Statistical Mechanics of Risk, Utility and Equilibrium; Analogies between Economics and Statistical Physics

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Abstract

Much has been made of the extent to which mainstream economics is founded on analogies with equilibrium concepts in physics. I argue that more fruitful analogies can be found with current ideas in non-equilibrium statistical mechanics. I begin by discussing *risk* in connection with rare events with large consequences, and relate it to the concept of *extensivity.* I then move on to a discussion of *additivity*, and the extent to which aggregate quantities are meaningful and the assumption of neoclassical economics that assets can be *substituted* and related to a single one dimensional measure. Next I move on to the concept or *utility* and *money* in the context of state *vs.* process variables of thermodynamics. Much of the rest of the paper is concerned with exploring differences between *equilibrium* and *non-equilibrium* statistical mechanics. The absence of extremum properties in the latter gives rise serious stability concerns, unlike the situation in equilibrium theory where extremum properties guarantees stability. I also explore the issue "illusion of control" which arises in multiagent systems where agents have minds of their own, but has no analogy in simulations of physical systems of atoms and molecules. Finally I discuss the concepts of *irreversibility* which can be ignored in equilibrium and *dissipative structures* which appears far from equilibrium.

1 Introduction

History has shown that ideas from very disparate fields of knowledge often cross fertilize, and the relationship between physics and economics is no exception. On some occasions ideas from economics predates the appearance of similar ideas in physics. For example Louis Bachelier developed a theory of market fluctuations, incorporating what is now known largely as Wiener processes, a few years before Einstein's 1905 theory of Brownian motion. Later the theory was cleaned up mathematically by Norbert Wiener and eventually led to the Black-Scholes theory and hedge funds. Often satirists and poets see concepts way before they are discovered by scientists in either field. An example is Jonathan Swift and the idea of fractals[1]. This idea was picked up by Vilfredo Pareto in his theory that the income distribution of the elite is scale free, following a universal power law independent of the political system[2]. Scale free here means that no matter where you are within the hierarchy there will be people above you that you can envy and people below which are less successful. Benoit Mandelbrot developed the ideas of fractals much further, both in economics and in the physical sciences. The idea of *scaling* dominated statistical physics in the late 1960's and the 1970's. Subsequently the physics community has come to a growing realization that a ramified hierarchical structure, first established with the taxonomic tree of of Linneus, is a general feature of evolving driven systems, and can be found in such diverse areas as Darwinian evolution, the internet and the world wide web, markets, and seismic fault zones to name a few (for general discussions see, Barabási [3], Bak [4]). Historically, neoclassical economics has borrowed many ideas from equilibrium thermodynamics, and by concentrating on the key concepts of risk, value, extensivity, equilibrium, irreversibility and dimensionality (the possibility of scarce resource substitution) I will argue that most of the resulting analogies are misleading. Better analogies can be found in modern non-equilibrium statistical mechanics.

[1] "So Nat'ralists observe, a Flea Hath smaller Fleas that on him prey, And these have smaller Fleas to bit'em, And so proceed ad infinitum".

[2] The income distribution for the majority, who are not members of the elite, is not scale free. To a reasonable approximation it can be described by a log-normal distribution with two parameters describing the mean and variance of the logarithm of the income [1]. Econophysicists who try to model this distribution often confuse income with wealth. Inequality is even more pronounced for wealth than for income[2], since people with low incomes often accumulate debt rather than savings. Savings for retirement represents a large fraction of this wealth. Unfortunately, since it is reported differently depending on whether it is stored in public or private funds, or pensions paid from general revenue, comparison between the wealth distribution in different societies is difficult.

In section 2 I discuss, in the context of rare events with large consequences, crucial differences between extensive and non-extensive systems. Extensive system share common properties with ordinary matter, while non-extensive systems typically have a hierarchical structure. In particular connections are made between non-extensivity and aspects of *behavioral finance*, notably *prospect theory*. It is found that behavior, which is commonly explained away in terms of bounded rationality becomes less irrational when seen from the perspectives of different rungs in the hierarchy.

In section 3 I caution against the reliance in conventional economic theory on aggregate quantities such as GDP and indexes, and contrast this approach with the multidimensional approach of ecological economists, and other areas of science where it is generally accepted that quantities of different physical dimension should not be added.

Section 4 argues that conventional economic theory fails to appreciate the subtlety of the first law of thermodynamics in attempts to find an analogy with thermodynamics and equilibrium theories of economics. Consequences for theories of utility and money are explored.

Section 5 is concerned with the concept of equilibrium in physics and economics. I argue that if on the economics of production is incorporated into the theory, equilibrium theory is not applicable. The consequences are many and serious.

2 Risk and additivity

Our ability to make informed decisions is limited by uncertainties [5]. Nevertheless, in order to make any kind of quantitative analysis it is necessary to have a measure of *value* associated with possible outcomes and an estimate their *likelihood*.

The simplest approach is to attach a monetary value $m(r)$ to each possible result r. If the probability of r is $p(r)$ the expected loss or profit is commonly taken to be the *mean*[3]

$$\langle m \rangle = \sum_r p(r)m(r) \tag{1}$$

Similarly, *ensemble averages* such as (1) are fundamental to statistical physics. The field of probability theory owes much of its early development to Daniel Bernoulli who analyzed games of chance using this type of analysis. However, he realized early on that (1) is not an adequate measure when rare

[3]I use the physics notation $\langle\rangle$ rather than the notation $E(m)$ to indicate expected value.

events with large payoffs are involved. To make the point the Bernouilli brothers invented the *St. Petersburg game* in which a fair coin is tossed until the outcome is "tails". If this occurs at the $r'th$ throw the player receives 2^r ducats. The probability of this payoff is 2^{-r} and it is easy to see that the expected outcome from (1) is infinite. Clearly there is a limit (typically of the order 10-20 ducats) that a reasonable person can be expected to pay in order to play the game once only. Daniel Bernoulli attempted to resolve the difficulty by introducing the concept of *utility* $u(m)$. The expected utility is then

$$\langle u \rangle = \sum_r p(r)u(m(r)) \tag{2}$$

If $u(m)$ is *concave* ($\partial^2 u/\partial m^2 < 0$) the player is *risk adverse*, while if $u(m)$ is *convex* the player is *risk seeking*. A risk adverse person would then associate a reduced value to rare events with high payoff.[4]

The association of risk aversion with saturation of the player's greed is too *ad hoc* to be satisfactory, and Nicolas Bernouilli [6] instead attempted to resolve the problem by downplaying the significance of very rare events. He suggested that players made their decision based on a subjective probability, which gives zero weight to very unlikely events. This explanation was not generally accepted until recently when the approach was made systematic with the *prospect theory* of Kahneman and Tversky [7, 9, 8]. The St. Petersburg game has been analyzed from the point of view of prospect theory by Rieger and Wang [10]. Prospect theory is put in the more general context of behavioral finance in a a comprehensive and readable form by Barberis and Thaler [11]. In its simplest form prospect theory associates the expected *value* associated with the probability distribution $p(r)$ with

$$\langle v \rangle = \sum_r m(r)w(p(r)) \tag{3}$$

shifting the nonlinearity from the value of the outcome to the significance of the probability (which typically depends on the context. Also probabilities of loss and gains are perceived differently[5]). Of course, one could in principle

[4] A commonly used utility function, actually suggested by Bernouilli, is $u = \ln m$ For the Petersburg game

$$\langle u \rangle = \sum_{r=1}^{\infty} \frac{r \ln 2}{2^r} = \ln 4$$

i.e. this player should be willing to pay 4 ducats to play the game *once*. Most people would probably be willing to pay a bit more.

[5] A possible choice for (3) would be the normalized q-expectation value with $w(p) = p^q / \sum p^q$, with $q > 1$ for risk adverse players, *e.g.* for $q = 1.5$ the game is worth 4.41 ducats.

consider nonlinearities in both the utility of the monetary outcome and the weight of the probability (as was done in [12]).

As pointed out by Anteneodo and Tsallis [13] there is a close analogy between prospect theory and non-extensive statistical mechanics[6].

In most applications of thermodynamics and statistical mechanics there is an implicit assumption of *extensivity*. Thermodynamic quantities such as the energy, E, volume, V, entropy, S, are under this assumption proportional to the number of particles in the system, N, and are called *extensive*. Other quantities such as the temperature, T, pressure, P and chemical potential, μ are independent of system size if the system is large, and are called *intensive*.

The assumption of extensivity has been referred to as the *law of the existence of matter*. In a remarkable *tour de force* Lebowitz and Lieb [16] were able to prove extensivity in systems of particles interacting with long range Coulomb forces, when there are equal numbers of positively and negatively charged particles present. A consequence is that in ordinary matter the local environment on the microscopic scale is the same no matter if the object weighs 1 g, 1 kg or 1 ton. Economic systems are not extensive, mainly because their ramified structure. The economy of a rural community, a small town and a big city are qualitatively very different. The frequent occurrences of mergers, spin-offs and outsourcing in modern economies are evidence of large economies and diseconomies of scale [17].

Important examples of violation of extensivity in physics are systems such as planets, suns and galaxies held together by the law of gravity. The energy per particle in such a system grows with the number of particles. The total energy is thus a nonlinear function of system size, and if one attempts to compute the gravitational potential energy of an astronomical object by adding the energies of the constituent particles one obtains the wrong result. The assumption of extensivity in neoclassical economics is perhaps best illustrated by Margaret Thatcher's famous statement "...there is no such thing as society. There are individual men and women, and there are families"[18] .

In the case of probability distributions extensivity requires that the expected average outcome of a number of realizations would be independent of the number. The Petersburg game violates this requirement, the average over a number of realizations will typically grow with the number of times the game is played. Hence, while a "rational" individual may not wish to

[6]The seminal paper by Tsallis [14] took a rather long time to gain recognition, but there is now a very large literature on the subject. A useful bibliography can be found at http://tsallis.cat.cbpf.br/biblio.htm. A recent issue of Europhysics News reviews applications of non-extensive statistical in many different areas of research [15].

pay more than 10-20 ducats to play the game once, for a croupier, who accepts bets from many players, any prize is too low[7].

Non-linear probability expectations are a common cause of conflicts between the interests of individuals and their society. Since life may be short anyway, an individual may find it worth the risk not to wear a bicycle helmet or seat belt when moving around, and even take an extra drink before driving home from the pub. The incurred expenses to society makes such risky behavior highly undesirable. Consequently society tends to impose penalties on the individual for offending behavior, in order to make the interests of the individual and society coincide. Of course it would be nicer if one could use carrots instead of sticks to motivate the individual (for a useful review of of the literature on this problem see [19, 20]).

Non-linear probability expectations represent a distinct problem from that of *externalities* in economic theory (externalities occur when transactions give rise to costs or benefits to third parties). Both phenomena have a common origin in the non-extensivity of economic systems. Also,value judgments in non-extensive systems may be ambiguous since they generally will depend on perspective. E.g. if I own a piece of land I may wish to do things to which my neighbors object, while a higher level of government may in turn accuse my neighbors of NIMBYism.

3 Aggregates, dimensionality and ability to substitute

Aggregate economic quantities such as gross domestic product are misleading if economic properties are non-additive. This objection is not unrelated to objections against the GDP (gross domestic product) raised by the economist Marilyn Waring [21]. She argues that the concept of GDP is seriously flawed because of the failure to include important economic contributions from subsistence farming, unpaid house work, care giving and volunteering. Nor are depreciations of natural resources and environmental

[7]In the case of expected utility theory (2) with $u(m) = \ln(m)$ playing the game twice is worth $\sum_r \sum_s (\ln(2^r + 2^s)2^{-r}2^{-s} = \ln(9.63)$. 9.63 ducats is more than twice the value of playing it once. In the case of the normalized q-expectation value in (3) playing twice is worth exactly twice the amount it is worth playing once. In the case of the prospect theory of Kahneman and Tversky there is the additional complication that although the player's gain is the croupier's loss, gains and losses are evaluated differently. They also stress the importance of *framing*, which depends on the the current situation. The value of playing the game a second time will thus depend on the whether the first outcome is known.

values included in a meaningful way, although the associated values are vital for the maintenance of the fabric of society. In the introduction to the second edition of her book[21] Waring reports on attempts to improve the situation by assigning a monetary value to these assets. But, as she points out, it makes little sense to add the money made by the arms manufacturer and drug pusher to the value of the work of the daughter who takes care of her Alzheimer parent. Similarly, a species which becomes extinct remains extinct, while business losses can be replaced. Numerous attempts have been to produce indexes that correct for the bias inherent in the GDP. An example is the human development index promoted the United Nations. Unfortunately, it seems impossible to find an objective single index. Indeed, competing indexes that claim to take into account sustainability issues produce divergent results [22]. The problem is that converting assets to a single variable such as money or an index implicitly assumes that assets can be substituted. Ecology teaches us that this is not the case, just as nutritionists stress the importance of consuming food from the different food groups, and that we need to worry about trace elements and vitamins. Recently ecological economists have been thinking in terms of multidimensional capital. Common divisions are natural, social, human, physical and financial capital (see *e.g.* [23]).

- *Natural capital* represents the stock of environmental assets such as non-renewable resources, the capacity to generate renewable resources and absorb pollutants.
- *Social capital* constitutes the "glue" that holds society together allowing commonly shared values and civilized behavior.
- *Cultural capital* incorporates traditions and diversity associated with identity and history.
- *Human capital* incorporates accumulated knowledge and skills.
- *Physical capital* incorporates infrastructure equipment and buildings.
- *Financial capital* is what traditional economists and most econophysicists like.

In their book "*Priceless*" Frank Ackerman and Lisa Heinzerling [25] document efforts to put a price on the environmental efforts to save threatened or endangered species through surveys of what it would be worth to each household (an approach referred to as contingent valuation in the economics literature). Apparently it is worth \$216 to the average American household to save bald eagles and \$67 to save gray wolves. Adding it up this would mean that the eagles are worth \$23 billion, but the wolves only \$7 billion. This addition makes no sense, apart from the fact that such surveys are easy to manipulate. There are societal values associated with belonging to a civilized society, which go beyond the sum of individual values, and which are priceless, as suggested by the book title.

4 Utility and money

A fundamental objection to conventional utility theory was made by J. Willard Gibbs, the founder of modern thermodynamics, over a century ago. Mirowski[26] in his book "*More heat than light*" describes the relationship between Gibbs and Irving Fisher, who many people regard as one of the founders of 20th century economics. Gibbs was co-supervisor of Fisher's Ph.D. thesis and chaired his final thesis defense. Fisher based his economic theory on a close analogy with Gibbs theory of equilibrium thermodynamics. *E.g.,* the equilibrium price of a commodity is given by its marginal utility (derivative of the utility with respect to quantity). The thermodynamic analogy is that in equilibrium, at a given temperature, the pressure of a gas is the derivative of the Helmholtz free energy with respect to the volume. Gibbs objected that this identification reflected a poor understanding of the first law of thermodynamics

$$dE = \text{đ}Q - \text{đ}W \tag{4}$$

where E is the *energy*, Q is the *heat* given to the system and W the *work* done by the system. In elementary texts the first law is simply presented as the law of conservation of energy, but it is more subtle than that, as reflected in the different notation for the differential on the right and left hand side of (4). The energy is a *state variable i.e.* it is determined by the state of the system and has an *exact differential*. Q and W are *process variables* and have *inexact differentials*. Knowledge of the state of the system does not allow us to determine its "heat" or "work". Gibbs found it unreasonable to expect the utility to have exact differentials[8], hence the title of Mirowski's book.

[8]To give a trivial example: I may prefer to eat my salad after the main course. Many restaurants prefer to serve the salad before the main course in order to give the customer something to do while waiting for the meal to be prepared. In neither case is the benefit (cost) the sum of the benefits (costs) of the separate items. A related point was made by Bertrand [27] who points out in a scathing review of the work of Walras that if you

An analogous controversy in physics was settled in the mid 19th century. Prior to Joule's demonstration of the mechanical equivalence of heat, many scientists adhered to the Lavoisier *caloric theory* according to which heat was considered to be a fluid that flowed from hot to cold, but could neither be created or destroyed. Gibbs objection then is that marginalist economics is a kind of caloric theory.

According to Mirowski [26] the objections of Gibbs and others were never satisfactorily countered by neoclassical economists. In prospect theory the agents preferences are affected by *framing*, providing reference points. With sequential events this reference point will change in time and choices will depend on the order in which the events take place. As shown by Rieger [12] Nash theorem in game theory is then no longer valid and games no longer need to exhibit Nash equilibria (unlike what happens with expected utility theory). Thus, there will be no "end of history", evolution will keep moving along. A typical case of evolving frames is when we try something cautiously to find out if we like it or not. Depending on the outcome we either plunge in or shy away. Clearly, when it comes to acquired tastes, value and utility will be process and not state variables.

The impossibility of constructing a state dependent utility has important implications, since it restricts on our ability to apply a cost benefit analysis to value judgments[9] [25, 28], and also casts doubt on the usefulness of game theory for economic analysis[10]. Seen as a process variable the value of a human life is the life lived, not the accumulated value of the assets collected at its end. If one's goals are obtaining status, power, influence and respect, process may be more important than outcome. The 2005 Economics prize in memory of Alfred Nobel was given to two game theorists Thomas Schelling and Robert Aumann. Aumann [29] applies game theory within the rigid framework of conventional game theory, in which preferences are set permanently, and the possibility ignored that values and preferences are changing

want to make money buying and selling commodities and equities, timing is everything. Furthermore, the timing of the big players in turn affects the prices. However, marginalist theories assign a fundamental value to the differential of utility on quantity acquired, and requires that at equilibrium it equals the price. What if the concept of *fundamental value* is just an illusion?

[9] Recall the result of the previous section that in expected utility theory the monetary value of playing the Petersburg game twice is not twice the value of playing it once. If the different contributions to a cost benefit analysis do not add up, there is a serious problem.

[10] This objection does not apply to evolutionary game theory which is a *dynamic* theory in which survival and reproduction is related to *fitness*, a much easier concept to define than utility. Rieger [12] has an interesting discussion of how economic game theory can be modified to be compatible with prospect theory.

as a result of the process in repeated games. Schelling, on the other hand seems aware of the role of process. His acceptance speak stresses the role of taboos [30] and that once a taboo is broken an irreversible process is set in motion. Indeed, if utility is a process rather than a state variable, the rational choice model [19] of sociology is also out the window[11] . The severity of the objections will naturally depend on the context. For decisions taken once, or over a short period of time, the problem may not be severe, after all the caloric theory of heat also worked occasionally.

Another quantity which probably need to be considered more as a process than a state variable is *money*. In individual transactions money generally changes hand in well defined amounts while the aggregate quantity *money supply* is a rather murky concept [32]. As the authors of *Evolution, money and war* [33] points out "money in the bank" may not mean much in times of turmoil. Also recent court trials involving large corporations have shown that the balancing of debits and credits is sometimes more of an art than a science.

5 Equilibrium

A concept that often leads to false analogies between statistical mechanics, thermodynamics and economics is that of *equilibrium*. If the properties of a thermodynamic system are independent of time it is said to be in a *steady state*. Only if there are no macroscopic *currents* (*e.g.* flow of heat or particles) can the system be said to be in equilibrium. Equilibrium systems generally are closed systems, or systems in contact with a heat bath in which the pressure and/or temperature and chemical potential are *constant*. Non-equilibrium steady state systems typically involves driven system where external sources of heat, force or matter produce flow of heat or electrical and particle currents. Economics concerns itself with the transformation of natural resources, energy and labor into products and commerce. If there is no throughput there is no economy. From the standpoint of statistical mechanics the concept of economic equilibrium is a complete oxymoron – there can be no such thing. Nevertheless, modern economists often apply equilibrium concepts in which supply meets demand and markets are cleared, perhaps guided by a Walrasian auctioneer or Adam Smith's invisible hand. The chapter in Wealth of Nations, in which the invisible hand is introduced, can be found on the web site associated with [37]. It is noteworthy that the

[11] An important advocate of rational choice theory is Gary Becker, see *e.g.* his 1992 economic Nobel acceptance lecture[31].

context is trade between complementary economies. I find it easy to accept that, when common interests are recognized, it is as if an invisible hand is guiding the participants toward a deal. Problems arise when interests conflict.[12] The auctioneer on the other hand, if he existed, but not fed, would soon experience the fate of his physics cousin the Maxwell demon, and suffer a burnout. Once fed he becomes part of the system and subject to influence by vested interests. In the financial world independent auditors and credit rating agencies are supposed to fulfill a role somewhat analogous to the auctioneer. The failure of even highly reputable ones to do so, as came to light in recent scandals, illustrate the point.

In the 20th century the economics Nobel prize was given mostly to neoclassical economists applying equilibrium theory. It is only in recent years that the Bank of Sweden recognized that something was amiss, with the award of Nobel prizes in economics to the likes of Kahneman (2002), Åkerlöf (2001), Vernon Smith (2002) and Stiglitz (2001) who are more concerned with what actually happens than with what theory and ideology predicts. Considering subsequent prizes it is not clear, however, if this represents a real trend.

One difference between equilibrium and non-equilibrium steady states in physics is that the zeroth law of thermodynamics applies to the former but not to the latter. This law states for thermodynamic "forces" to be balanced the pressure, temperature and chemical potential must be constant at equilibrium. In contrast, in non-equilibrium steady states temperature, pressure and chemical potential gradients may occur. Unbalanced thermodynamic "forces" also occur when the system is driven by seemingly unrelated gradients. This gives rise to a number of important effects such as the thermoelectric effect in which an electromotive force is produced by a temperature difference, the thermomolecular effect in which a temperature difference produces a pressure gradient in a rarefied gas, and the Soret effect in which a temperature gradient tend to segregate components of liquid mixtures. Recently, Smith and Foley [34] attempted a modern justification of Irving Fisher's analogy between Gibbs thermodynamics and economics. In such theories the analogy of average wealth is the temperature [35]. A clear consequence is that if agents are free to choose, prices for the same commodity should not vary within the system. This is contrary to everyday experience, every serious shopper knows that the same groceries tend to have different prices in stores that cater mainly to wealthy or poor customers,

[12] Also note that with his pin factory model Adam Smith disputes the upwards slope of the supply curve needed to provide stability in the balance between supply and demand.

somewhat in analogy with the thermomolecular effect. On the macro scale when comparisons are made of wealth in different economies these are usually carried out at purchasing power parity (ppp) not at the actual exchange rates. The weekly "The Economist" applies a "Big Mac Index" in order to determine if a currency is over- or under-valued. This analysis is partially, but not completely, tongue in cheek. But, as anyone who has given more than a casual glance at the business section of newspapers would know, the proper value of currencies is often in dispute. One problem with ppp is that shoppers tend to have different baskets depending on whether they are rich or poor [36]. It is not too difficult to think of analogies to the thermoelectric effect (migration?) or the Soret effect (ghetto formation?).

Another, perhaps more important difference between equilibrium states and non-equilibrium steady states is how the system responds when disturbed. Equilibrium systems satisfy variational principles, typically the entropy is maximized, subject to constraints, or the appropriate free energy is minimized. If such a system is weakly disturbed the system will move towards equilibrium, and stability is generally assured by the variational property. Similarly, economic calculations in general equilibrium theory are treated as constrained optimization problems in which the question of stability need not be addressed. These types of variational principles are generally not available in non-equilibrium steady states, while in economics the absence of an unambiguous choice as to what is optimized allows the analysts to bias the result in favor of their master's interests.

In non-equilibrium theories stability issues are a major concern. Interestingly, when dynamics is introduced into neoclassical models instabilities and inconsistencies [37] pop up yielding untold riches to the connoisseurs of market foibles [38]. Typically, what happens in driven physical systems is that, when forcing is increased, *dissipative structures* appear[13]. *E.g.*, when sunlight reaches the earth more heat is absorbed at the surface than in the atmosphere. The air near the surface then becomes warmer than the air above. Since warm air is lighter than heavy air convective instabilities develop, which when combined with Coriolis forces gives rise to vortices, which may develop into storms. At certain latitudes these storms sometimes dissipate into devastating hurricanes. A much studied system is flow of water in pipes. At low flow velocities in small diameter pipes the flow is laminar, while turbulence suddenly appears at higher flow rates. The critical flow

[13] Ilya Prigogine obtained the Nobel Prize in chemistry in 1977 for his contributions to the theory of dissipative structures. This was one of the more controversial awards, but the importance of the concept cannot be denied.

rate depends on the *Reynolds number*

$$Re = \frac{\rho u d}{\eta} \tag{5}$$

where ρ is the fluid density, u the flow velocity, d the diameter of the pipe and η the viscosity of the fluid. The critical number is sensitive to the roughness of the pipe and external noise. Typically the critical number is around 1000, but with extreme care clever experimenters can bring it up to 100 000. Ghashghaie *et. al.* [39] showed that there is a close statistical similarity between turbulent Kolmogorov cascades and exchange rate fluctuations, although Arnéodo *et. al.* [40] warned that the two phenomena differed in fundamental aspects. Is it unreasonable to expect that in an economy a too strong driving force in the form of changing technology and trading pattern, rapid population growth, economic inequality, climate change and unsustainable resource use, can set up dissipative structures in the form of wars, sectarian conflicts and market bubbles and crashes[14]? In conventional economics such phenomena are dismissed as exogenous shocks. If one admits that the shocks are endogenous, once an instability occurs (or as Schelling puts it a taboo is broken) what happens next may still be impossible to predict. However, it may be possible to predict that an unstable situation is approaching. Whether events are endogenous or exogenous also matter when assigning blame when something bad happens. Market bubbles [47] and crashes are often blamed on "noisy traders" and uninformed herd mentality, although rational predators who target the noisy traders also muddy the water [48]. Presumably if all market players were trained economists everything would go smoothly. If, on the other hand, the system is intrinsically unstable, it is useless to blame the victims. The psycholgist Ellen Langer coined the phrase *illusion of control* [41] to describe situations in which people attribute personal success to skill when they were just lucky. *E.g.* most people think of themselves as better than average drivers, and often attribute chance success to "skill". Satinover and Sornette [42] used the concept to describe observed behavior in the *minority* and *Parrendo* games while De Bondt and Thaler [43] showed that financial analysts are prone attributing skill to lucky events and bad luck to mistakes.

An important consequence of the assumption that the onset of turbulence

[14]Possible candidates for such structures are the log-periodic oscillations that sometimes are seen as precursors of major events in market crashes [44], rupture of gas cylinders under high pressure [45] and major earthquakes [46]. These oscillations are associated with ramified structures in which the failure threshold differs at different levels in the hierarchy.

depends on the Reynolds number (5) is that the critical flow velocity depends on system size -if the diameter of the pipe doubles the critical flow velocity is halved. Similarly an increase in mass density (inertia) and a decrease in viscosity (friction) reduces the stability region for laminar flow. Do we expect a system size dependence for market instabilities? If so, this should be a matter of concern in times of increasing globalization (Some recent examples of work which raise this concern are [49, 17]). Is there an analogy between viscosity and transaction cost, regulations and red tape? or between inertia and increasing dependence on intangibles in asset evaluation[15] [50]?

A more subtle, but equally important difference between equilibrium and non equilibrium systems is the role of fluctuations. In equilibrium they are (except for isolated *critical* points in parameter space) Gaussian, large deviations from equilibrium are very rare and fluctuations do not give rise to macroscopic currents and there is no *arrow of time*. If a film is made of a series of fluctuating events and the film is afterward run backwards, an observer will be unable to tell the difference. In contrast, fluctuations in non-equilibrium system frequently have a *rectifying* effect, providing a sense of direction. All living things have a *metabolism* that allow bacteria to swim and eukariotic cells to transport vital chemicals on filaments in the cell. Similarly, the mycelium of mycorrhizal funghi transport useful chemicals which the funghi trade with trees and plants in the forest. Physicists try to model these phenomena through Brownian ratchets [51]. Recently the concept of Brownian ratchets have been extended to situations of economic interest in *Parrondo games* [52] in which two loosing strategies when combined result in a winning game. Of particular interest is the collective Parrondo game in which a large number of players vote to reach a common decision on one of two strategies although their interests diverge. No matter whether one votes according to ones own selfish interest [54] or for what is the best outcome for the collective [53], it is a losing game. But, if the decision is made randomly it is a winning game. Seen in an economic context the paradox is easy to resolve. If the two strategies are profit taking and reinvesting, choosing only one of them is a losing proposition over time, but if combined the situation may be sustainable. On the other hand, if only short term interest is the basis for strategy selection, the result is ruin.

[15] It is generally accepted that the invention of the steam engine played a pivotal role in the industrial revolution. For the engine to work Watts needed the centrifugal governor. As the demand for more powerful engines grew, the mass of the flywheel was increased, and the friction of the shaft was reduced, with ensuing deleterious effects on the stability of the device. The need to solve this problem was important in the development of modern control engineering.

6 Conclusion

As could be expected there has been criticism of equilibrium theory from many sources in the economics literature (see e.g. Ackerman [55] and references therein). A physicist reader perplexed by the economics literature will find the book by Keen [37] invaluable, as well his warning to the econophysics community [56]. Some of the points raised by me can also be found in the work of McCauley [57]. The analogies used by classical and neoclassical economists with physics are often pointed out. Sometimes the question is asked "why does something that works so well in physics not work in economics?". The purpose of the present note has been to point out that this type of theory does not work so well in physics either. But, the history of the natural sciences is full of examples that the discarding of useless concepts carry much benefit and little cost. In many ways the lack of concern with dynamics makes the general equilibrium theory of economics like meteorology without the weather. The misery of hurricanes for the affected people is abated, when they contemplate evacuating in front of an approaching storm, if they don't need to base their decision on forecasts based on general equilibrium theory. I find it disconcerting that as late as 2006 in "The Economist" [58] a prominent place was given to a special report describing large scale computer modeling using Walrasian general equilibrium theory to attack important macroeconomic problems.

Since economics impinges on so many other fields and on everyday living experience it is only natural to try to find analogies outside economics proper.

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