Sustainability Science

Simon Levin. Brazil, 2014

www.anualadearhitectura.ro

The central problem facing societies is achieving a sustainable future

www.anualadearhitectura.ro

Can we grow economically without compromising options for future generations?

(Brundtland report)

Brundtland Commission
"Our Common Future"

- Intergenerational equity

- "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

Sustainability means many things

- Financial markets and economic security

Financial engineering
Mathematical economics
Corporate sustainability

www.centralbanking.com/

Sustainability means many things

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

Energy exploration
Combustion efficiency
Network management
Alternative energy
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

Healthy ecosystems provide free
“services” to human communities,
including: water filtration, groundwater

Are the services we derive from ecosystems sustainable?

marinebio.org/i/

Yesterday: 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

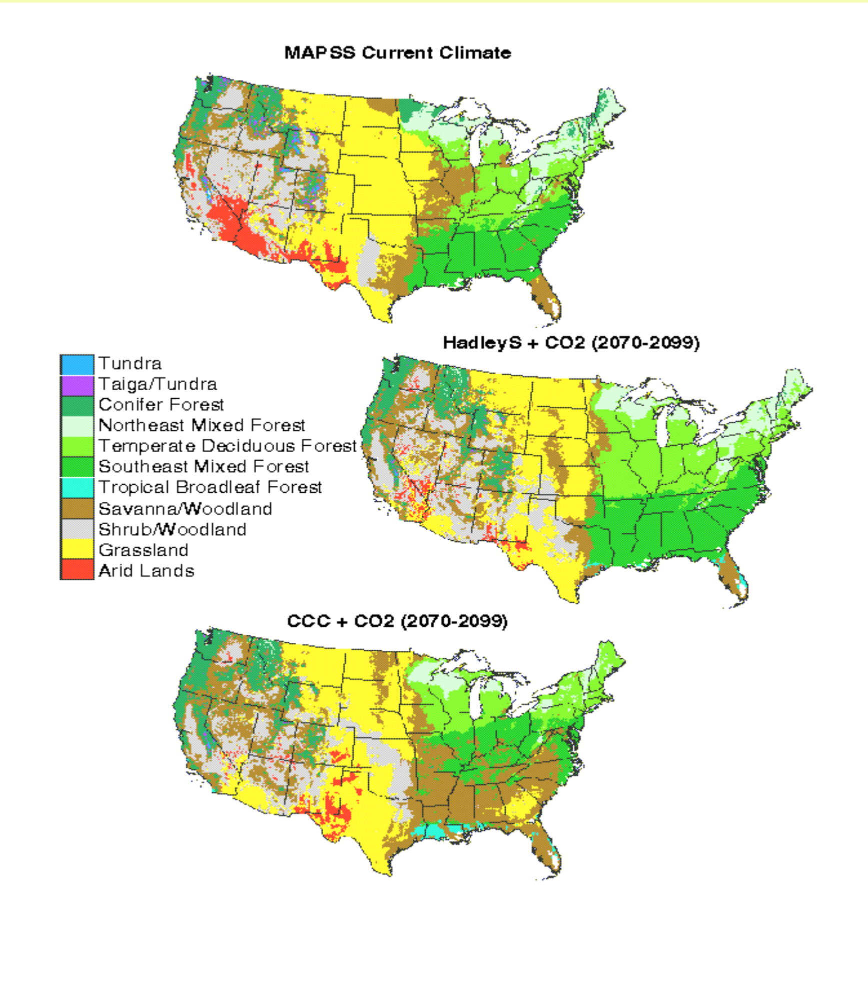
- How robust are the properties of ecosystems?
- How does the robustness of macroscopic properties relate to ecological and evolutionary dynamics on finer scales?
- Are ecosystems at critical points?

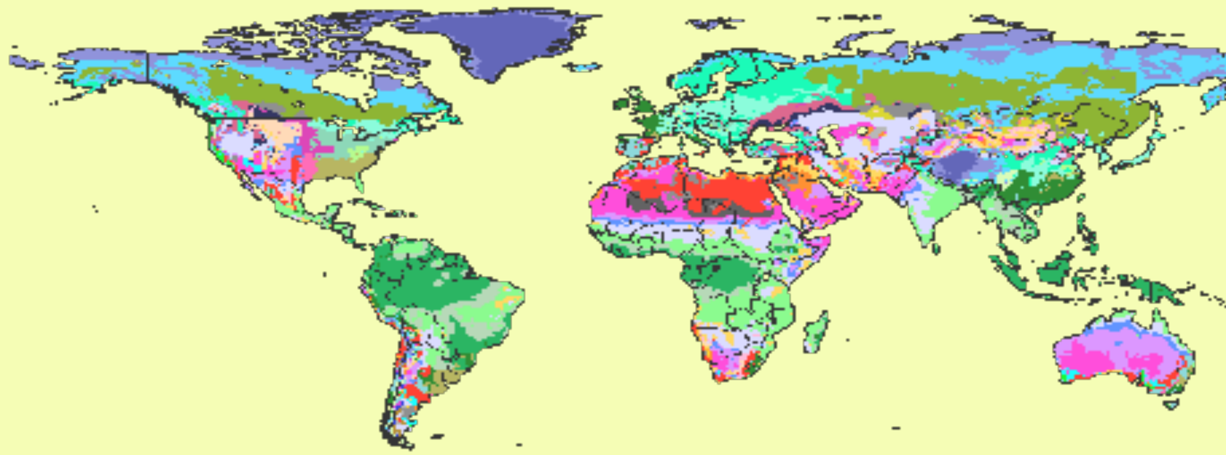
Forest growth models can scale from individual to ecosystem

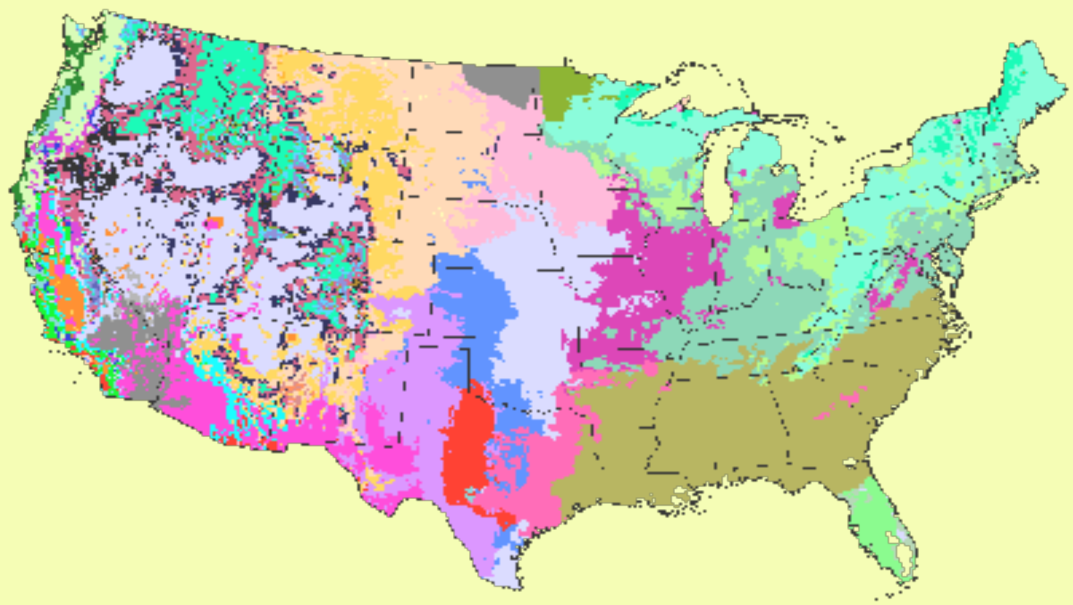
(Pacala, Botkin, Shugart, others)

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/ma

Scaling: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

Michaelis-Menten uptake functions/Bonachela et al.

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

MJ Follows *et al*, *Science* **315**, 184 (2007)

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

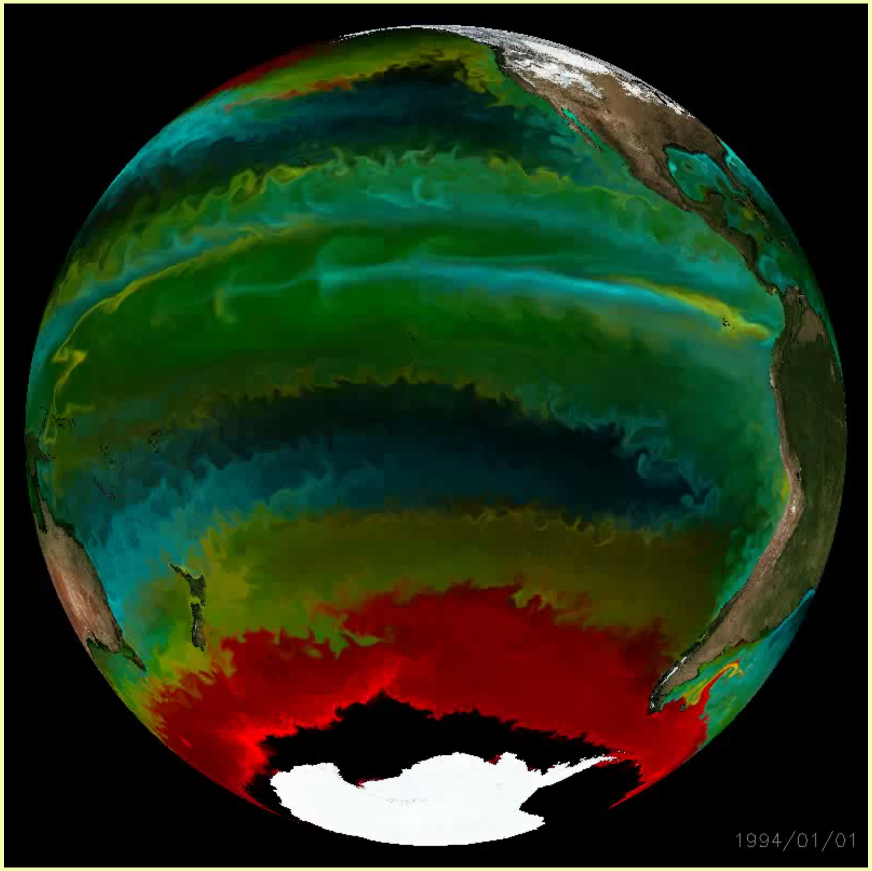
Darwin model: Follows, Dutkiewicz, Chisholm, …

Prochlorococcus

Synechococcus

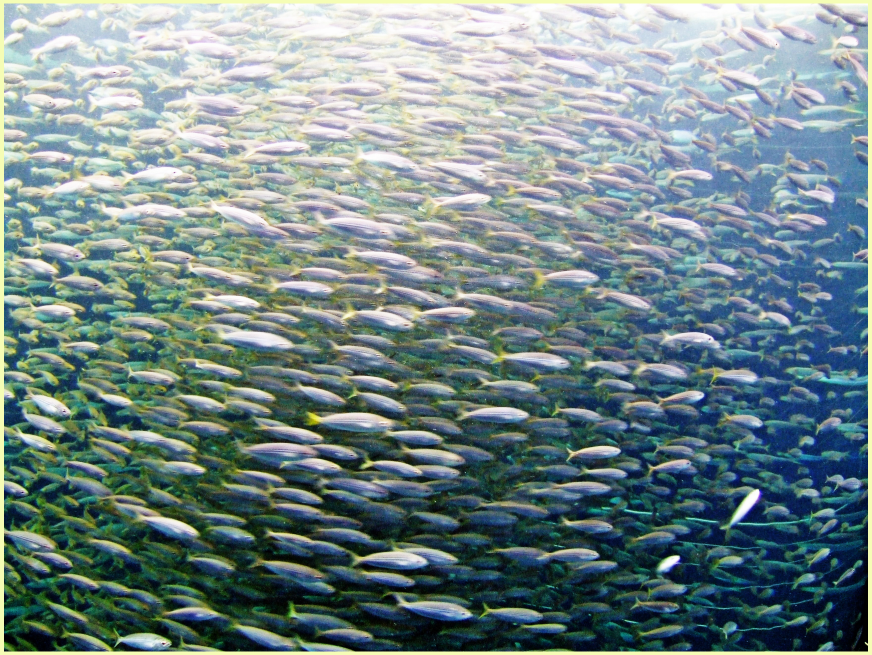
Diatoms

Large eukaryotes



Ecosystems and the Biosphere are Complex Adaptive Systems

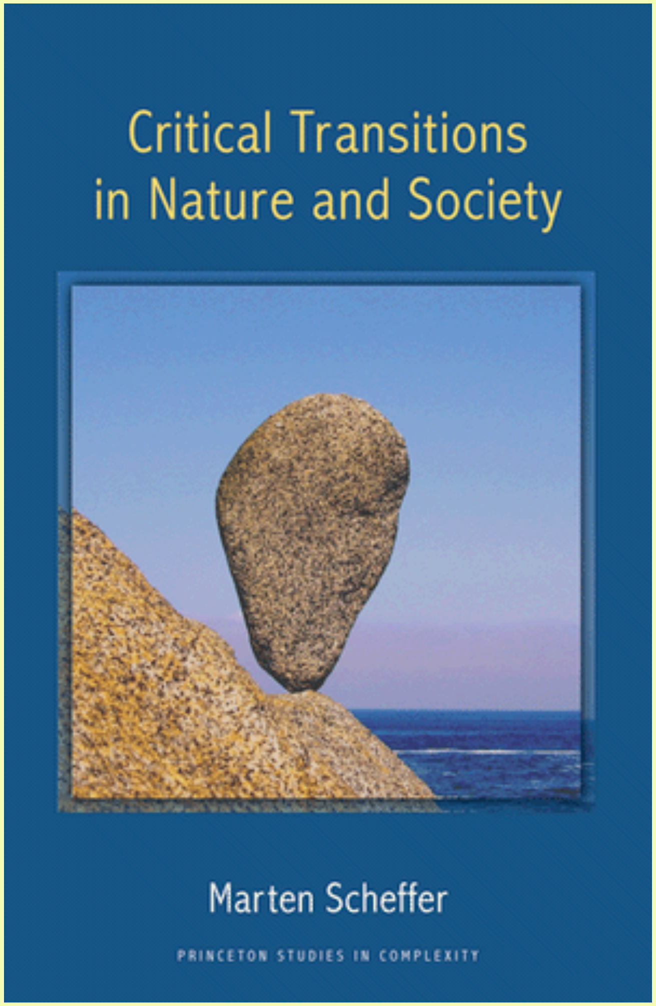
Heterogeneous collections of individual units (agents) that interact locally, and evolve based on the outcomes of those interactions.



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

Many such transitions have characteristic early warning signals

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



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.

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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

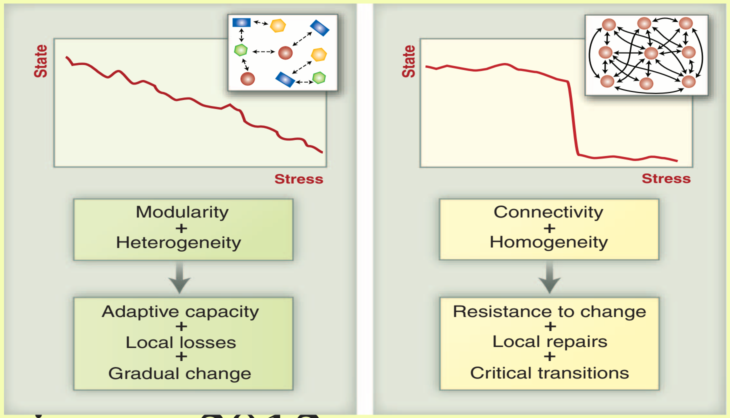
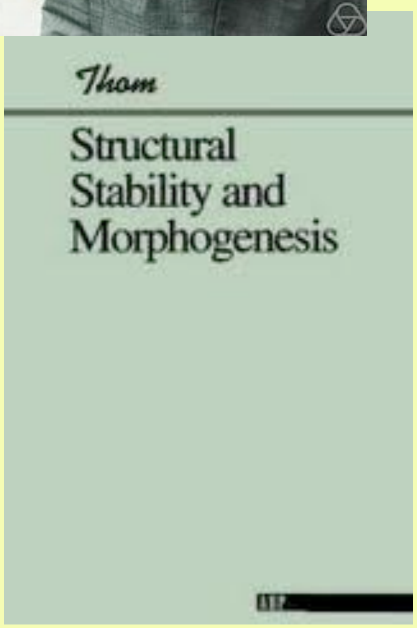
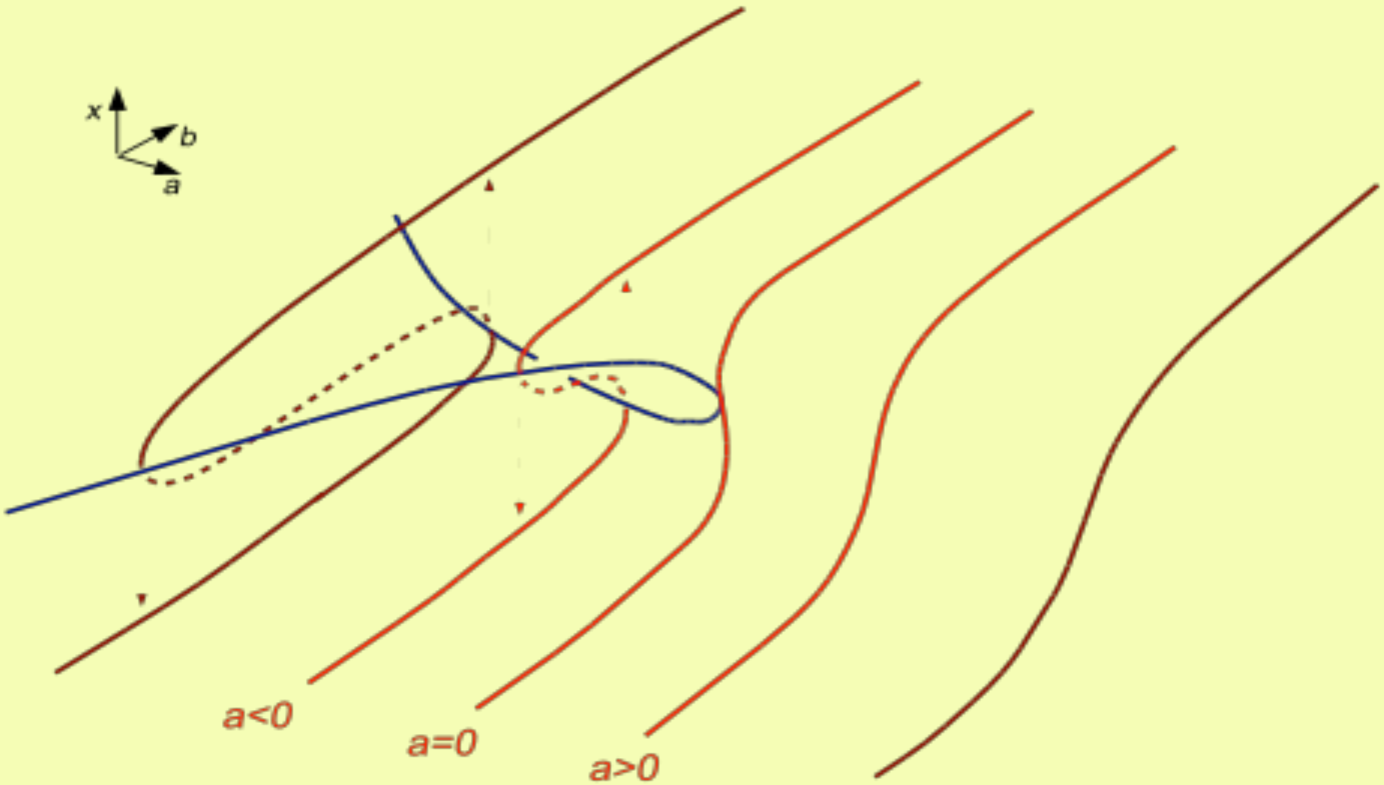


Fig. 1. The connectivity and homogeneity of the units affect the way in which distributed systems with local alternative states respond to changing conditions. Networks in which the components differ (are

Caution is needed…mechanisms need to be identified





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

Elementary catastrophe theory vs. applied catastrophe theory

Nature Vol. 269 27 October 1977 **759**

review article

Claims and accomplishments of applied catastrophe theory

Raphael S. Zahler* & Hector J. Sussmann†

Several representative attempts to apply catastrophe theory to biological and social science problems turn out on close analysis to be characterised by incorrect reasoning, far-fetched assumptions, erroneous consequences, and exaggerated claims. Catastrophe theory seems to have made no significant contributions to biology and the social sciences, and to have no advantage over other better-established mathematical tools which have been used to better effect.

EMBRYOLOGY, ethology, ecology, and geology; physics, economics, dynamics, and linguistics; prison riots, literary symbolism, and the Vietnam war—these are some of the subjects to which catastrophe theory is said to be applicable. Its novel mathematical apparatus seems to be a near-universal tool, according to its proponents: "Properly understood and

S. Mabrey, J. F. Chlebowski, E. S. Crelin, J. F. G. Auchmuty, N. Van Arkel whose comments have been of great help in the preparation of this paper.

The cusp catastrophe

Most applied catastrophe theory is based on the 'cusp cata-

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) statistical methods that can distinguish between signatures of early warning behaviors and noise.

Keywords Early warning signals · Regime shifts · Bifurcation · Critical slowing down

Are there critical biosphere thresholds?

REVIEW

doi:10.1038/nature11018

Approaching a state shift in Earth's biosphere

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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.

Humans now dominate Earth, changing it in ways that threaten its ability to sustain us and other species[1–3]. This realization has led to a growing interest in forecasting biological responses on all scales from local to global[4–7].

However, most biological forecasting now depends on projecting recent trends into the future assuming various environmental pressures[5], or on using species distribution models to predict how climatic changes may alter presently observed geographic ranges[8,9]. Present work recognizes that relying solely on such approaches will be insufficient to characterize fully the range of likely biological changes in the future, especially because complex interactions, feedbacks and their hard-to-predict effects are not taken into account[6,8–11].

Particularly important are recent demonstrations that 'critical transitions' caused by threshold effects are likely[12]. Critical transitions lead to state shifts, which abruptly override trends and produce unanticipated necessary to address the root causes of human-driven global change and to improve our management of biodiversity and ecosystem services[3,15–17,19].

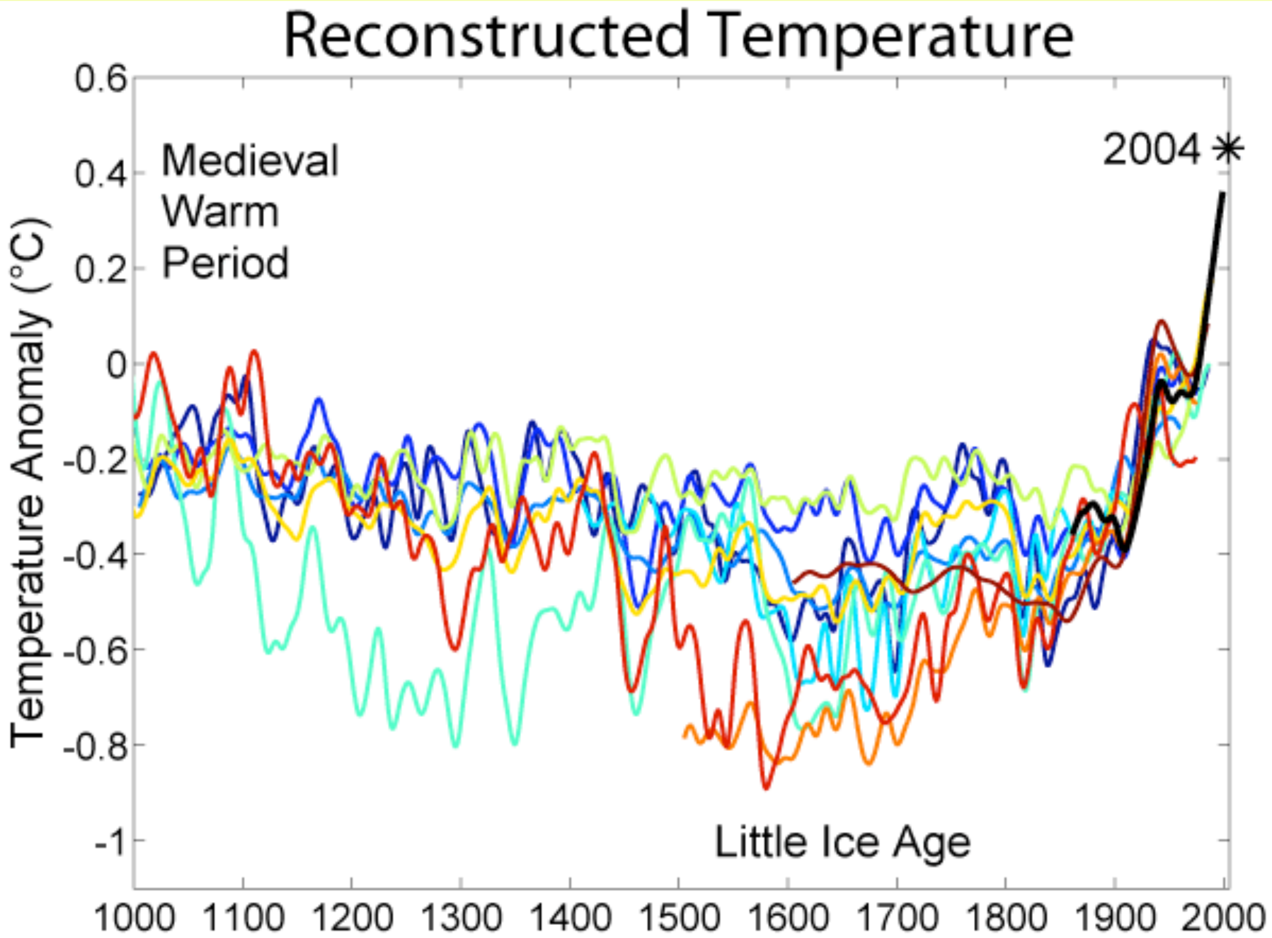
Basics of state shift theory

It is now well documented that biological systems on many scales can shift rapidly from an existing state to a radically different state[12]. Biological 'states' are neither steady nor in equilibrium; rather, they are characterized by a defined range of deviations from a mean condition over a prescribed period of time. The shift from one state to another can be caused by either a 'threshold' or 'sledgehammer' effect. State shifts resulting from threshold effects can be difficult to anticipate, because the critical threshold is reached as incremental changes accumulate and the threshold value generally is not known in advance. By contrast, a state shift caused by a sledgehammer effect—for example the clearing of a forest using a bulldozer—comes as no surprise. In both

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?

Scientific consensus is strong on many core environmental issues



Robert Rohde, for Global Warming Art

But adequate action to address them has been lacking

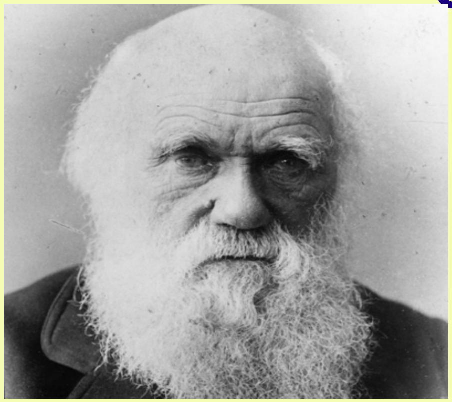
- Primary limitations to solutions not scientific knowledge, but rather
- Willingness of people and governments to commit to the common good
- And to cooperate in finding solutions that benefit all

www.edie.net

The central issues are issues of behavior and culture

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

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



mashriqq.com/?p=1081

Carole Levin

What are public goods?

- *…[goods] which all enjoy in common in the sense that each individual's consumption of such a good leads to no subtractions from any other individual's consumption of that good…*

Samuelson (1954)

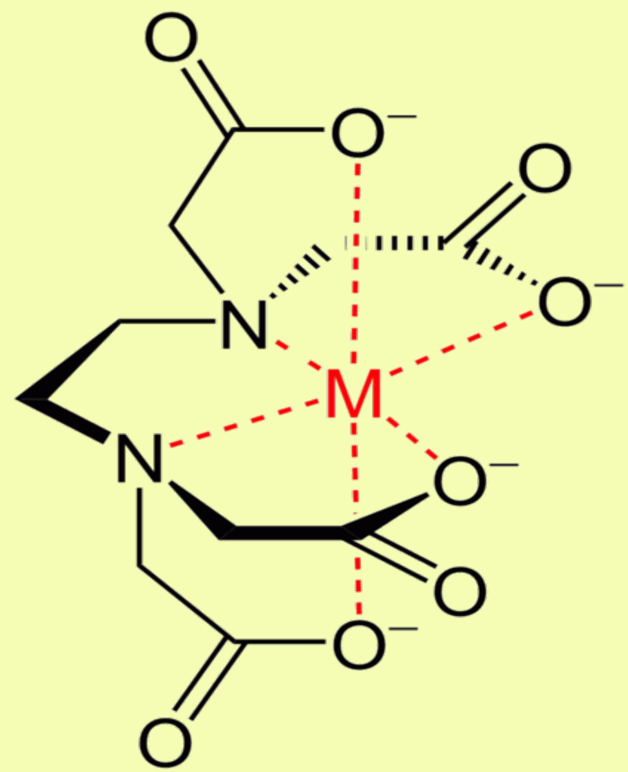
This distinguishes them technically from common-pool resources

http://en.wikipedia.org/wiki/File:Traditional_fishery

- But for this lecture, I will lump them together

Organisms produce many public goods

- Information
- Nests
- Siderophores
- Fixed nitrogen
- Antibiotics
- Extracellular polymers

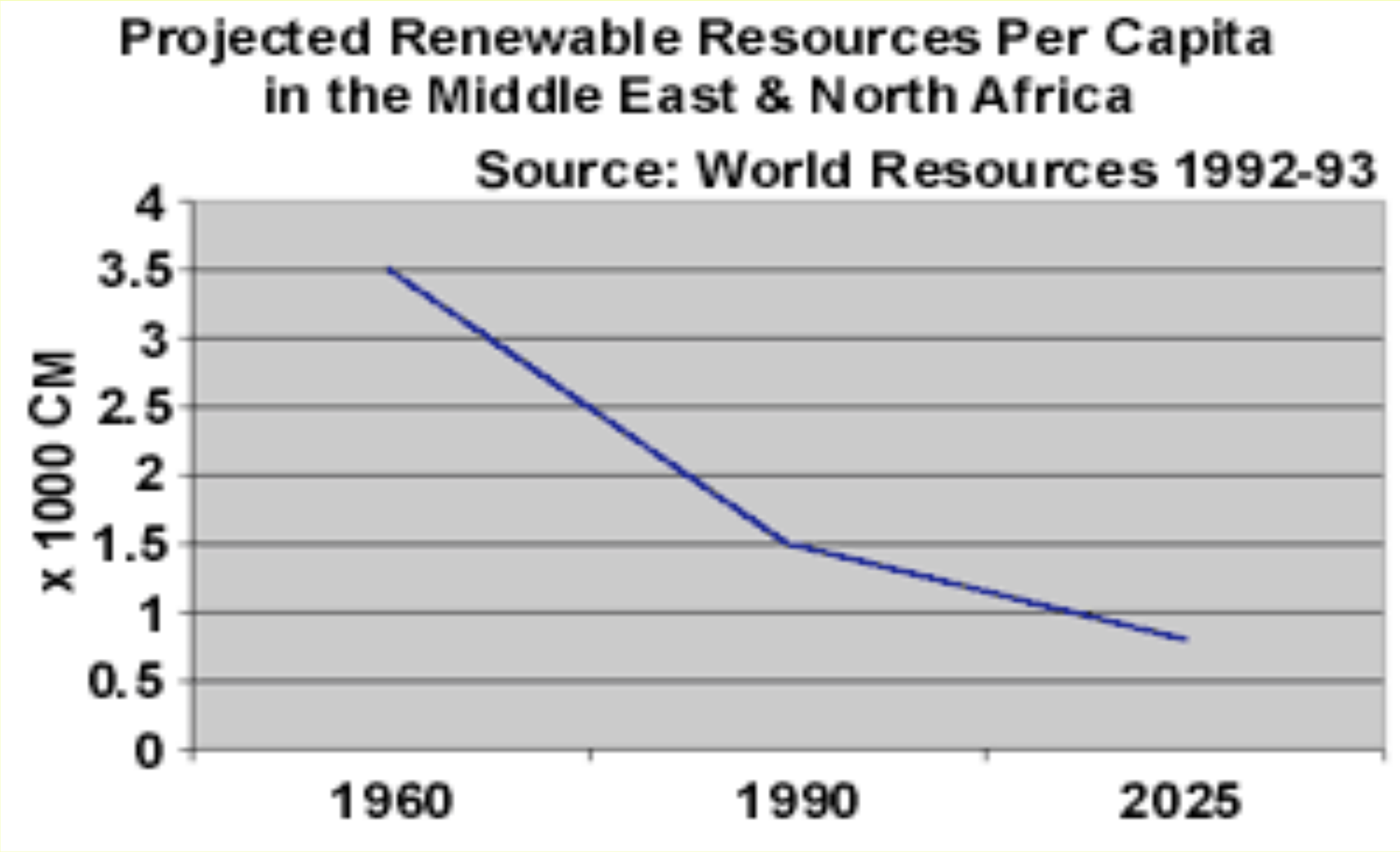


upload.wikimedia.org

The prototypical public good is the Commons we all share

http://www.commonslearningalliance.c

Globally, we are eroding our public goods



We discount

- The future

/www.damninteresting.net

We discount

- The future
- The interests of others

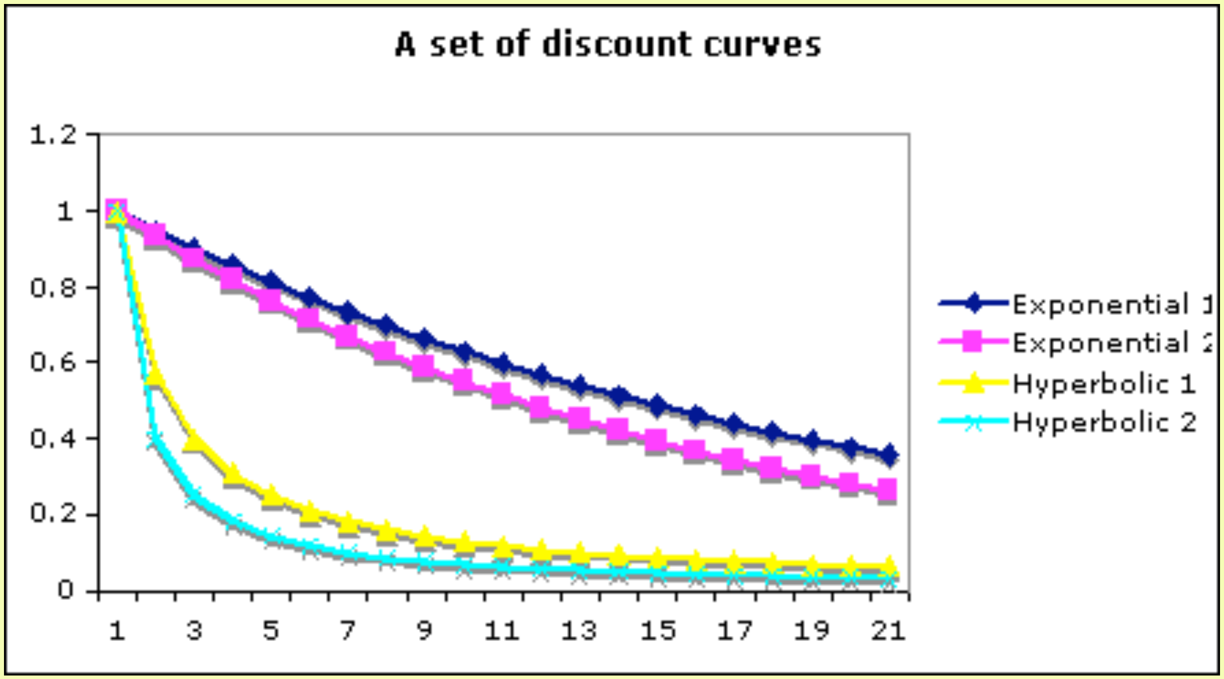
info.acoustiblok.com

How has evolution shaped

- Our personal and societal discount rates?
- Our concern for others (prosociality)?
- Collective behavior and decision-making?
- Multicellularity and the emergence of societies?

Discounting

- Key to how individuals and societies value the future…and to cooperation



http://www.uab.edu/philosophy/faculty/ross

Discounting

- Key to how individuals and societies value the future…and to cooperation in sustaining it
- Exponential discounting:
  - Payoff *B* at time *t* is worth *B exp(-δt)* today (time *0*)

$$PV = Be^{-\delta t}$$

$$PV(T) = \int_{T}^{\infty} B(t)\exp(-\delta(t-T))\,dt$$

Discounting

- Key to how individuals and societies value the future…and to cooperation in sustaining it
- Non-constant discounting:
  - Payoff *B* at time *t* is worth *B* $exp(-\delta(t))$ today (time *0*)

$$PV = Be^{-\delta(t)}$$

Discounting

- Key to how individuals and societies value the future…and to cooperation in sustaining
- Non-constant discounting:
  - Payoff *B* at time *t* is worth *B exp(-δt)* today (time *0*)

$$PV = Be^{-\delta(t)}$$

Hyperbolic $PV = B/(1+rt)$

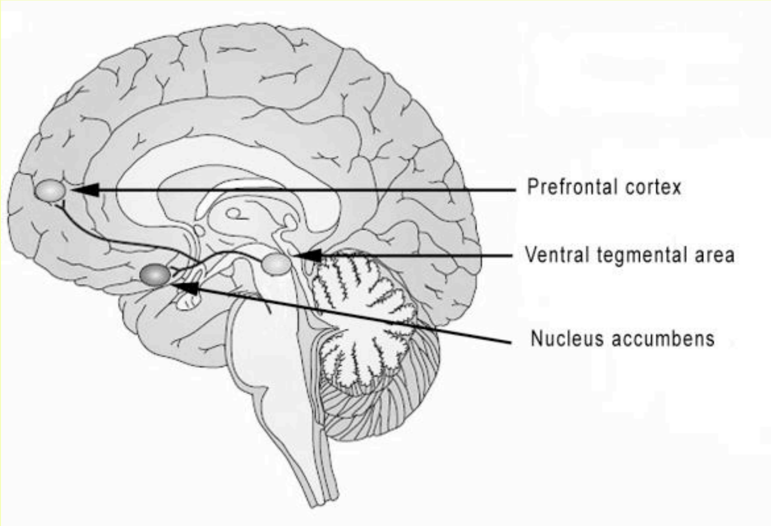
$$\delta(t) = \ln(1+rt)$$

Hyperbolic discounting…consequences

- Intertemporal inconsistency

Hyperbolic discounting…proximate explanations

- Averaging of different exponential discount curves
- Conflicting objectives
- Conflicting regions of the brain



Hyperbolic discounting…ultimate

- Uncertainty (Sozou, Dasgupta and Maskin)
- Bounded rationality

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 Cambridge and Fellow of St John's College, both in Cambridge, United Kingdom. Lawrence Goulder is Professor and Shuzo Nishihara Chair in Environmental and Resource Economics, Stanford University, Stanford, California. Gretchen Daily is Associate Professor of Biological*

Intertemporal social welfare

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

Table 2

Growth Rates of Per Capita Genuine Wealth

Country	*(1)* *Genuine Investment as Percent of GDP*	*(2)* *Growth Rate of Unadjusted Genuine Wealth*	*(3)* *Population Growth Rate*	*(4)* *Growth Rate of Per Capita Genuine Wealth—before TFP Adjustment*	*(5)* *TFP Growth Rate*	*(6)* *Growth Rate of Per Capita Genuine Wealth—after TFP Adjustment*	*(7)* *Growth Rate of per capita GDP*
Bangladesh	7.14	1.07	2.16	−1.09	0.81	0.30	1.88
India	9.47	1.42	1.99	−0.57	0.64	0.54	2.96
Nepal	13.31	2.00	2.24	−0.24	0.51	0.63	1.86
Pakistan	8.75	1.31	2.66	−1.35	1.13	0.59	2.21
China	22.72	3.41	1.35	2.06	3.64	8.33	7.77
Sub-Saharan Africa	−2.09	−0.31	2.74	−3.05	0.28	−2.58	−0.01
Middle East/ North Africa	−7.09	−1.06	2.37	−3.43	0.23	−3.82	0.74
United Kingdom	7.38	1.48	0.18	1.30	0.58	2.29	2.19
United States	8.94	1.79	1.07	0.72	0.02	0.75	1.99

Accounting for technology growth

Table 2

Growth Rates of Per Capita Genuine Wealth

Country	(1) Genuine Investment as Percent of GDP	(2) Growth Rate of Unadjusted Genuine Wealth	(3) Population Growth Rate	(4) Growth Rate of Per Capita Genuine Wealth—before TFP Adjustment	(5 TF Gro Ra	Growth Rate of Per Capita Genuine Wealth—after TFP Adjustment	(7) rowth ate of capita GDP
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Nepal	13.31	2.00	2.24	−0.24	0.	0.63	1.86
Pakistan	8.75	1.31	2.66	−1.35	1.	0.59	2.21
China	22.72	3.41	1.35	2.06	3.	8.33	7.77
Sub-Saharan Africa	−2.09	−0.31	2.74	−3.05	0.	−2.58	0.01
Middle East/ North Africa	−7.09	−1.06	2.37	−3.43	−0.	−3.82	0.74
United Kingdom	7.38	1.48	0.18	1.30	0.	2.29	2.19
United States	8.94	1.79	1.07	0.72	0.	0.75	1.99

How much should we leave to future generations?

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The problem of intergenerational transfer of resources has strong parallels in evolutionary theory

R.Klopfer

Intergenerational resource transfers with random offspring numbers

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

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

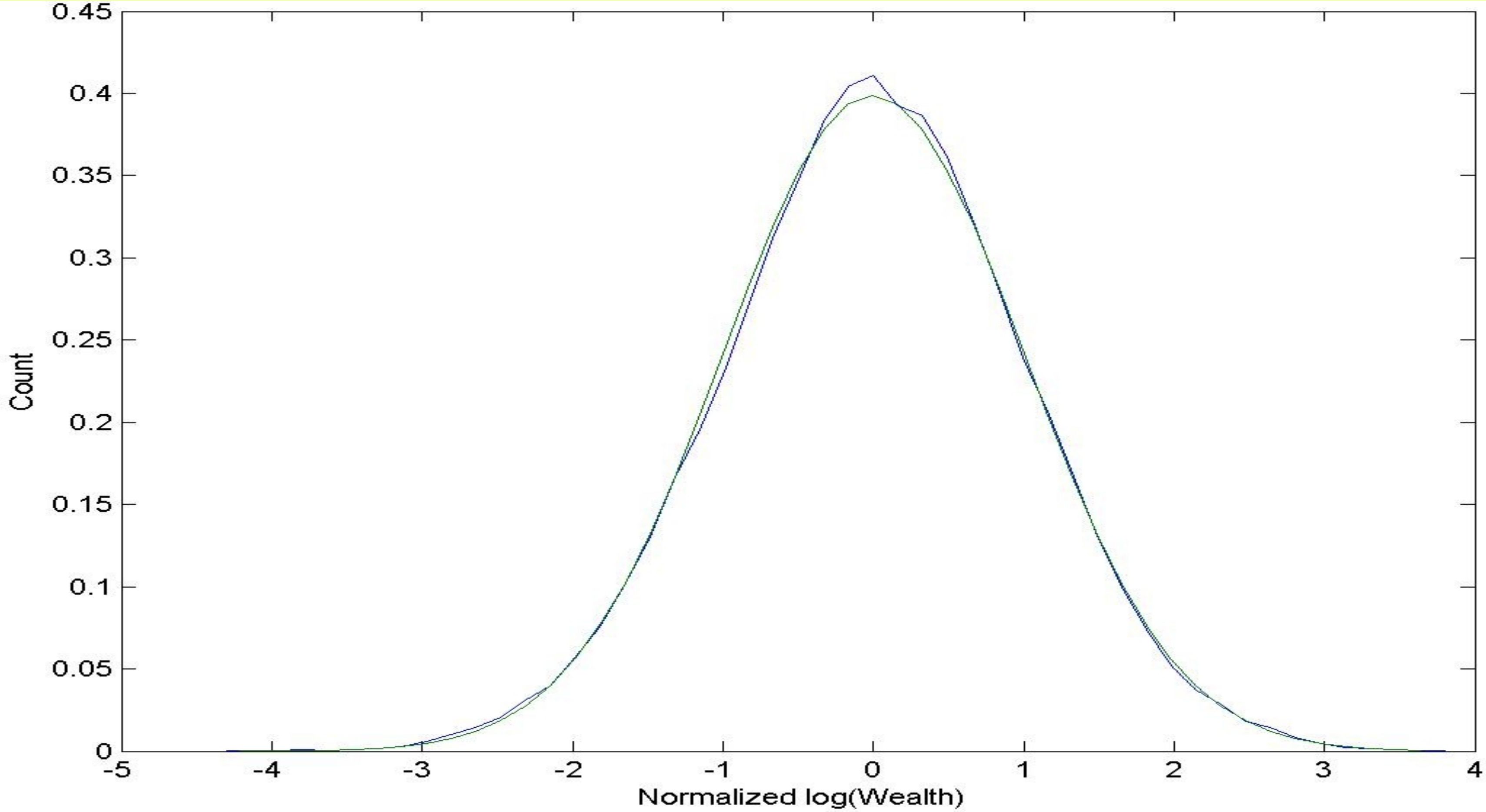
A problem common to biology and economics is the transfer of resources from parents to children. We consider the issue under the assumption that the number of offspring is unknown and can be represented as a random variable. There are 3 basic assumptions. The first assumption is that a given body of 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) will ultimately have a log-normal distribution.

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 human litter is a single individual, for which parental care is high, whereas fish may produce millions of offspring with low individual probabilities of survival.

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

Arrow and Levin, PNAS



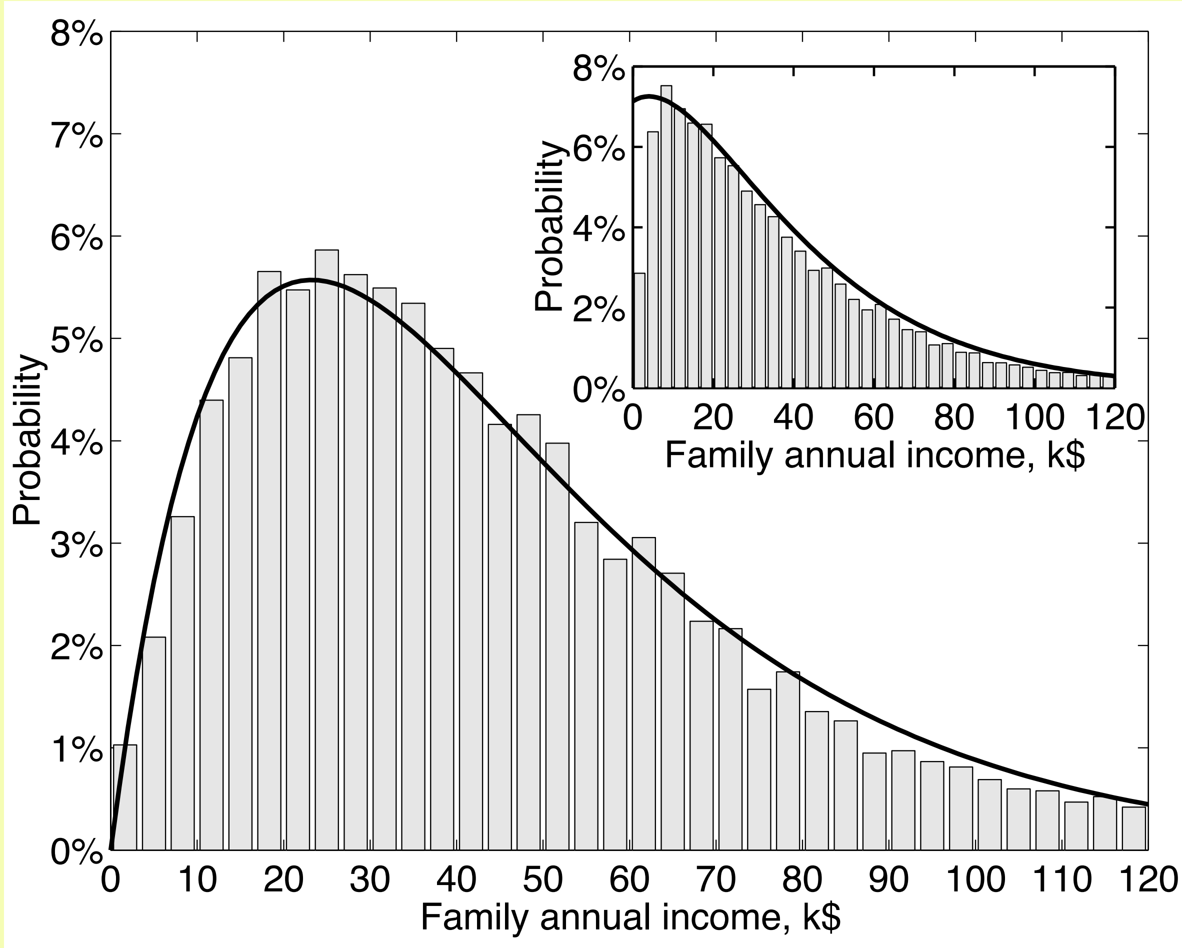


Fig. 4. Histogram: Probability distribution of income for families with two adults in 1996 [11]. Solid line: Fit to equation (5). Inset histogram: Probability distribution of income for all families in 1996 [11]. Inset solid line: $0.45P_1(r) + 0.55P_2(r)$.

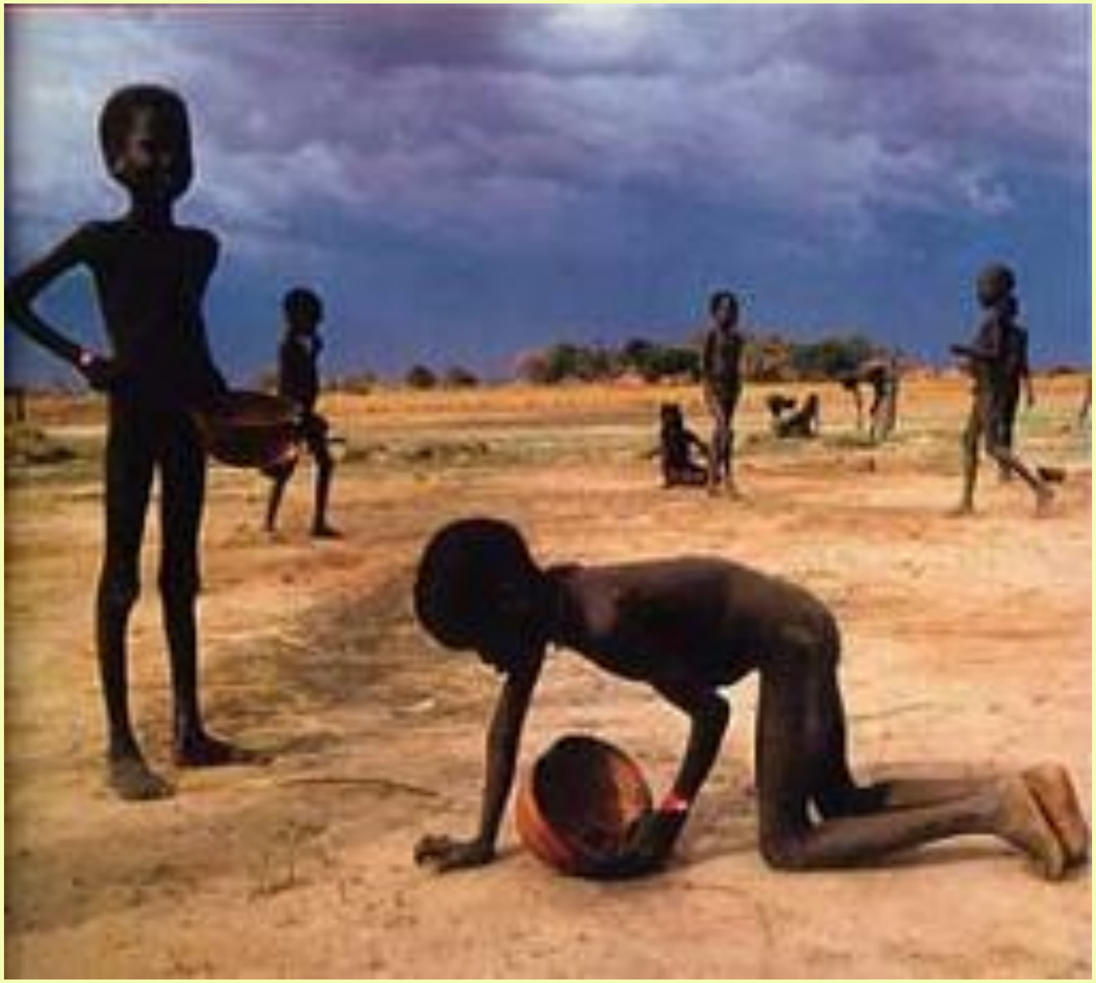
Eur. Phys. J. B **20, 585{589 (2001) THE EUROPEAN PHYSICAL JOURNAL B**
Evidence for the exponential distribution of income in the USA
A. Dragulescu and V.M. Yakovenko

Extensions (with Ricky Der)

- Modify assumptions to try to produce Pareto tail
  - Number of offspring contingent on wealth
  - Wealthy have higher return on investment
  - Other sources of uncertainty
- *Introduces challenging problems in functional equations…extensions of Schröder's equation:given a(z) and p(z), find f such that*

$$f(p(z))=a(z)f(z)$$

Indeed, inter-generational equity is only part of the problem

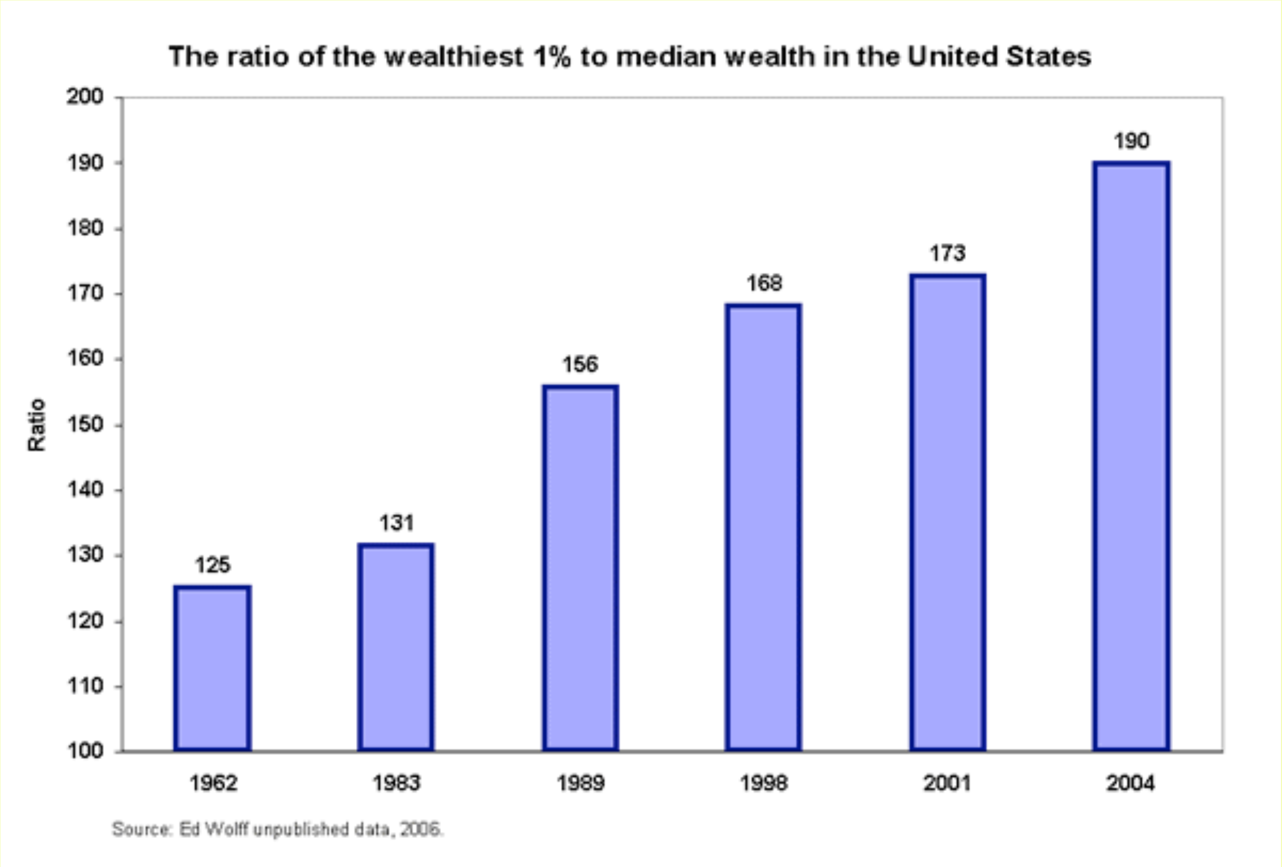


i94.photobucket.com/albums/l96/carlalynne

Also need to consider intra-generational equity

Sao Paolo

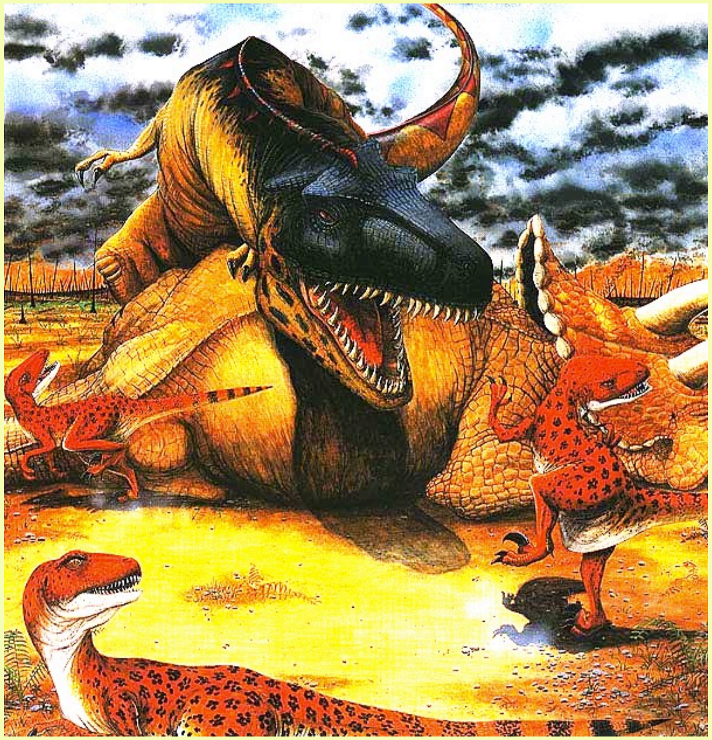
Inequity in the distribution of wealth is increasing



www.epi.org/page

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

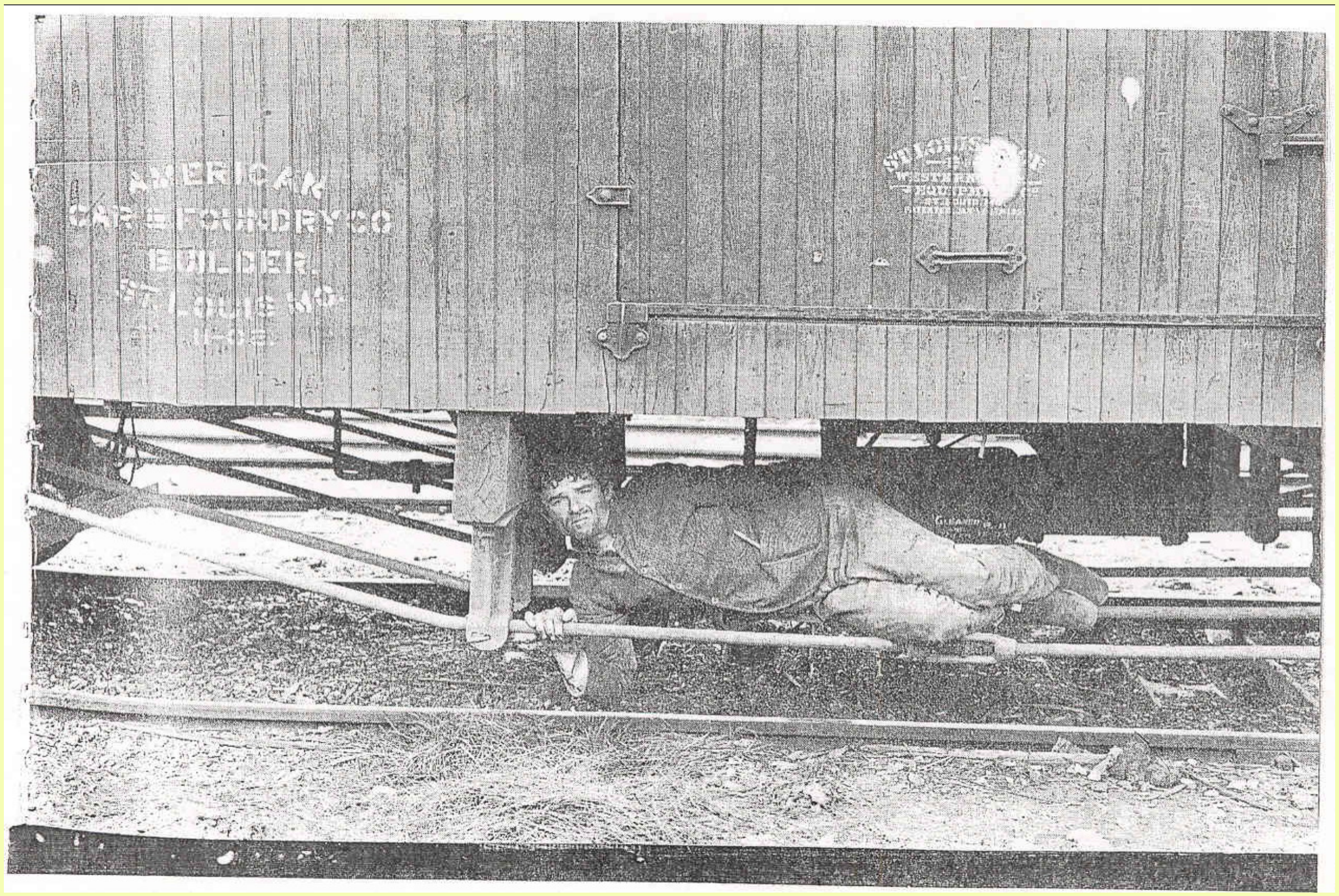
- Individual agents act largely in their own self-interest
- Social costs are not adequately accounted for

This is exaggerated when the individual agents are nations

The challenge….achieving cooperation at the global level

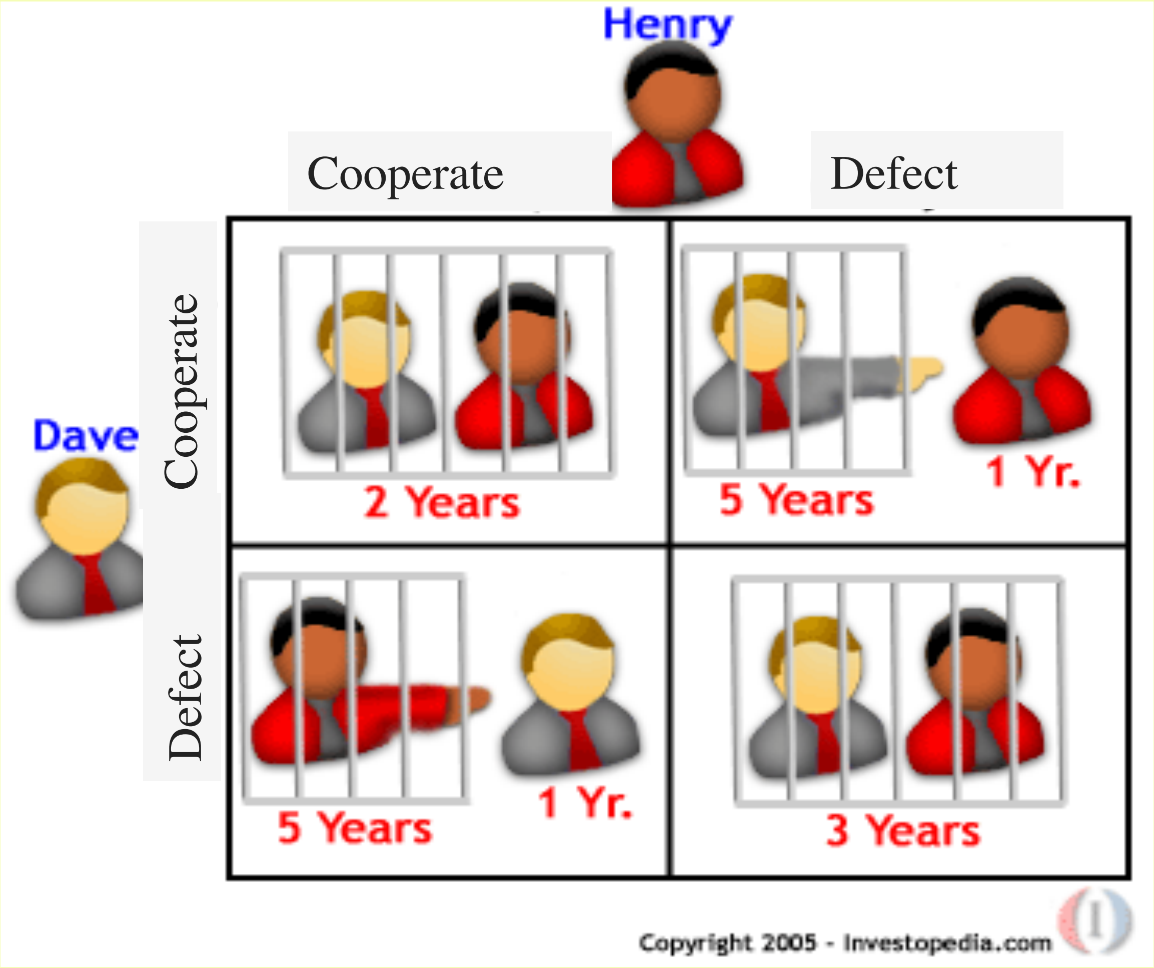
un.org

The problem: Free-riders



www.americanpopularculture.com

Prototypical problem: Prisoners' dilemma



Only stable solution: Nash equilibrium

Cooperation loses

Columbia.edu

William Forster Lloyd (1832)
The Tragedy of the Commons

Aelbert_Cuyp

The Commons solution (Hardin, Ostrom)

"Mutual coercion, mutually agreed upon"

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

http://www.guardian.co.uk

Pastoralism and sharing of grazing grounds

- With Avinash Dixit and Daniel Rubenstein

meshakenya.wordpress.com

In societies, insurance agreements spread risks, and create public goods and common-pool resources

http://dritoday.org/feature.aspx?id=

Insurance (with Avinash Dixit and Dan Rubenstein)

- Agistment and similar arrangements have emerged
- Pastoralism and sharing of grazing grounds
- Group ranches

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

Basic framework

- Good years A_H, bad years A_L
- When one has a good year, and other has a bad year, m cattle moved from bad to good
- x, z are investments in cattle, land

Variety of mechanisms: Repeated game

- Social optimum: Choose transfers to maximize total welfare

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

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

- Self-enforcing? Depends on discount rate

Variety of mechanisms: Repeated game

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

Variety of mechanisms: Repeated game

- Social optimum
- Self-enforcing?
- If not, second-best solutions to make them self-enforcing
- Prosociality may facilitate cooperation

Jacopo Bassano, d. 1592, copyright 2006, The National Gallery, London

Dixit-Levin: Effects of prosociality on public goods contributions

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

Individual utility:

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

where Z_g is the public pool in group g

Dixit-Levin

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 perhaps

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

Dixit-Levin

- Optimize utility with respect to x, z
- Public contribution may emerge because of local prosociality (Dixit)
- Local prosociality can produce global cooperation
- Topology of network is important

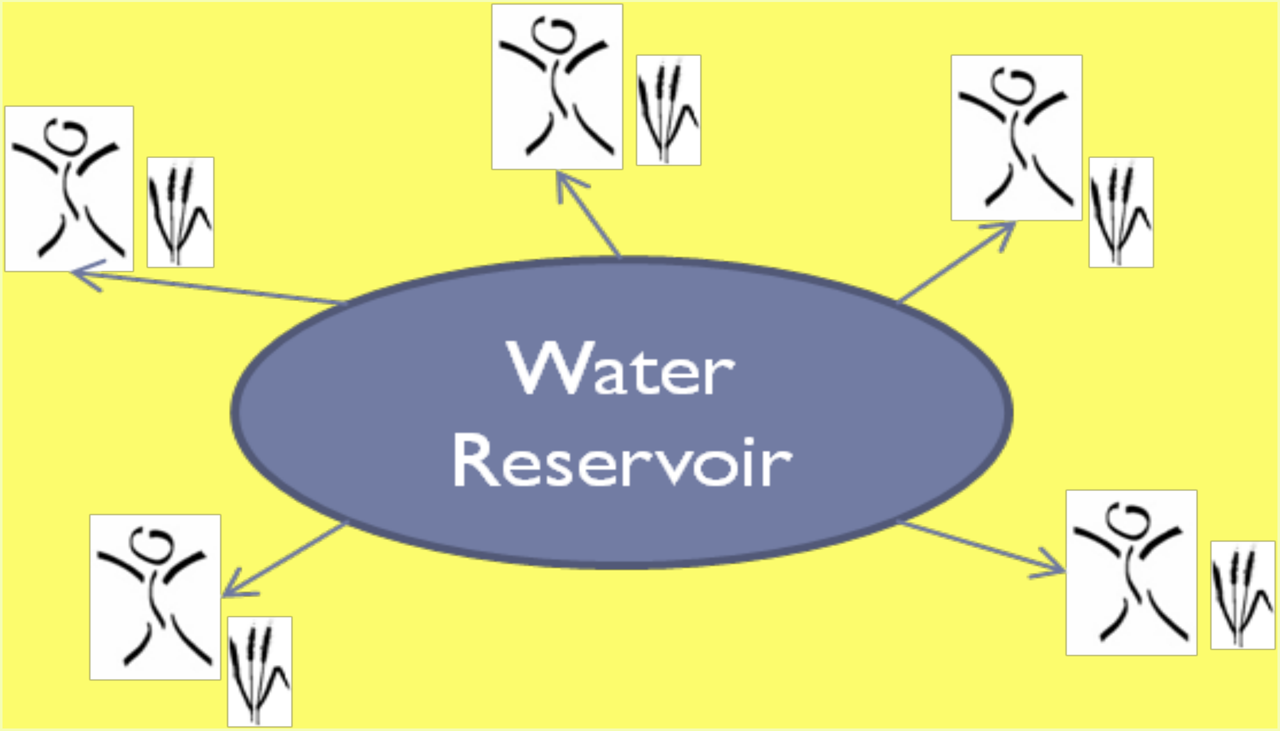
E. Fehr

Social norms… and repeated interactions

- Humans will punish others who deviate from social norms, at cost to themselves
- Punishment itself is a norm, and can evolve from repeated interactions
- Norms are important to understand prosocial behavior

Ostracism norms can sustain resources

with Alessandro Tavoni and Maja Schlüter



Avoiding Tragedy– Managing the Commons

Users self-organize:

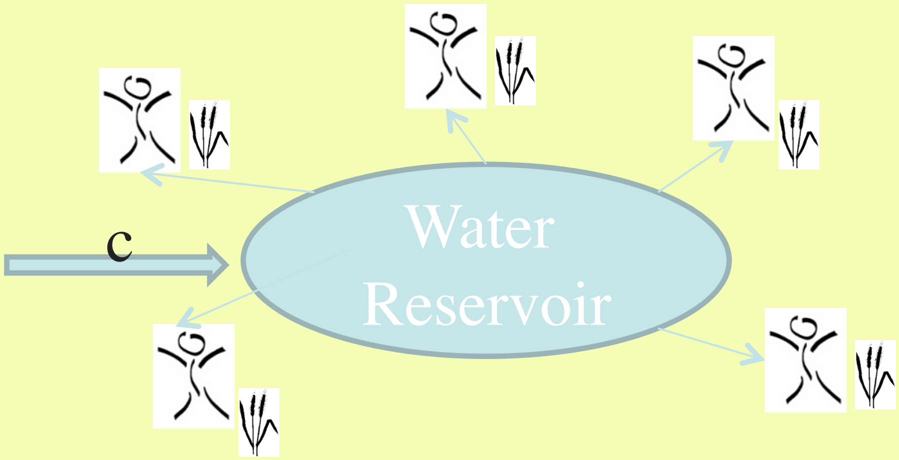
–to develop norms and institutions, to design sanctions, etc. (Ostrom, 1990)

–to establish and maintain cooperation, i.e. individual restraint from short-sighted resource overexploitation

–Dependent on characteristics of the resource system and the user community

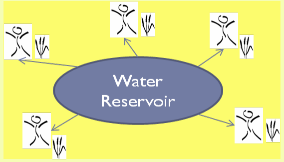
The Model - Environmental Settings

Common pool resource such as a groundwater reservoir



$dR/dt =$

$$dR/dt = c - \delta(R/R\max)^k - \kappa ER$$



Equity-driven ostracism

- Agents that withdraw more than socially accepted are ostracized and refused help -> reduction in utility

$$U_C = \pi_C(E,R)$$

$$U_D = \pi_D(E,R) - \omega(f_c)\frac{\pi_D(E,R) - \pi_C(E,R)}{\pi_D(E,R)}$$

Payoff from production

Ostracism function

Intensity of defection (inequity)

The ostracism function

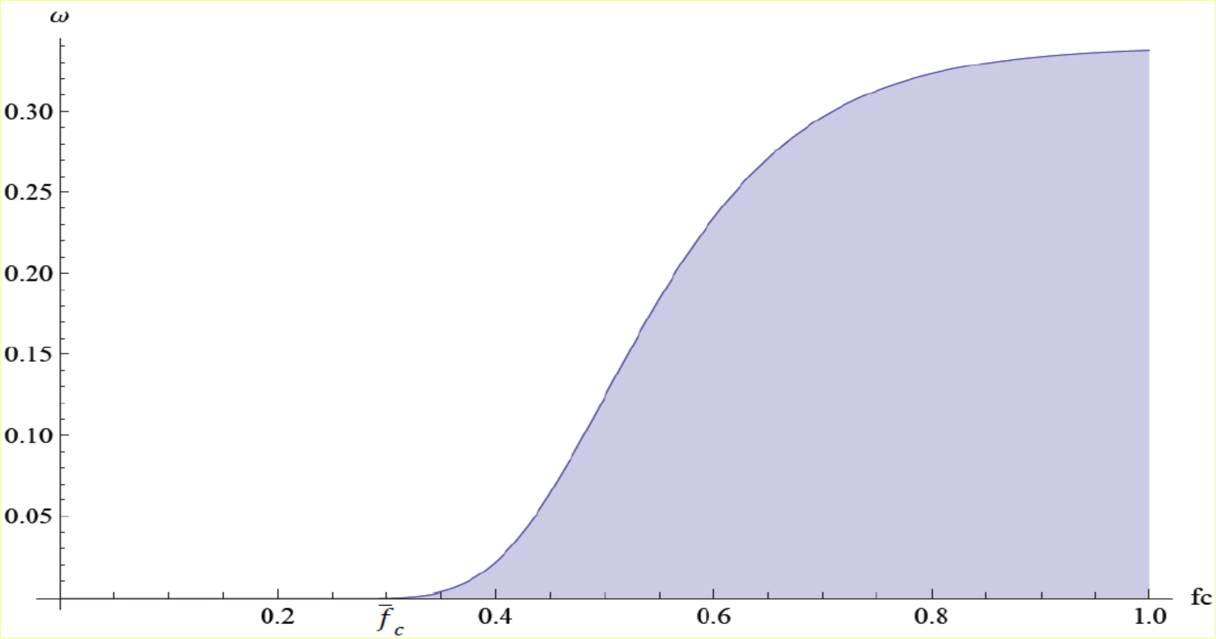


Figure 3: Ostracism function according to the Gompertz growth function $\omega(f_c) = he^{te^{gf_c}}$, where h, t, g are parameters governing, respectively, the maximum sanctioning (asymptote), the sanctioning effectiveness threshold (displacement) and the growth rate of the function. e is the Euler's number, $h = 0.34$,

Population evolution / Learning

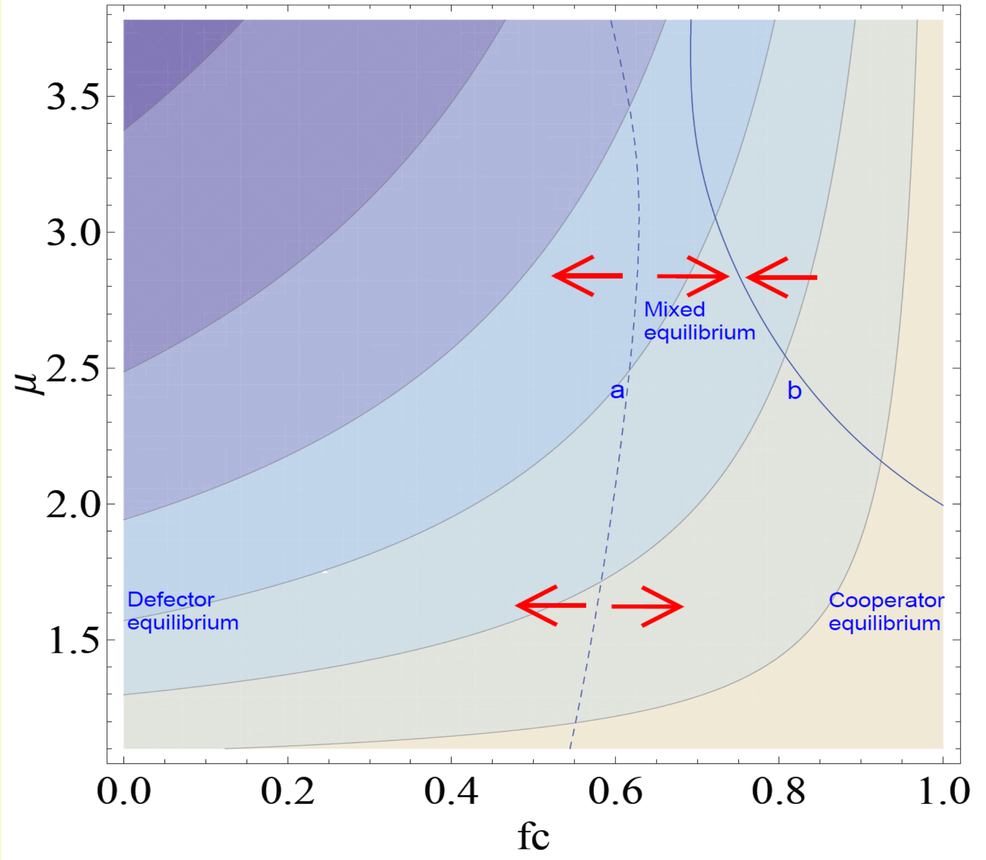
Replicator Dynamics: imitate successful behavior

$$\dot{f}_C = f_C(U_C - \overline{U}) = f_C(1 - f_C)(\pi_D - \pi_C)(\frac{\omega(f_C)}{\pi_D} - 1)$$

ABM simulations: agents update their strategy with probability equal to utility difference

Tavoni, Schlueter, Levin
Coordination game

Selfishness



Frequency of cooperators

Conclusions

- When reputational considerations matter, and a sufficient social stigma is attached to violators of a norm, sustainable outcomes can be achieved
- Norm observers and norm violators coexist
- Important to get above threshold number of observers
- Resource variation favors cooperation

Future work

- Interaction of agents through social networks
- Introduction of gradient in resource access
- Allowing agents to learn to adjust the extraction level to new resource conditions in the analytical model (dynamic Nash and Pareto extractions)
- Field experiments in Uzbekistan

These examples are of specific interest, but more broadly are models for addressing (international) cooperation

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

In general, in societies, contributions to public goods/cpr depend upon

- Intrinsic prosociality
- Reciprocal arrangements and contracts
- Norms, laws, taxes and incentives

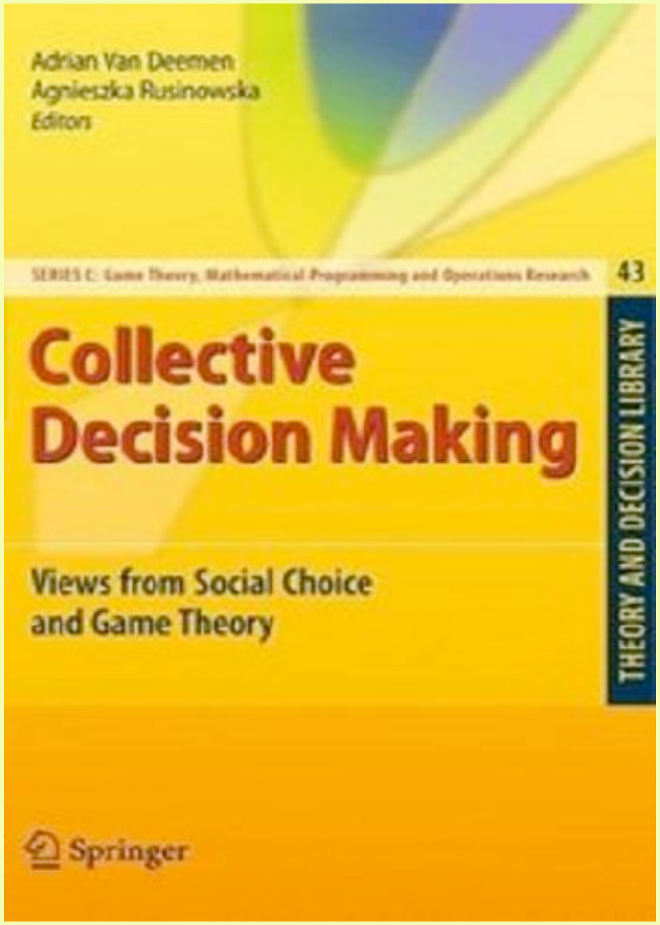
Summary so far:

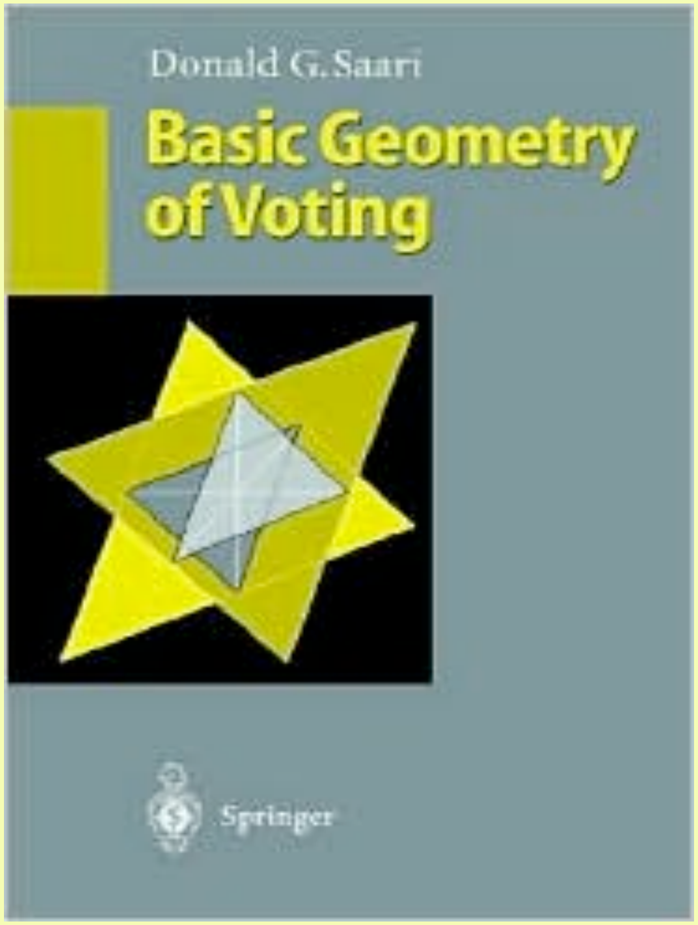
- Collective action can be effective if it includes enforcement
- Prosociality is an important contributor to the maintenance of public goods and common pool resources
- How are collective decisions made?

Key issues

- Learning from Nature
- Discounting
- Prosociality and spite
- Collective phenomena

Voting theory





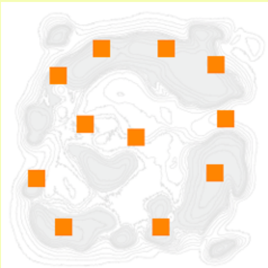
The dynamics of collective phenomena and collective decision-making

Claudio Carere
plus StarFLAG EU FP6 project

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

How do social norms become established

- What is the role of leadership?
- How is consensus achieved in democratic societies?
- What is the role of the unopinionated?

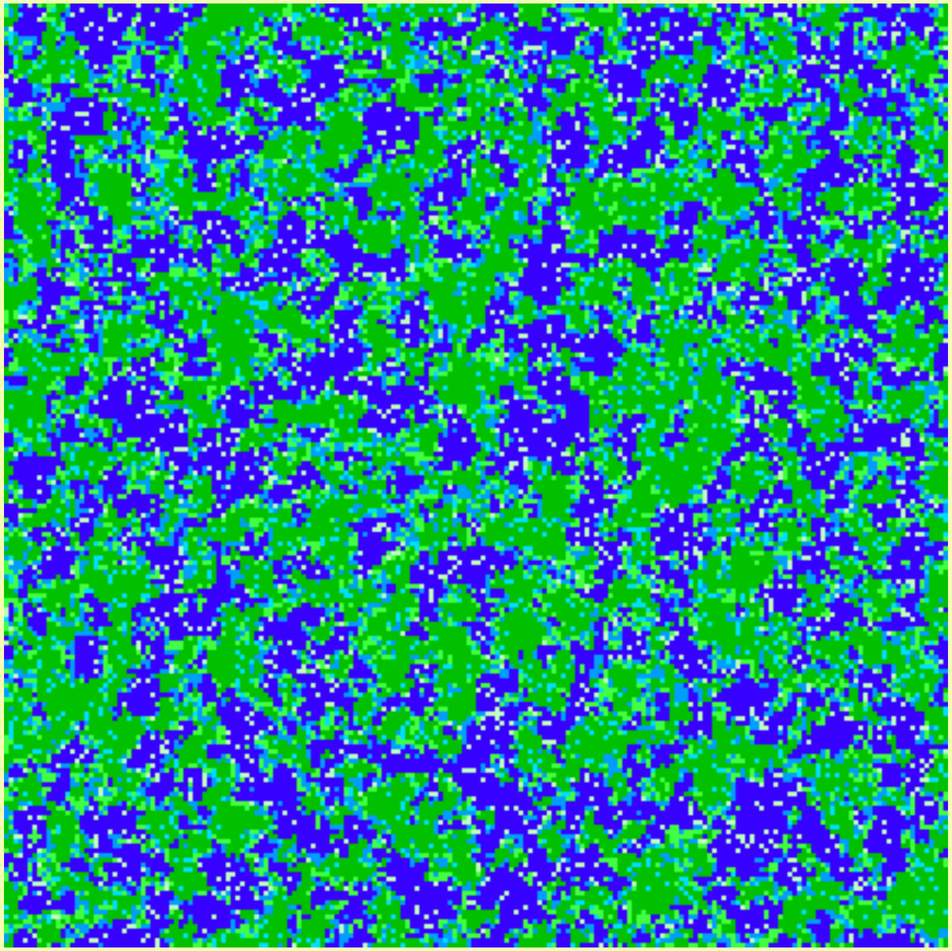


http://www.gridcafe.org/

Durrett and Levin, 2005

- Individuals have group "labels," as well as opinions
- Individuals meet other individuals on a network or grid
- Individuals change opinions based on opinions of similar neighbors (group membership+opinions)
- Individuals change groups (more rarely) if they are out of sync with the group

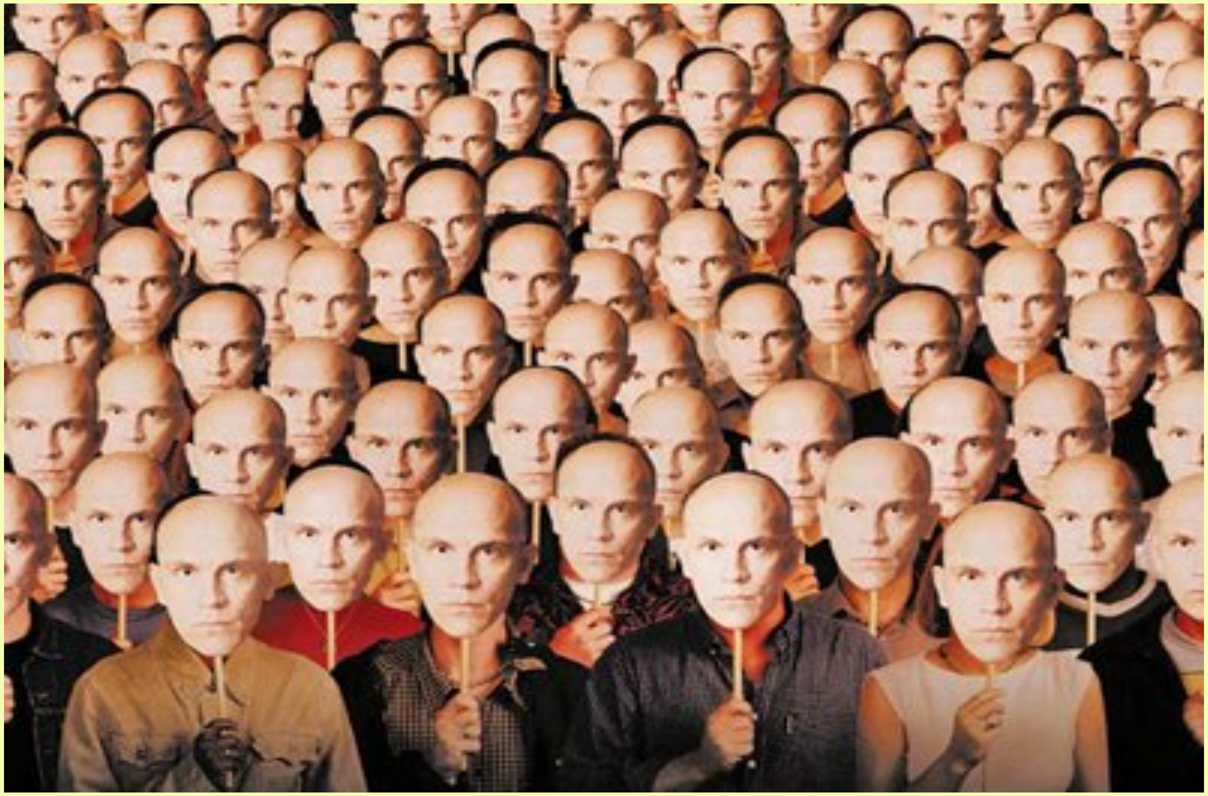
Durrett and Levin, 2005



Role of leadership and collective decision-making

Couzin, Krause, Franks, Levin

Unopinionated or uninformed individuals are crucial to nature of consensus



http://motherjones.com/kevin-drum

Science (16Dec 2011)

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]

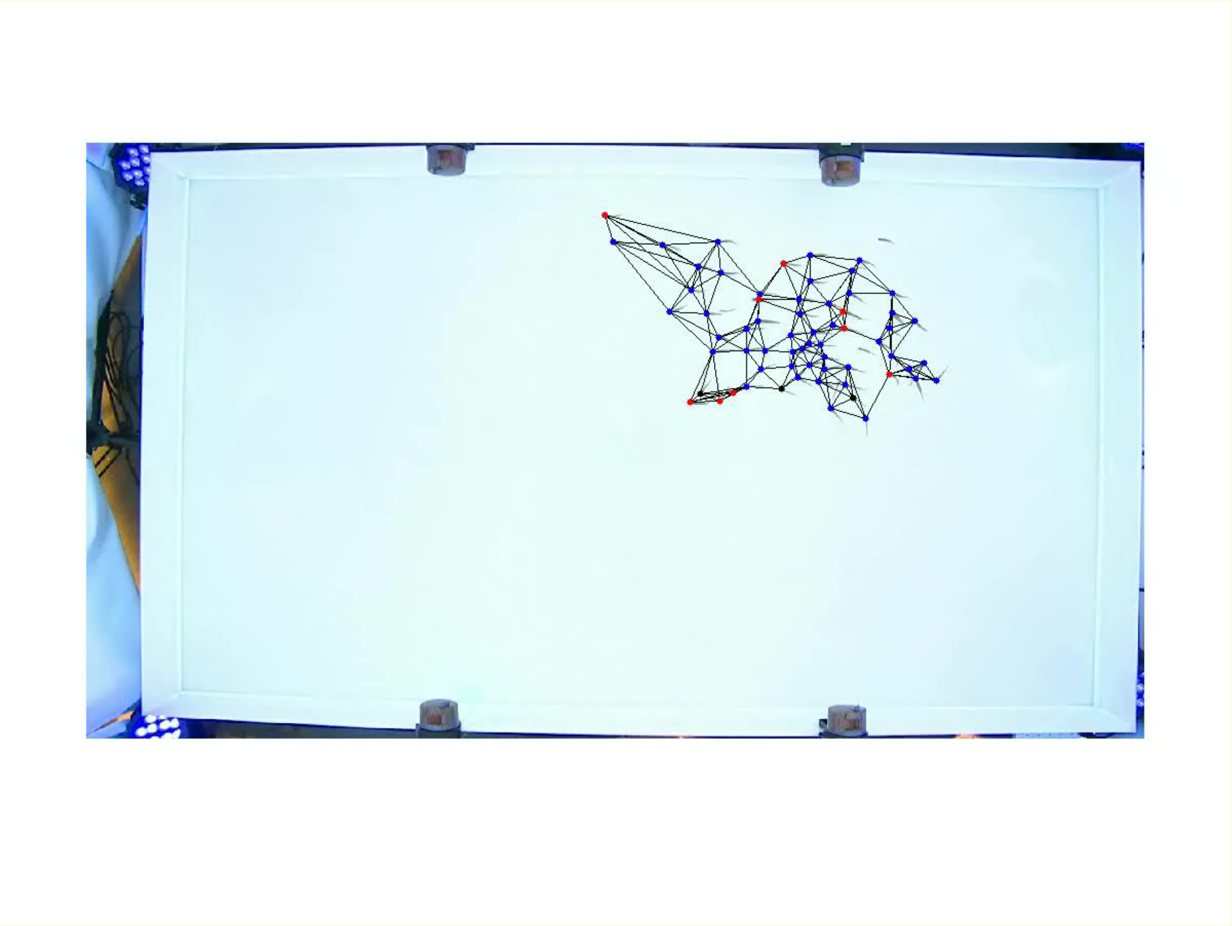
Conflicting interests among group members are common when making collective decisions, yet failure to achieve consensus can be costly. Under these circumstances individuals may be susceptible to manipulation by a strongly opinionated, or extremist, minority. It has previously been argued, for humans 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 eu-social insects, making consensus decisions is often

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

Similar conclusions emerge from multiple angles

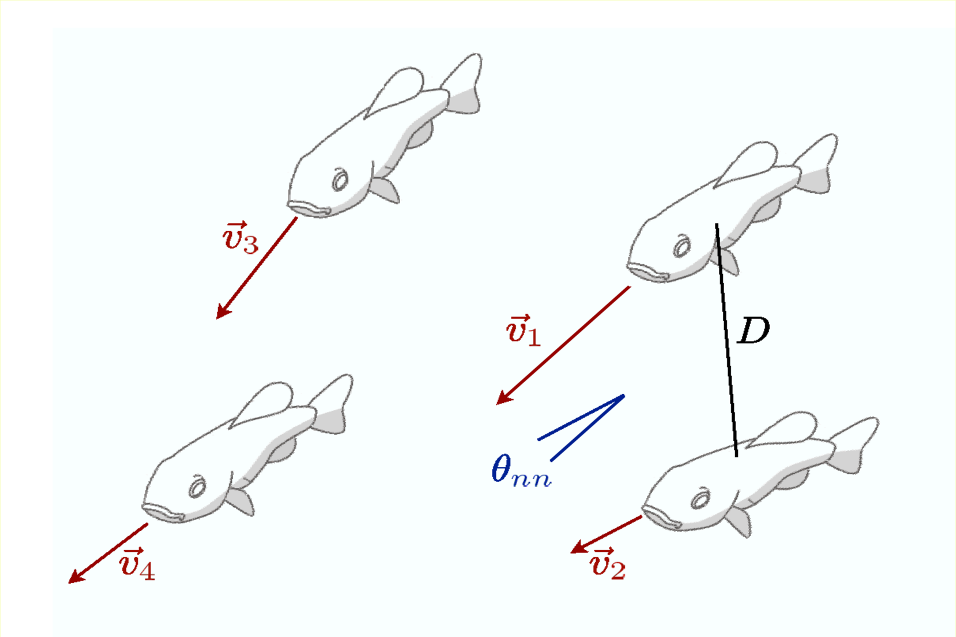
- Experimental studies with fish



Ariana Strandburg-Peshkin, et al.

Similar conclusions emerge from multiple angles

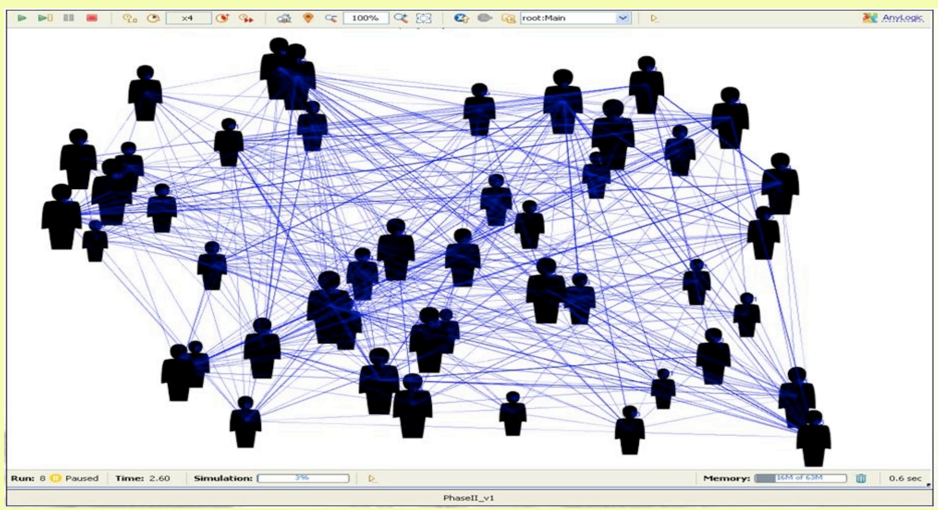
- Experimental studies with fish
- Simulation and analytical models of movement



Courtesy Iain Co

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

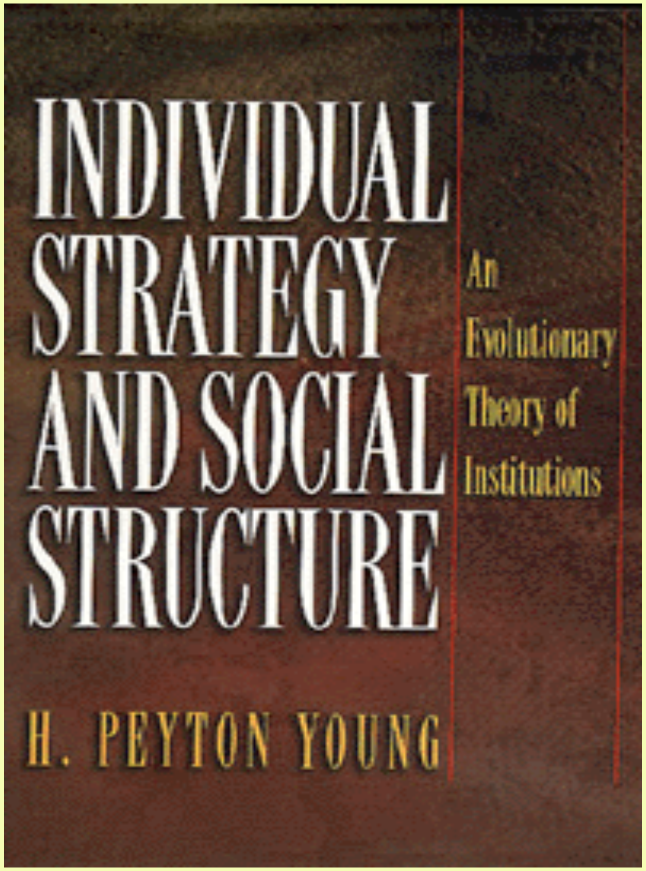
Young-Jun Son, Leon Zhao, Keith Provan and Brian McGough

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**
- **Induced opinion changes: Focal individual changes opinion with probability that depends nonlinearly on number of opposing individuals it is connected to**
- **Each uninformed individual switches state spontaneously with probability q….lower probability of switching away from preferred state**
- **Links are made or broken, with probabilities based on similarity of opinions**

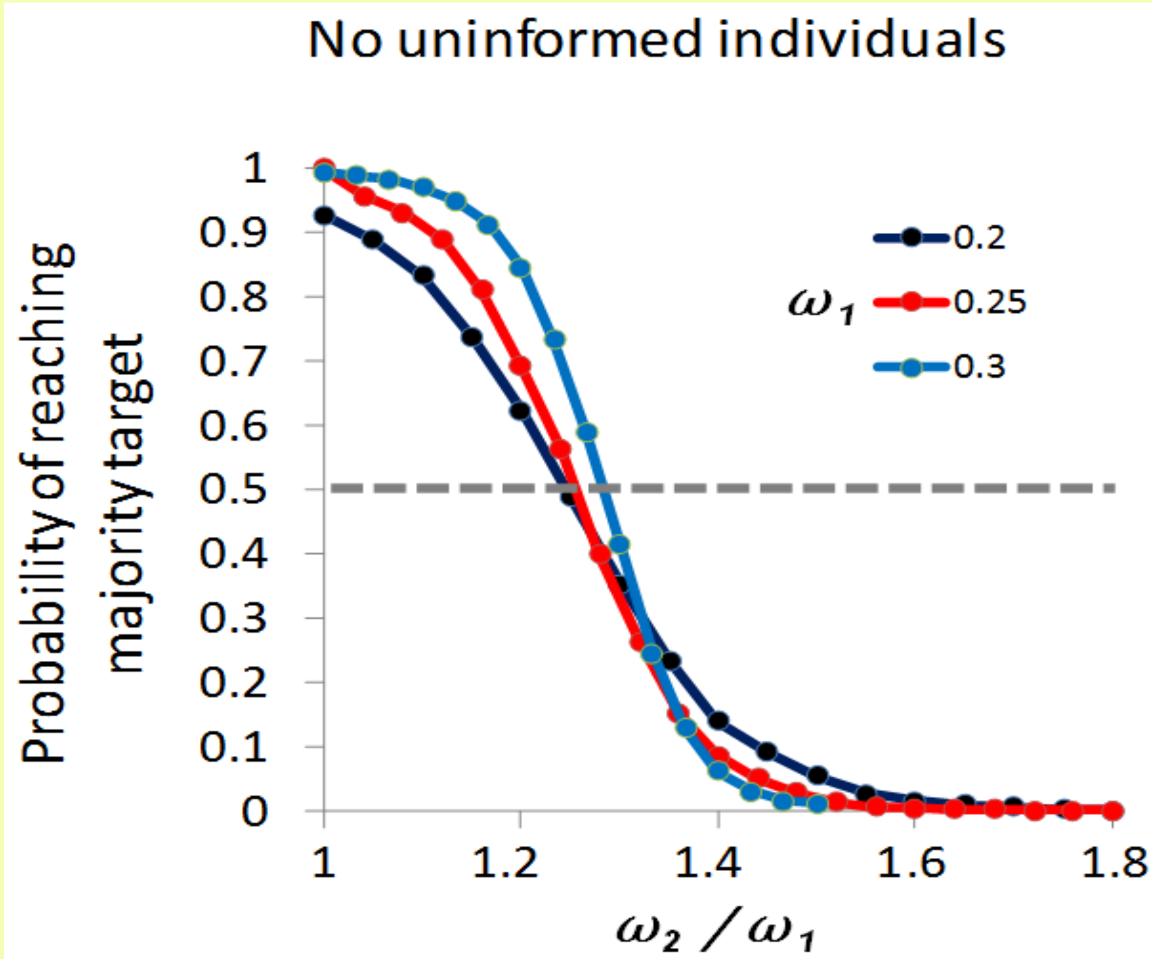
Also consider a modified convention model



Collective decision-making

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

SIMILAR RESULTS FROM ALL



Increasing strength of minority opinion →

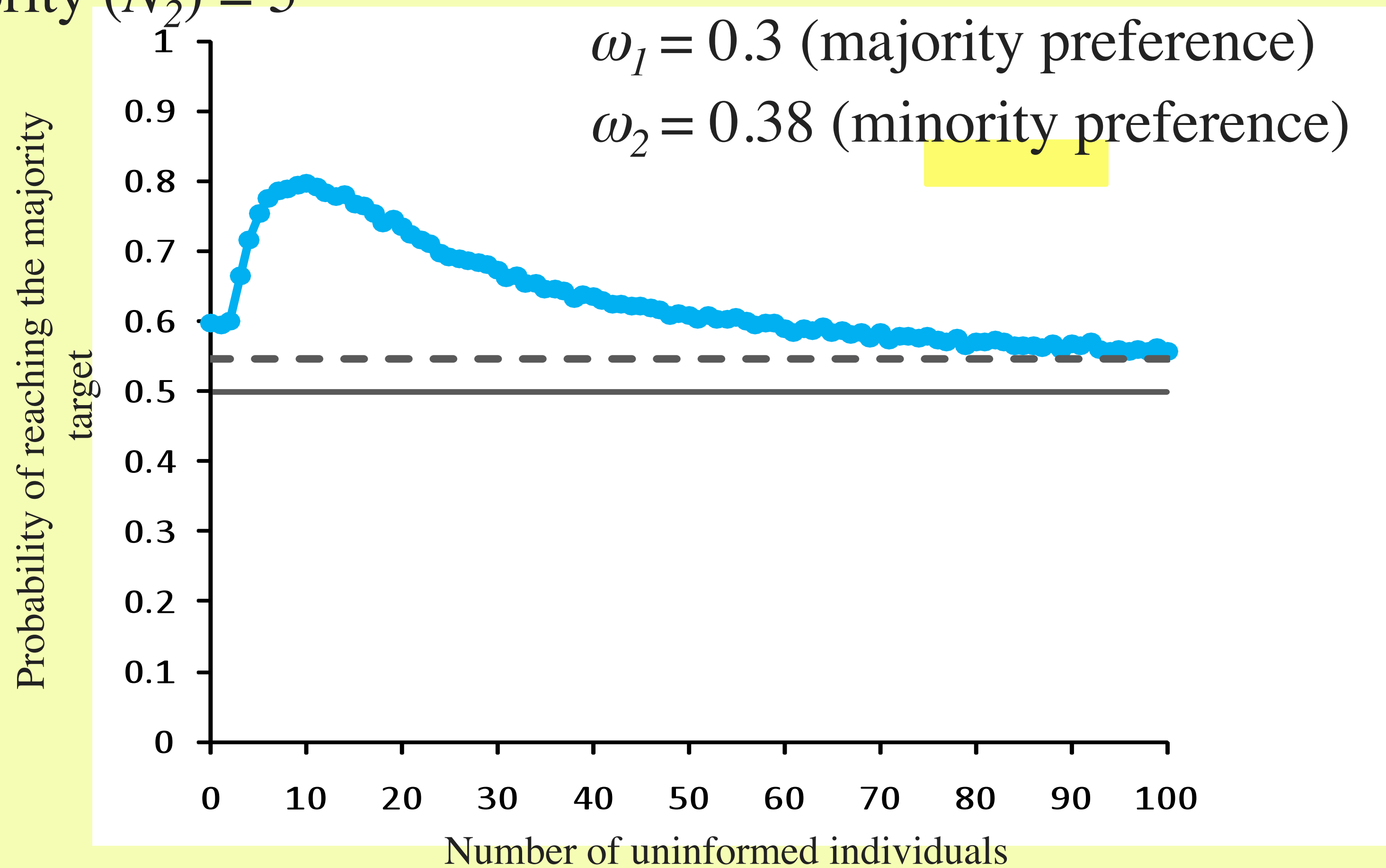
ω_1 = majority preference ω_2 = minority preference

Collective decision-making

The importance of uninformed individuals

targets model

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

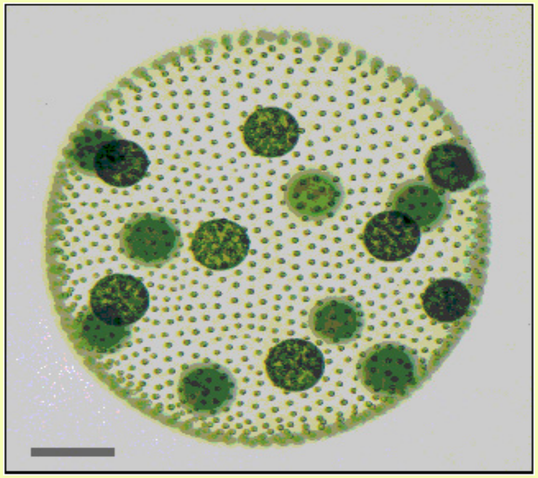


Very robust conclusion under parameter variation

Managing the Commons is both an environmental and an evolutionary challenge

- In human societies: mutual coercion, mutually agreed upon
- Users self-organize, to develop norms and institutions, design sanctions (Ostrom 1990)
- To establish and maintain cooperation, i.e. individual restraint from short-sighted resource overexploitation

Societies emerge as multicellular organisms

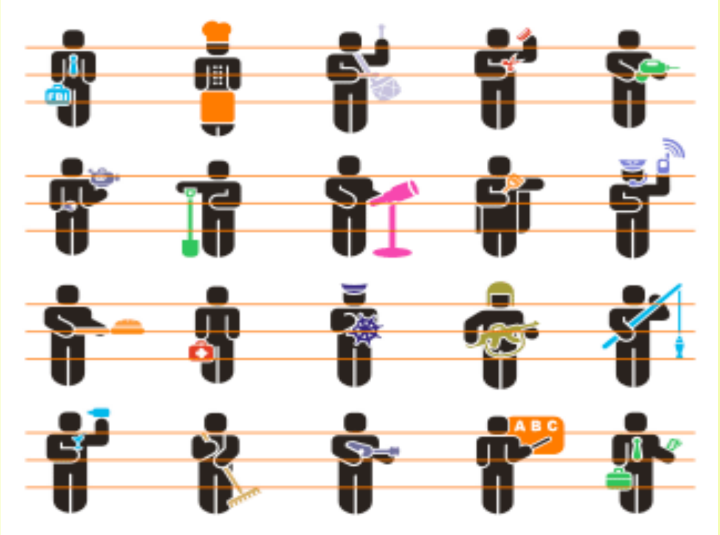


http://www.gambassa.com/public/project/

With cooperation and differentiation of function

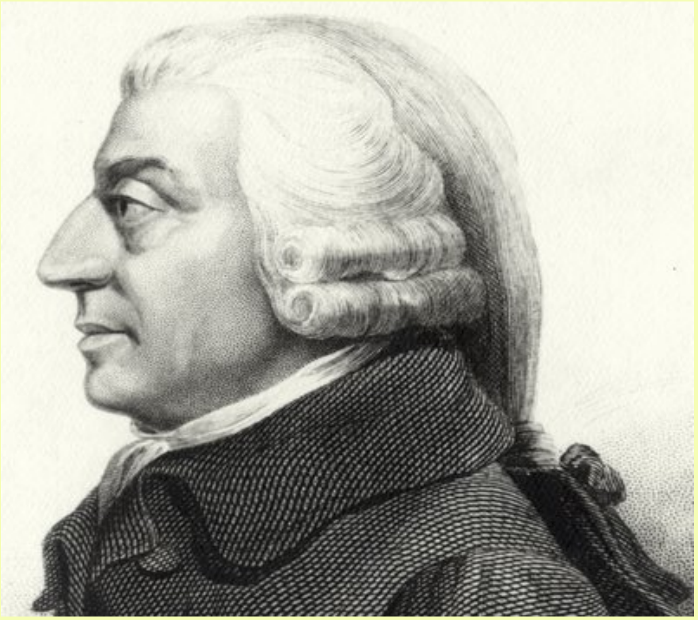
Must such features self-organize, or can government policies stimulate?

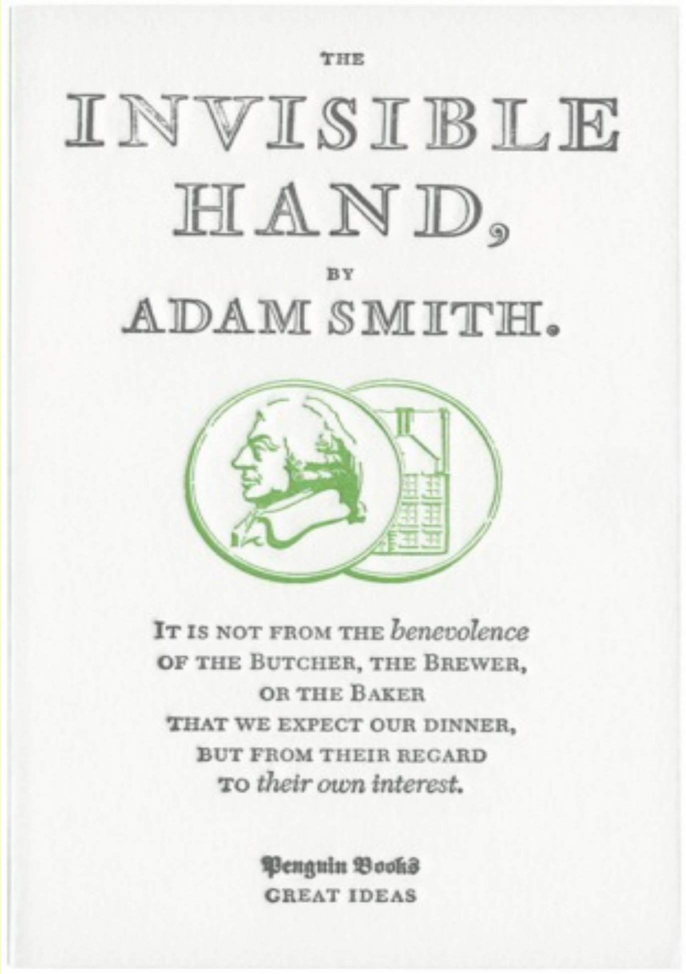
What is the optimal distribution?



http://architects2zebras.com/2011

Adam Smith (1776)





"By pursuing his own interest he frequently promotes that of the society more effectually than when he really intends to promote it."

http://organizationsandmarkets.files.wordpres

The invisible hand does not protect society

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

http://www.latinamericanstudies.org/maya

Those lessons are magnified for ecological and environmental systems

media-2.web.britannica.com

The CAS perspective means

- In both cases, management requires a balance between free-market and regulation
- New institutions must be adaptive
  - Can adaptive features be built in?
  - Robustness
- Trust and cooperation essential
  - Key to macroscopic goals is in microscopic incentives
  - Montreal Protocol?

Management challenge is to integrate

- Bottom-up mechanisms, like cooperation and collective action
- Top-down mechanisms, like rewards and punishments

To achieve

- Adaptive, polycentric governance and agreements
  - Immune system
  - Ostrom and climate change

Can cooperation be extended to the global level?

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

Lariviere

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