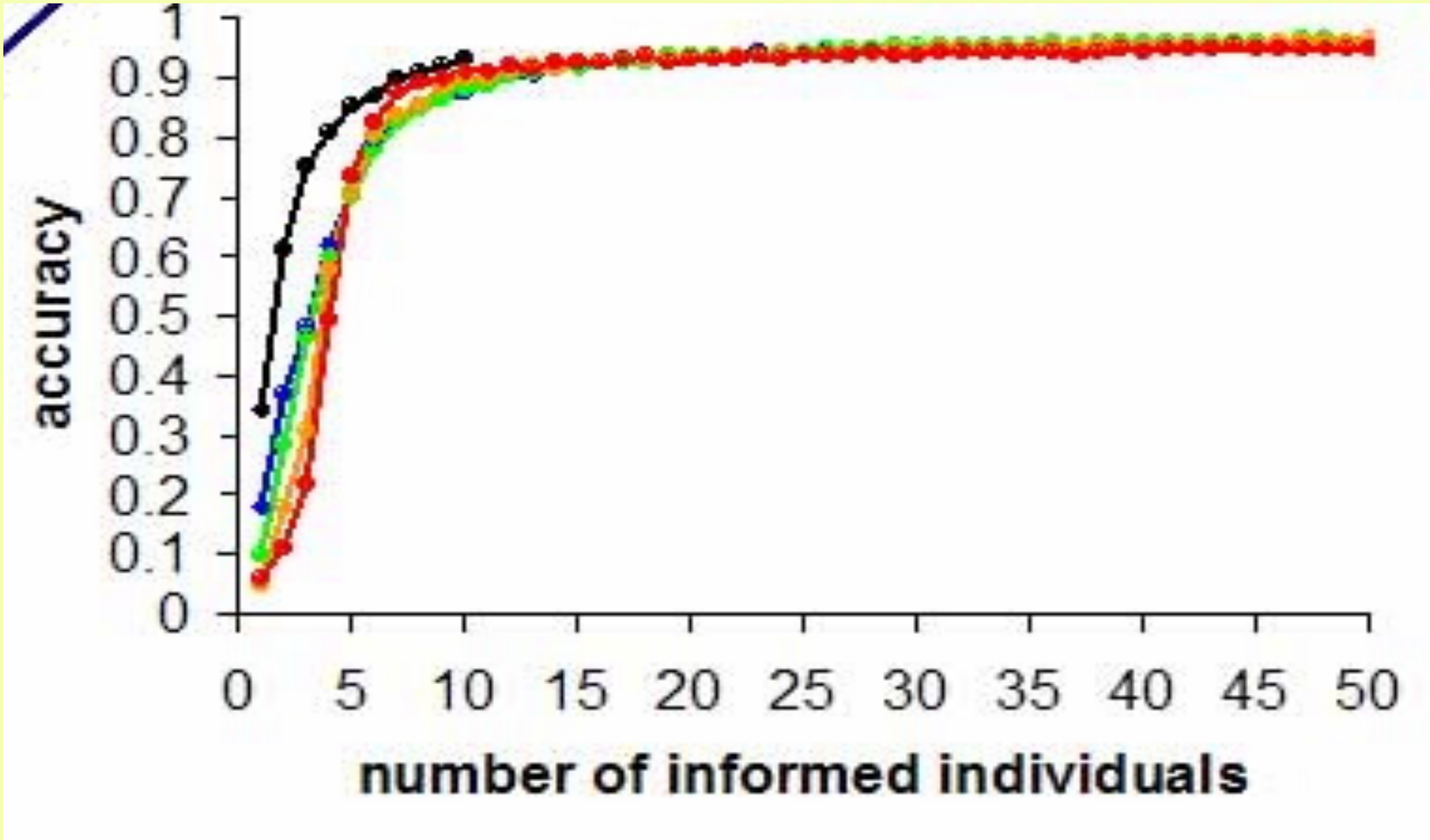
5 informed individuals in group of 100.

Courtesy Iain Couzin

10 informed individuals in group of 100.

Courtesy Iain Couzin

Animal groups may be led by a small number of individuals



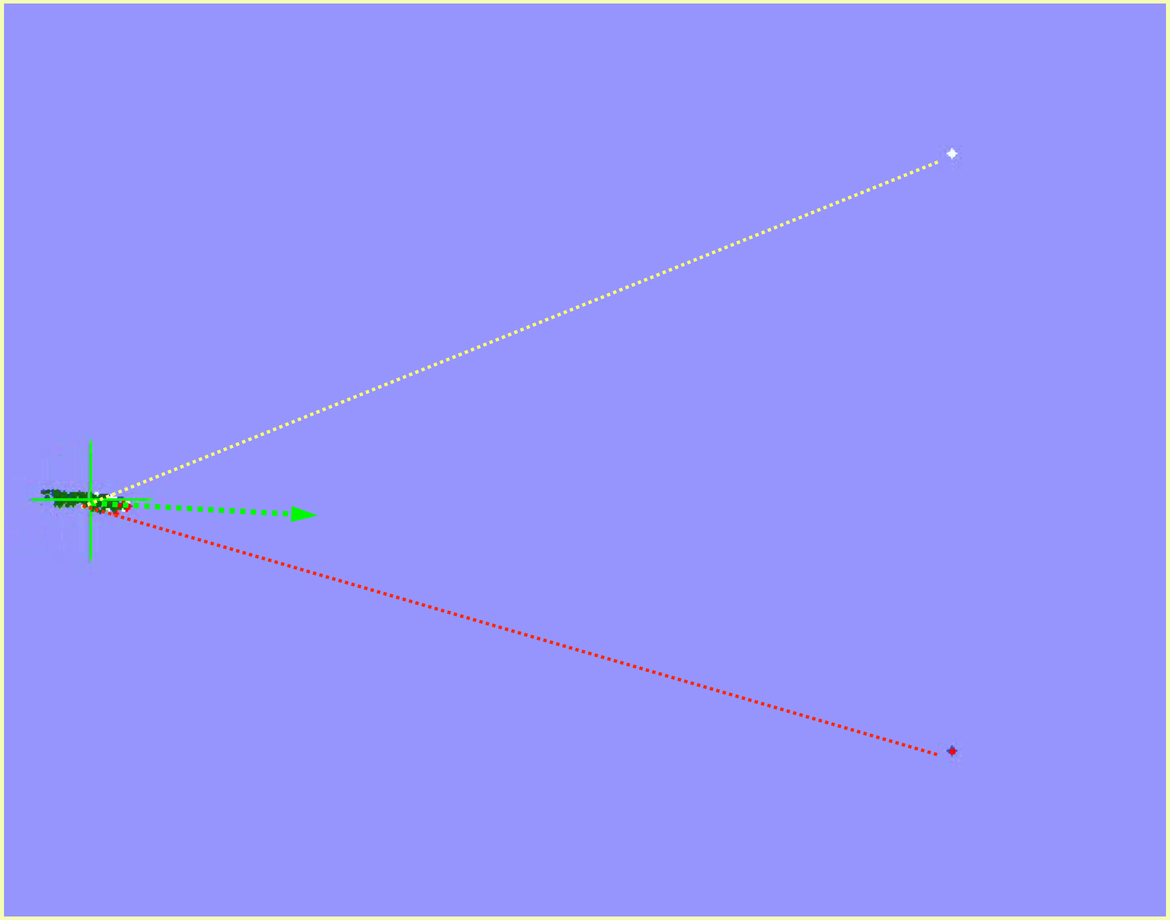
From Couzin et. al, Nature 2005

So too are human societies

http://interactivedemocracy.blogspot.com/

Collective decision-making

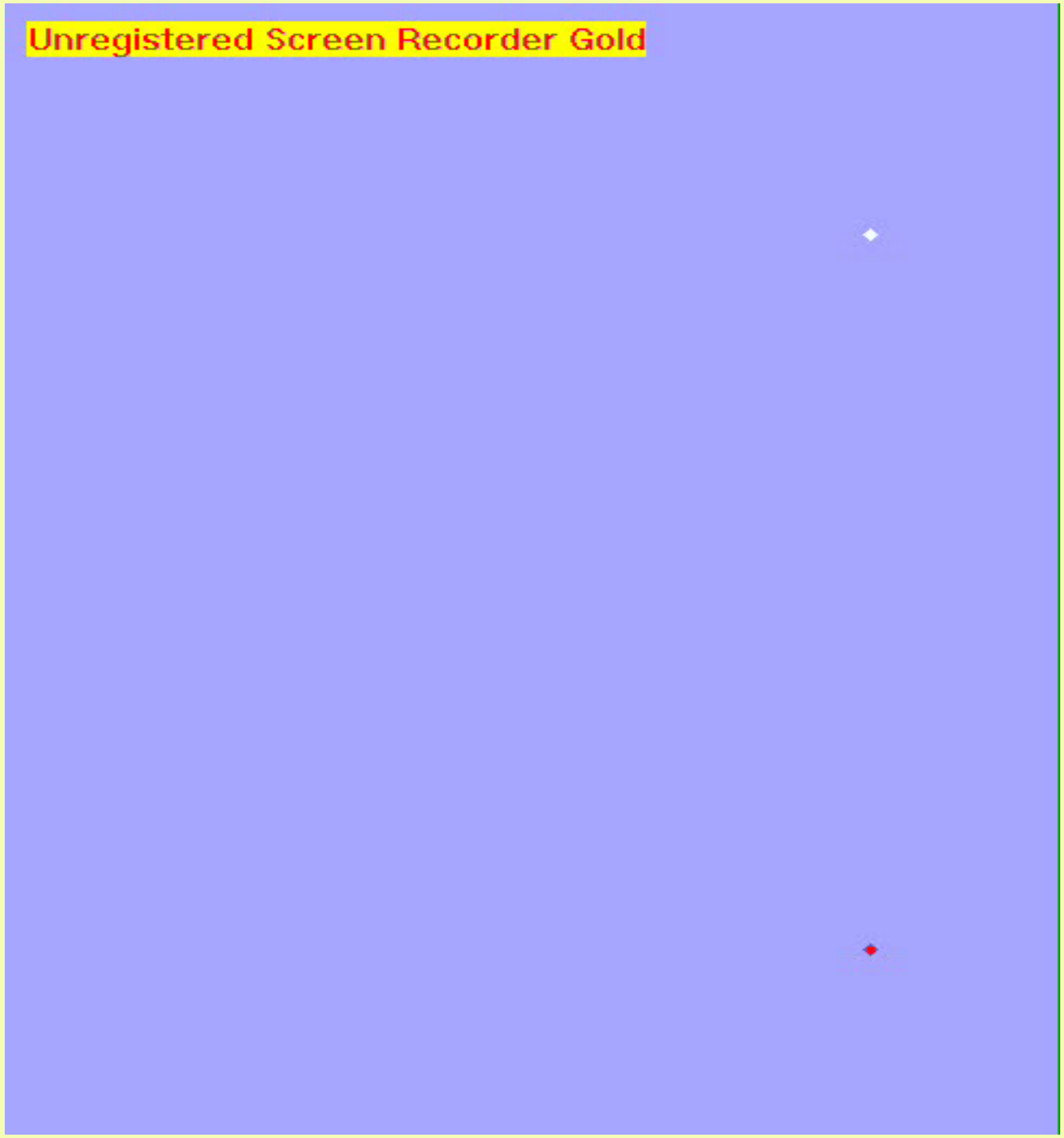
Competing preferences



Courtesy Iain Couzin

Collective decision-making

Courtesy Iain Couzin



Courtesy Iain Couzin

Leonard, Couzin, Kevrekidis, Levin, and colleagues

First-order mathematical analysis

Kuramoto model

$$
\begin{aligned}
\dot{\theta}_j &= \sin(\bar{\theta}_1 - \theta_j) + k \sum_{l=1}^{N} \sin(\theta_l - \theta_j) & j &= 1, \ldots, N_1 \\
\dot{\theta}_j &= \sin(\bar{\theta}_2 - \theta_j) + k \sum_{l=1}^{N} \sin(\theta_l - \theta_j) & j &= N_1 + 1, \ldots, N_1 + N_2 \\
\dot{\theta}_j &= k \sum_{l=1}^{N} \sin(\theta_l - \theta_j) & j &= N_1 + N_2 + 1, \ldots, N
\end{aligned}
$$

Analysis of models of animal grouping

- On fast time scale, individual groups reach consensus (gradient system)
- On slow time scale, groups interact with each other as units
- Unopinionated individuals are crucial to deriving consensus
- Strongly opinionated minorities can exert disproportionate influence, but that becomes more difficult with large numbers of unopinionated

Science (16Dec 2011)

Consensus may also be emergent more generally: Multiple models

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 decisions. Reaching a consensus decision, therefore, frequently depends on individuals resolving

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 facilitating the establishment of extremist opinions in populations (*9*, *14*).

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, ω_1 and ω_2. See (*15*) for details.

If the strength of the majority preference (ω_1)

Decision-making in human groups: Adaptive network model

(after Huepe et al., 2011)

- **Network with (large) N nodes, initialized with Erdos-Renyi random graph with mean degree 10**
- **Focal individual changes opinion with probability that depends nonlinearly on number of opposing individuals it is connected to**
- **Each individual also switches state spontaneously probabalistically. Lower probability of switching away from preferred state**
- **Links are made or broken, with probabilities based on similarity of opinions**

Conclusions of all models and experiments

- With few unopinionated individuals, a strongly opinionated minority can dominate decision-making
- Increasing the number of unopinionated makes this more difficult
- Strong implications for collective decision-making…and how to influence collective decisions

Ecological systems and socio-economic systems alike are complex adaptive systems

http://www.latinamericanstudies.org/maya

Ecological sustainability-mathematical challenges

- Dynamical systems models of processes
- Scaling from microscopic to macroscopic
- Early warning indicators of critical transitions
- Lessons for design of management systems
- Game theoretic and decision-theoretic methods for dealing with global cooperation
- Mechanism design

Challenge is to integrate

- Bottom-up mechanisms, like evolved prosociality
- Top-down mechanisms, like rewards and punishments
- Collective action

To achieve

- Adaptive, polycentric governance and agreements

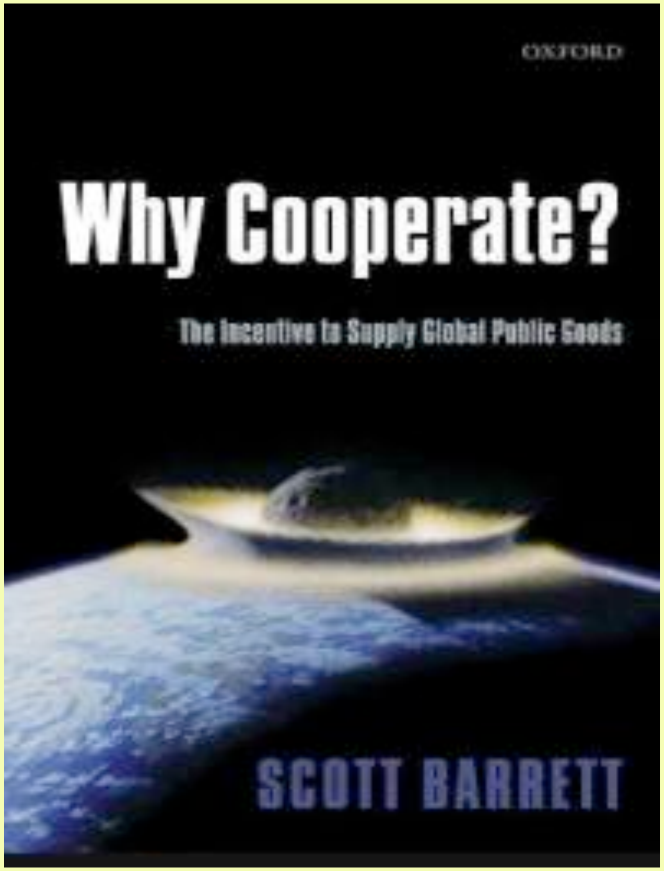
Emergence of cooperation within groups is often for the benefit of conflict with *other* groups

Lariviere

Can cooperation be extended to the global level?

http://dragancastellon.wordpress.com/

Global environmental agreements



Systems analysis-
mathematical challenges

- Scaling from microscopic to macroscopic
- Early warning indicators of critical transitions
- Lessons for design of adaptive management systems in the face of uncertainty
- Game theoretic methods for dealing with global cooperation, including prosociality
- Mechanism design for achieving cooperation
- "Emergence of the social contract" (Sigmund)

Understanding how to achieve international cooperation is at the core of achieving sustainability in dealing with our common enemy: environmental degradation

…so that we can achieve a sustainable future
for our children and grandchildren

Thank you

Carole Levin