

# Nurturing Breakthroughs: Lessons from Complexity Theory

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## Abstract

I outline a general theory of innovation and progress in human society, based on the combat between two opposite forces (conservatism/inertia and speculative herding “bubble” behavior). I contend that human affairs are characterized by ubiquitous “bubbles”, which involve huge risks which would not otherwise be taken using standard cost/benefit analysis. Bubbles result from self-reinforcing positive feedbacks. This leads to explore uncharted territories and niches whose rare successes lead to extraordinary discoveries and provide the base for the observed accelerating development of technology and of the economy. But the returns are very heterogeneous, very risky and may not occur. In other words, bubbles, which are characteristic definitions of human activity, allow huge risks to get huge returns over large scales. We outline some underlying mathematical structure and a few results involving positive feedbacks, emergence, heavy-tailed power laws, outliers/kings/black swans, the problem of predictability and the illusion of control, as well as some policy implications.

In order to address the question, “how can complexity science support policy decision making?”, it seems to me that one needs first to embrace the larger question of what is driving a human being, a human groups or a human society. Only then can policy decision making identify and aim correctly its targets. My perception is that these questions can now be addressed with a fresh perspective, informed and inspired by science. Indeed, the scientific enterprise is now offering insights on many of the questions in social sciences that were before only the realm of normative approaches or philosophical discourses. Via novel experimental procedures, new technology and new conceptual insights, science can now help address from an evidence-based approach such questions as: what is happiness? What is driving human beings? Why do we cooperate?

My discussion is organized in four short parts.

1. The first one recognizes that most systems are punctuated by rare but large events which often dominate their organization. The progress of science and technology is no exception, as innovations, discoveries, blockbusters are exceptional events in their impact. This statement can be quantified by heavy-tailed distributions.
2. Complementing the first part which emphasizes the statistics of the impacts of innovations, the second part focuses on a classification of their time dynamics, by presenting a simple classification of the dynamics of complex systems in terms of the interplay

between endogenous and exogenous shocks. This allows us to separate the impact of external influences from the role played by the constitution of the inner structure in understanding and predicting blockbusters. This is applied to different critical events in economics and the social sciences taken as proxies of innovation dynamics: social unrest shocks, internal downloads, dialog in email traffic, the dynamics of commercial sale in response to advertisement or to word-of-mouth, volatility clustering and shocks in financial markets, dynamics of exploits and patches following disclosures of software vulnerability, movie blockbusters, the dynamics of YouTube video sharing, and so on.

3. The third part documents the phenomenon that I coin “breakdown of the human Galilean invariance principle”, namely that humans being bored by steady state tend to act to develop intermittent accelerating outcomes. As a consequence of their individual actions aggregated at the collective level, one can observe super-exponential acceleration of their processes punctuated by corrections and crashes. The mathematical description of these processes emphasizes the importance of positive feedbacks. Based on this idea, I propose that “bubbles” are generic results of collective human activities and that they seem to be not only inherently associated with human societies but are also a vehicle of giant leaps in progress.
4. Lastly, the question of control and management of complex systems is alluded to by stressing the phenomenon of “illusion of control” and its consequence for practical policies.

The last section concludes.

## 1 Heavy-tail distribution of breakthroughs and blockbusters

Many studies report evidences of positive economic benefits derived from basic research [Martin et al., 1996; NAS, 1997]. In certain areas such as biotechnology, semi-conductor physics, optical communications [Ehrenreich, 1995], the impact of basic research is direct while, in other disciplines, the path from discovery to applications is full of surprises. As a consequence, there are persistent uncertainties in the quantification of the exact economic returns of public expenditure on basic research. This gives little help to policy makers trying to determine what should be the level of funding.

Some industries, such as the pharmaceutical and movie industries, are characterized by the occurrence of “block-busters,” i.e. remarkably successful products with exceptional sales much larger than the typical product. Determining how exceptional are these blockbusters is an important question for firm strategy and economies of scale. Taking the movie industry as a proxy because the data is unambiguous, plentiful and of good quality, Sornette and Zajdenweber [1999] have shown that the distribution of gross revenues of Hollywood movies from theatres from top box office 100 is stable over twenty years and is well-described by a power law distribution with exponent  $\alpha$  approximately equal to 1.5, such that the mean exists but not the variance. Grabowski and Vernon [1990, 1994] constructed a discounted present value per new chemical entity and divided the drugs in

decile in descending order, leading to a value distribution compatible with a power law distribution of the tail with exponent approximately equal to  $2/3$  [Sornette, 2002a; and unpublished], for which neither the mean nor the variance exist. Scherer [1998] has studied the distribution of royalties from U.S. University patent portfolios, of the quasi-rents from marketed pharmaceutical entities and the stock market returns from three large samples of high-technology venture start-ups. The tails of the distributions are again compatible with a power law distribution with exponent less than 1 but there is a noticeable curvature when going to small returns. D. Harhoff and F.M. Scherer (private communication) have studied a sample of approximately 800 high-value patents and find that the distribution most closely approximates a log normal while the power law hypothesis is strongly rejected when using the whole sample. The issue whether the extreme tail of the distribution of returns from innovation is asymptotically a power law with a small exponent is thus a delicate statistical problem. This is not specific to this domain of application, see for instance Sornette [2004].

Sornette and Zajdenweber [1999] have suggested that these uncertainties on what should be the relevant policy on research support have a fundamental origin to be found in the interplay between the intrinsic “fat tail” power law nature of the distribution of economic returns of innovations, characterized by a mathematically diverging variance, and the stochastic character of discovery rates. In the regime where the cumulative economic wealth derived from research is expected to exhibit a long-term positive trend, they show that strong fluctuations blur out significantly the short-time scales: a few major unpredictable innovations may provide a finite fraction of the total creation of wealth. In such a scenario, any attempt to assess the economic impact of research over a finite time horizon encompassing only a small number of major discoveries is bound to be at best unreliable and at worst misleading.

In the Kuhnian view of how science works [Kuhn, 1970], periods of “normal science” are interrupted by revolutions. If discovery “sizes” are indeed distributed according to a power law distribution, it is natural to wonder if Kuhn was only half-correct: it seems possible that there is no such thing as “normal science”, and that science instead evolves through a succession of “revolutions” of all sizes. This idea has been put forward in another context by M. Buchanan [1996]. Accordingly, history only takes notice of the really huge “revolutions” –quantum theory and relativity, for example– even though there are less significant others going on all the time. As a signature of this idea, there should be some kind of Gutenberg-Richter law for ideas –a power law distribution of their impact, as found by Redner [1998] and Dieks and Chang [1976] for the impacts of scientific publications.

This suggests to bring the problem of research economic benefits into the growing basket of natural and societal processes characterized by extreme behavior. They range from large natural catastrophes such as volcanic eruptions, hurricanes and tornadoes, landslides, avalanches, lightning strikes, catastrophic events of environmental degradation, to the failure of engineering structures, social unrest leading to large-scale strikes and upheaval, economic drawdowns on national and global scales, regional power blackouts, traffic gridlock, diseases and epidemics, etc. These phenomena are extreme events that occur rarely, albeit with extraordinary impact, and are thus completely under-sampled and thus poorly constrained. They seem to result from self-organising systems which develop similar patterns over many scales, from the very small to the very large. There is an urgency to assimilate in our culture and policy that we are embedded in extreme phenomena. Our

overall sense of continuity, safety and confort may just be an illusion stemming from our myopic view. Let us unleash the battle of giants between extraordinary discoveries and extreme catastrophes.

## 2 Interplay between Endogenous and Exogenous shocks (endo-exo): from commercial sales to happiness

### 2.1 Motivations

Self-organized criticality, and more generally, complex system theory contend that out-of-equilibrium slowly driven systems with threshold dynamics relax through a hierarchy of avalanches of all sizes. Accordingly, extreme events are seen to be endogenous [Bak and Paczuski, 1995; Bak, 1996] in contrast with previous prevailing views. In addition, the preparation processes before large avalanches are almost undistinguishable from those before small avalanches, making the prediction of the former basically impossible (see [Sornette, 2002b] for a discussion). But, how can one assert with 100% confidence that a given extreme event is really due to an endogenous self-organization of the system, rather than to the response to an external shock? Most natural and social systems are indeed continuously subjected to external stimulations, noises, shocks, sollicitations, forcing, which can widely vary in amplitude. It is thus not clear a priori if a given large event is due to a strong exogenous shock, to the internal dynamics of the system organizing in response to the continuous flow of small sollicitations, or maybe to a combination of both. Adressing this question is fundamental for understanding the relative importance of self-organization versus external forcing in complex systems and for the understanding and prediction of crises.

This leads to two questions:

1. Are there distinguishing properties that characterize endogenous versus exogenous shocks?
2. What are the relationships between endogenous and exogenous shocks?

Actually, the second question has a long tradition in physics. It is at the basis of the interrogations that scientists perform on the enormously varied systems they study. The idea is simple: subject the system to a perturbation, a “kick” of some sort, and measure its response as a function of time, of the nature of the sollicitations and of the various environmental factors that can be controlled. In physical systems at the thermodynamic equilibrium, the answer is known under the name of the theorem of fluctuation-dissipation, sometimes also refered to as the theorem of fluctuation-susceptibility [Stratonovich, 1992] In a nutshell, this theorem relates quantitatively in a very precise way the response of the system to an instantaneous kick (exogeneous) to the correlation function of its spontaneous fluctuations (endogenous). An early example of this relationship is found in Einstein’s relation between the diffusion coefficient  $D$  of a particle in a fluid subjected to the chaotic collisions of the fluid molecules and the coefficient  $\eta$  of viscosity of the fluid [Einstein, 1905; 1956]. The coefficient  $\eta$  controls the drag, i.e., response of the particle velocity when subjected to an exogenous force impulse. The coefficient  $D$  can be shown to be a

direct measure of the (integral of the) correlation function of the spontaneous (endogenous) fluctuations of the particle velocity.

In out-of-equilibrium systems, the existence of a relationship between the response function to external kicks and spontaneous internal fluctuations is not settled [Ruelle, 2004]. In many complex systems, this question amounts to distinguishing between endogeneity and exogeneity and is important for understanding the relative effects of self-organization versus external impacts. This is difficult in most physical systems because externally imposed perturbations may lie outside the complex attractor which itself may exhibit bifurcations. Therefore, observable perturbations are often misclassified.

It is thus interesting to study other systems, in which the dividing line between endogenous and exogenous shocks may be clearer in the hope that it would lead to insight about complex physical systems. The investigations of the two questions above may also bring new understanding of these systems. The systems to which the endogenous-exogenous question (which we will refer to as “endo-exo” for short) is relevant include the following:

- Biological extinctions such as the Cretaceous/Tertiary KT boundary (meteorite versus extreme volcanic activity (Deccan traps) versus self-organized critical extinction cascades),
- immune system deficiencies (external viral/bacterial infections versus internal cascades of regulatory breakdowns),
- cognition and brain learning processes (role of external inputs versus internal self-organization and reinforcements),
- discoveries (serendipity versus the outcome of slow endogenous maturation processes),
- commercial successes (progressive reputation cascade versus the result of a well orchestrated advertisement),
- financial crashes (external shocks versus self-organized instability),
- intermittent bursts of financial volatility (external shocks versus cumulative effects of news in a long-memory system),
- the aviation industry recession (9/11/2001 terrorist attack versus structural endogenous problems),
- social unrests (triggering factor or rotting of social tissue),
- recovery after wars (internally generated (civil wars) versus imported from the outside) and so on.

It is interesting to mention that the question of exogenous versus endogenous forcing has been hotly debated in economics for decades. A prominent example is the theory of Schumpeter on the importance of technological discontinuities in economic history. Schumpeter argued that “evolution is lopsided, discontinuous, disharmonious by nature... studded with violent outbursts and catastrophes... more like a series of explosions than a gentle, though incessant, transformation” [Schumpeter, 1939]. Endogeneity versus exogeneity is also paramount in economic growth theory [Romer, 1996].

## 2.2 Epidemic model of social interactions by word-of-mouth

Our approach to the endo-exo question is based on epidemic cascade models of social interactions (see Sornette, 2005 and <http://www.er.ethz.ch/essays/origins> for reviews). Let us consider an observable characterizing the activity of humans within a given social network of interactions. This activity can be the rate of visits or downloads on an internet website, the sales of a book or the number of newspaper articles on a given subject. We envision that the instantaneous activity results from a combination of external forces such as news and advertisement, and of social influences in which each past active individual may impregnate other individuals in her network of acquaintances with the desire to act. This impact of an active individual onto other humans is not instantaneous as people react at a variety of time scales. The time delays capture the time interval between social encounters, the maturation of the decision process which can be influenced by mood, sentiments, and many other factors and the availability and capacity to implement the decision. The contacts and exchanges between humans lead to information cascades.

This leads to identify a critical parameter, the branching ratio  $n$ , which controls the propensity for news, shocks, changes to propagate and percolate within the social network. When  $n < 1$ , the social network is sub-critical and local changes remain localized. When  $n$  reaches 1, the system is critical, characterized by power laws in the distribution of group sizes impregnated by a given change. For  $n > 1$ , the network is super-critical as local changes have a finite probability to propagate and invade the entire network. The regime  $n \geq 1$  is the one of interest for marketing campaigns, for policy targets, more generally, for any action that aims at a maximum impact with a minimal cost. Typically, an external input of amplitude  $S$  is amplified by the network effect of word-of-mouth epidemics by the factor  $1/(1 - n)$  (for  $n < 1$ ), suggesting that policy making and marketing campaigns should not only optimize their action  $S$  but also target mature and receptive networks characterized by a branching ratio close to, equal to or even larger than 1.

These ideas and quantitative results are relevant to social unrest shocks, internal downloads, dialog in email traffic, the dynamics of commercial sale in response to advertisement or to word-of-mouth, volatility clustering and shocks in financial markets, dynamics of exploits and patches following disclosures of software vulnerability, movie blockbusters, the dynamics of YouTube video sharing, and so on.

## 2.3 A conjecture on Happiness

Recent works by Kahneman and others show that humans have a kind of reference point for happiness [Reichhardt, 2006]. This reference point may be different from one human being to the next. From two kinds of interviews, researchers have documented that humans are subjected to burst of happiness or despair which then relax after some time to their previous happiness level, similar to the relaxation of the response function due to an exogenous shock. Someone who gains a big lottery or someone who suffers a major accident leading to paralysis for instance will have a large instantaneous perturbation in their level of happiness, but remarkably both will return after some time and some adjustment to basically their previous level of happiness.

This suggests that happiness and well-being in humans can be approached by the generic endo-exo approach outlined in the previous section. The guideline offered by this insight is

that we need to understand what are the individual, cultural and societal variables that may control the “criticality” parameter  $n$  of our response to the incessant flux bathing our life, so that, under a constant background of “happiness sources”  $S$ , the overall happiness level is amplified to  $S/(1-n)$  by internal and social cascades. This suggests to emphasize the policy impact on  $n$  (our internal state) more than on  $S$ , the external sources of improvements.

## 3 Bubbles everywhere

### 3.1 Breakdown of “Galilean invariance principle” in human psychology

I propose the idea that the collective dynamics of human affairs exhibit a breakdown of “Galilean invariance principle”. In physics, Galilean Invariance is a principle of relativity which states that the fundamental laws of physics are the same in all inertial frames. Its direct consequence is that deviations of a body from constant velocity can only occur upon the application of a force. The analogy is that constant velocity or rate of change is boring to human beings, who tend to act to develop intermittent accelerating outcomes. As a consequence of their individual actions aggregated at the collective level, one can observe super-exponential acceleration of their processes punctuated by corrections and crashes. I take as evidence of this the example of stock market bubbles and crashes. The perhaps most striking illustration is the market of Hong Kong, arguably until 1997 the freer market in the world with complete flexibility in the mobility of capital and its investment use. While the Hang Seng Hong Kong index from 1979 to 1997 is characterized by an approximately constant annual return of 14%, this average return is a very poor description of what was actually occurring in the market: either it was super-exponential accelerating, or it was crashing. This observation has been described and generalized to many bubbles and crashes in different parts of the world and at many epochs [see Sornette, 2003a,b and references therein].

The underlying mechanism involves positive feedbacks on prices, i.e., to the fact that, conditioned on the observation that the market has recently moved up (respectively down), this makes it more probable to keep it moving up (respectively down) in an amplified move, so that a large cumulative move ensues. The concept of “positive feedbacks” has a long history in economics and is related to the idea of “increasing returns”— which says that goods become cheaper the more of them are produced (and the closely related idea that some products, like fax machines, become more useful the more people use them). “Positive feedback” is the opposite of “negative feedback”, a concept well-known for instance in population dynamics: the larger the population of rabbits in a valley, the less they have grass per rabbit. If the population grows too much, they will eventually starve, slowing down their reproduction rate which thus reduces their population at a later time. Thus negative feedback means that the higher the population, the slower the growth rate, leading to a spontaneous regulation of the population size; negative feedbacks thus tend to regulate growth towards an equilibrium.

In contrast, positive feedback asserts that the higher the price or the price return in the recent past, the higher will be the price growth in the future. Positive feedbacks, when unchecked, can produce runaways until the deviation from equilibrium is so large that other

effects can be abruptly triggered and lead to rupture or crashes. The positive feedback leads to speculative trends which may dominate over fundamental beliefs and which make the system increasingly susceptible to any exogenous shock, thus eventually precipitating a crash. There are many mechanisms in the stock market and in the behavior of investors which may lead to positive feedbacks. They can be roughly divided into two classes.

- Technical and rational mechanisms for positive feedbacks:
  1. option hedging,
  2. insurance portfolio strategies,
  3. trend following investment strategies,
  4. asymmetric information on hedging strategies.
  
- Behavioral mechanism for positive feedbacks based on imitation:
  1. it is rational to imitate,
  2. imitation is the highest cognitive task,
  3. we mostly learn by imitation,
  4. cultural imitation and “conventions.”

Sornette [2003a,b] present detailed documentation and arguments emphasizing the positive feedbacks by imitation, which is also known as the “herd” or “crowd” effect.

### **3.2 Positive effect of ubiquitous “bubbles” in human affairs**

I propose to generalize the observation that financial markets exhibit alternating regimes of over-enthusiasm leading to bubbles followed by phases of consolidation, bearish trends or even crashes. In finance and economics, the term “bubble” refers to a situation in which excessive public expectations of future price increases cause prices to be temporarily elevated without justification from fundamental valuation. I extend this definition to human affairs as follows.

*Definition of a “bubble” in human affairs:* a “bubble” occurs when excessive public/political expectations of positive outcomes cause over-enthusiasm and unreasonable investment and efforts.

During bubbles, people take inordinate risks that would not otherwise be justified by standard cost-benefit and portfolio analysis. Instead, people rationalize their risk-taking behavior by new models of net-present-value, such as witnessed during the new economy bubbles of IT and Internet companies that culminated in 2000: the new accounting method over-emphasized the “real option” value of companies associated with the new niches that they were opening. I want to emphasize the role of bubbles in human affairs because they seem inherently associated with the innovation process and the creation of new technology. Bubbles lead to a lot of destruction of value but also to the exploration and discovery of exceptional niches. Only during these times do people dare explore new opportunities, many of them unreasonable and hopeless, with rare emergences of great lucky outcomes. This is the wild risk regime of extremely heavy tails in the distribution of economic returns on investments. I envision this mechanism as the leading one controlling the appearance of



disruptive innovations and major advances. In a word, bubbles (collective over-enthusiasm) seem a necessary evil to foster our collective attitude towards risk taking and break the stalemate of society resulting from its tendency towards risk avoidance. Bubbles are times of self-organized self-excited auto-catalytic amplification of risks that allow the exploration of new niches. I contend that society needs bubbles because the bubbles lead to a very risky behavior that lead to great potential returns. In absence of bubble psychology, no large risks are taken and no large return can derive leading to stagnation.

To illustrate this hypothesis, many examples can be put forward. Here, I discuss briefly only a few salient cases.

- **Great boom of railway shares in Britain in the 1840s.** Consider the great boom in railway shares in Britain in the 1840s. The boom and collapse not only depleted the wealth of many individuals, but cut briefly into the capital available for normal trade and finance. The overbuilding of railroads meant that few could earn back a return commensurate with the capital put into them.

Yet, Britain ended up with an extensive railway system ahead of other industrializing nations. Even if the building was done inefficiently, the gains to the economy were rather large.

- **Appolo program.** On the fifth flight, Appolo 11 landed on the moon, July 20, 1969; Armstrong and Aldrin became the first humans to land and walk, at an estimated cost of 20 to 25 billion (of 1969 US dollars). At this time, what were the anticipations for the following 30 years, at the horizon of the new millenia? Great expectations included to put the Moon and Mars in “mankind’s sphere of economic influence” (to use a phrase later chiseled by Presidential Science Advisor Jack Marburger). In the late 1960s, it was thought that permanent bases on the Moon would be routinely operated and that mankind would have already landed on Mars and beyond.

What is the state of space exploration and conquest in 2007? Would mankind be able to land again on the Moon and at what cost? Personally, as a teenager at the time of the historical landing who has become a grown-up over these more than 30 years, and as a scientist having contributed to space science [Anifrani et al., 1995; 1999; Maveyraud et al., 2001; Le Floc’h and Sornette, 2003], I find the present situation on space exploration quite disappointing and depressing. It is clear that the expectations have been unfulfilled and that there are still major obstacles to overcome: protection of humans from cosmic rays, medical problems appearing in absence of gravity, reliability of spacecrafts, propulsion efficiency to cite a few.

It is clear that, as vividly expressed by NASA administrator Michael Griffin [2007], space exploration is perhaps the best incarnation of the “real reasons” for taking risks in unreasonable (to standard cost/benefit analysis) endeavors. The “real reasons” that go beyond reason perhaps help define human beings. They include the enthusiasm for new things, the wonder and awe of discoveries, the challenges of competition, the taking of hard challenges... for the sake of the challenge.

- **Human Genome project.** “The ultimate goal of this initiative is to understand the human genome” (US Department of Energy, 1984, 1986). A ‘rough draft’ of the genome was finished in 2000 (announced jointly by then US president Bill Clinton and

British Prime Minister Tony Blair on June 26, 2000). May 2006: sequence of the last chromosome for a total estimated cost of \$3 billion. The claims was/is that knowing the sequence of the genes would open immediately the door to great discoveries in medicine.

However, for any reasonable scientist acquainted with complex systems (and the human body and its immune system in particular are clearly very complex systems by all definitions of the term), it was clear that this was completely oversold: knowing the sequence of letters in a text without knowing the language brings little and the major obstacles remain, which is that of understanding the text. This involves many many-body problems (since hundreds to thousands genes act often in concert and each may have several actions in multitude of diseases and expressions). But this “bubble” or enthusiasm on genomics has served its goal of promoting a branch of research. This bubble led to huge investments, huge risks were taken, and little return has occurred in most of the investment, except for some niches. It is interesting to read the statements of the community in the post-bubble era, emphasizing that decades are needed to really exploit the data.

- **Dolly the Sheep (July 5, 1996 February 14, 2003).** “Suspendous” and “mind-boggling” were just two reactions to the birth of Dolly, the first mammal cloned from an adult cell. Suddenly, the idea of herds of identical prize bulls, or sheep producing medicines for humans in their milk, seemed wholly plausible. Then there was therapeutic cloning, which would provide genetically matched human tissue to patch up even the most seriously ill patient...

A New Scientist article in 2006 [Aldhous and Coghlan, 2006] states: “Much of the excitement surrounding the creation of the first animal clone has vanished and therapeutic cloning is in the doldrums. But her influence should not be downplayed...”

A report in Nature [Check, 2007] confirms: “...these advances haven’t led to big improvements in the cloning process, or yielded huge commercial payoffs.”

- **The IT and Internet bubble until March 2000.** The so-called “new economy” bubble on information technology and the internet has been associated with huge investments (and big losses) on the IT sector. Few of the “dot-com” companies into which investors have poured billions of dollars of capital have lived to pay them an adequate return. Many companies have died but a few have survived and some have become giants (Yahoo, Google,...).

The world has also set the pace on trying out new Internet business models, and presumably will benefit enormously from the experience gained by the tens of thousands of engineers, entrepreneurs, and web designers who have acquired human capital in a new industry. Thus again, a bubble has left many “dead” but a few great innovations emerged, with the accumulation of new human capital.

I am sure many other examples will jump to the mind of the reader, that would warrant a detailed discussion.

## 4 Illusion of control

Human beings like to believe they are in control of their destiny. This ubiquitous trait seems to increase motivation and persistence, and is probably evolutionarily adaptive. The success of science and technology, with the development of ever more sophisticated computerized integrated sensors in the biological, environmental and social sciences, illustrate the quest for control as a universal endeavor. The exercise of governmental authority, the managing of the economy, the regulation of financial markets, the management of corporations, and the attempt to master natural resources, control natural forces and influence environmental factors all arise from this quest.

Langer [1975]’s phrase, “illusion of control” describes the fact that individuals appear hard-wired to over-attribute success to skill, and to underestimate the role of chance, when both are in fact present. Whether control is genuine or merely perceived is a prevalent question in psychological theories. Outcomes, especially when they are the result of aggregations of individual optimization processes. But how good really is our ability to control? How successful is our track record in these areas? There is little understanding of when and under what circumstances we may over-estimate or even lose our ability to control and optimize

Satinover and Sornette [2007a,b] have demonstrated analytically using the theory of Markov Chains and by numerical simulations in two classes of games, the Minority game and the Parrondo Games, that agents who optimize their strategy based on past information actually perform worse than non-optimizing agents. In other words, low-entropy (more informative) strategies under-perform high-entropy (or random) strategies. This provides a precise definition of the illusion of control in set-ups a priori defined to emphasize the importance of optimization

Our robust message is that, under bounded rationality, the simple (large-entropy) strategies are often to be preferred over more complex elaborated (low-entropy) strategies. This is a message that should appeal to managers and practitioners, who are well-aware in their everyday practice that simple solutions are preferable to complex ones, in the presence of the ubiquitous uncertainty. More examples should be easy to find. For instance, control algorithms, which employ optimal parameter estimation based on past observations, have been shown to generate broad power law distributions of fluctuations and of their corresponding corrections in the control process, suggesting that, in certain situations, uncertainty and risk may be amplified by optimal control. In the same spirit, more quality control in code development often decreases the overall quality which itself spurs more quality control leading to a vicious circle. In finance, there are many studies suggesting that most fund managers perform worse than random and strong evidence that over-trading leads to anomalously large financial volatility. Let us also mention the interesting experiments in which optimizing humans are found to perform worse than rats [Grandin and Johnson, 2004]. We conjecture that the illusion-of-control effect should be widespread in many strategic and optimization games and perhaps in many real life situations. This puts the question at a quantitative level so that it can be studied rigorously to help formulate better strategies and tools for management and policy, which take into account the intrinsic limitations of control in complex set-ups with feedbacks.

## 5 Concluding remarks

I have tried here to weave an outline of how the science of complexity, which include evidence from both the natural and the social sciences, may help in policy decision making. In this journey, as can be expected, we find more questions than answers, more puzzles than solutions, more challenges than settlements.

Several other important ingredients have been left out. For instance, recent research in cognitive sciences and in anthropology suggest that human beings are made to interact with no more than about 150 other humans [Dunbar, 1998], otherwise conflicts arise and fragmentation follows. Actually, carefully studies of human groups show the existence of a delicate hierarchy of natural group sizes [Zhou et al., 2005], that may be a result of evolution. This suggests that the coordination of human activities in large modern society needs to recognize this essential cognitive limitation probably deeply rooted in our emotional and rational brain.

Another ingredient which in my mind needs to be incorporated in a science-based approach to policy decision making is the context-dependent, cultural as well as evolutionary control of human cooperation, based on the existence of feedbacks such a reward and punishments [Fehr and Fischbacher, 2003; Darcet and Sornette, 2006]. The fundamental question here is to identify the springs at the origin of cooperation and the elements (structural and dynamical) that may hinder or destroy it.

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