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INTRODUCTION

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> "Economic theorists, like French chefs in regard to food, have developed stylized models whose ingredients are limited by some unwritten rules. Just as traditional French cooking does not use seaweed or raw fish, so neoclassical models do not make assumptions derived from psychology, anthropology, or sociology. I disagree with any rules that limit the nature of the ingredients in economic models." – George A. Akerlof, *An Economic Theorist's Book of Tales* (1984)

Over the past couple of decades, a large number of physicists have started exploring problems which fall in the domain of economic science. The common themes that are addressed by the research of most of these groups have resulted in coining a new term "Econophysics" as a collective name for this venture. Bringing together the techniques of statistical physics and nonlinear dynamics to study complex systems with the ability to analyze large volumes of data with sophisticated statistical techniques, the discoveries made in this field has already attracted the attention of mainstream physicists and economists. While still somewhat controversial, it provides a promising alternative to (and more empirically-based foundation for the study of economic phenomena than) the mainstream axiom-based mathematical economic theory.

Physicists have long had a tradition of moving to other fields of scientific enquiry and have helped bring about paradigm shifts in the way research is carried out in those areas. Possibly the most well-known example in recent times is that of the birth of molecular biology in the 1950s and 60s, when pioneers such as Schrodinger (through his book *What is Life?*) inspired physicists such as Max Delbruck and Francis Crick to move into biology with spectacularly successful results. However, one can argue that physicists are often successful in areas outside physics because of the broad-based general nature of a physicist's training, rather than the applicability of physical principles as such in those areas. The large influx of physicists since the late 1990s into topics which had traditionally been the domain of economists and sociologists

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have raised the question: does physics really have some significant insights for these areas? Or, is it a mere fad, driven by the availability of large quantities of economic data which are amenable to the kind of analysis techniques that physicists are familiar with?

The coining of new terms such as econophysics and sociophysics (along the lines of biophysics and geophysics) have hinted that many physicists do believe that physics has a novel perspective to contribute to the traditional way of doing economics. Others, including the majority of mainstream economists, have been dismissive until very recently of the claim that physics can have something significant to contribute to the field, which is seen by them to be primarily a study of interactions between rational agents, able to formulate complex strategies to maximize their individual utilities (or welfare).

However, even before the current worldwide crisis revealed the inadequacies of mainstream economic theory, economists had realized that this new approach of looking at economics problem cannot be simply ignored, as evidenced, e.g., by the entry of the terms “econophysics" and “economy as a complex system" in the New Palgrave Dictionary of Economics (Macmillan, 2008). The failure of economists by and large to anticipate the collapse of markets worldwide in 2008 over such a short space of time has now led to some voices from within the field of economics itself declaring that new foundations for the discipline are required. The economists Lux and Westerhoff in an article published in Nature Physics this year [1] have suggested that econophysics may provide such an alternative theoretical framework for rebuilding economics. As Lux and other economists have pointed out elsewhere [2], the systemic failure of the standard model of economics arises from its implicit view that markets and economies are inherently stable. Similar sentiments have been expressed by Bouchaud in an essay in Nature last year [3].

However, worldwide financial crises (and the accompanying economic turmoil) are neither new nor as infrequent as economists would like to believe. It is therefore surprising that mainstream economics has ignored, and sometimes actively suppressed, the study of crisis situations. The famous economist Kenneth Arrow even tried to establish the stability of economic equilibria as a mathematical theorem; however, what is often forgotten is that such conclusions are crucially dependent on the underlying simplifying assumptions, such as, perfectly competitive markets and the absence of any delays in response. It is obvious that the real world hardly conforms to such ideal conditions. Moreover, the study of a wide variety of complex systems (e.g., from cellular networks to the internet and ecosystems) over the past few decades using the tools of statistical physics and nonlinear dynamics has led to the understanding that inherent instabilities in dynamics often accompanies increasing complexity.

Table 1.1 The economy machine. A reconstruction of the Moniac (at the University of Melbourne), a hydraulic simulator of a national economy built in 1949 by A. W. H. Phillips of the London School of Economics, that used the flow of colored water to represent the flow of money. It is currently again being used at Cambridge University for demonstrating the dynamic behavior of an economic system in economics first-year lectures. [Source: http://airminded.org, Photo: Brett Holman]

The obsession of mainstream economics with the ideal world of hyper-rational agents and almost perfect competitive markets has gone hand in hand with a formal divorce between theory and empirical observations. Indeed, the analysis of empirical data has ceased to be a part of economics, and has become a separate subject called econometrics. Since the 1950s, economics has modeled itself more on mathematics than any of the natural sciences. It has been reduced to the study of self-consistent theorems arising out of a set of axioms to such an extent that it is probably more appropriate to term mainstream economics as *econo-mathematics*, i.e., mathematics inspired by economics and that too having little connection to reality. This is strange for a subject that claims to have insights and remedies for one of the most important spheres of human activity. It is a sobering thought that decisions made by the IMF and World Bank which affect millions of lives are made on the basis of theoretical models that have never been subject to empirical verification. In view of this, some scientists (including a few economists) have begun to think that maybe economics is too important to be left to economists alone. While a few have suggested that econophysics may provide an alternative theoretical framework for a new economic science, we think that the field as it stands is certainly an exciting development in this direction, and intend to give an introduction to it here.

Before describing in this book how physicists have brought fresh perspectives to bear on understanding economic phenomena in recent times, let us point out here that despite the present state of economics, there has been a long and fruitful association between physics and economics. Philip Mirowski, in his book, More Heat Than Light (1989) [4] has pointed out that the pioneers of neoclassical economics had indeed borrowed almost term by term the physics of 1870s to set up their theoretical framework. This legacy can still be seen in the attention paid by economists to maximization principles (e.g., of utility) that mirrors the framing of classical physics in terms of minimization principles (e.g., the principle of least action). Later, Paul Samuelson, the second Nobel laureate in economics and the author of possibly the most influential textbook of economics, tried to reformulate economics as an empirically grounded science modeled on physics in his book Foundations of Economic Analysis (1947). While the use of classical dynamical concepts such as stability and equilibrium has also been used in the context of economics earlier (e.g., by Vilfredo Pareto), Samuelson's approach was marked by the assertion that economics should be concerned with "the derivation of operationally meaningful theorems", i.e., those which can be empirically tested. Such a theorem is "simply a hypothesis about empirical data which could conceivably be refuted, if only under ideal conditions". Given the spirit of those times, it is probably unsurprising that this is also when the engineer-turned-economist Bill Philips (who later became famous for the Philips curve, a relation between inflation and employment) constructed the Moniac, a hydraulic simulator for the national economy (Fig. 1.1), that modeled the flow of money in society through the flow of colored water. The mapping of macroeconomic concepts to the movement of fluids was a direct demonstration that the economy was as much a subject of physical inquiry as other more traditional subjects in physics.

This was however the last time that physics would significantly affect economics until very recently, as the 1950s saw a complete shift in the focus of economists towards proving existence and uniqueness of equilibrium solutions in the spirit of mathematics. A parallel development was the rise of mathematical game theory, pioneered by John von Neumann. To mathematically inclined economists, the language of game theory seemed ideal for studying how selfish individuals constantly devise strategies to get the better of other individuals in their continuing endeavor to maximize individual utilities. The fact that this ideal world of paranoid, calculating hyper-rational agents could never be reproduced in actual experiments carried out with human subjects where "irrational" cooperative action was seen to be the norm, could not counter the enthusiasm with which economists embraced the idea that society converges to an equilibrium where it is impossible to make someone better off without making someone else worse off. Further developments of rational models for interactions between economic agents became so mathematically abstract, that an economist recently commented that it seems (from an economic theorist's point of view) even the most trivial economic transaction is like a complicated chess game between Kenneth Arrow and Paul Samuelson (the two most famous American economists of the post-war period). The absurdity of such a situation is clear when we realize that people rarely solve complicated maximization equations in their head in order to buy groceries from the corner store. The concept of bounded rationality has recently been developed to take into account practical constraints (such as the computational effort required) that may prevent the system from reaching the optimal equilibrium even when it exists.

It is in the background of such increasing divergence between economic theory and reality that the present resumption of the interrupted dialogue between physics and economics took place in the late 1980s. The condensed matter physicist Philip Anderson jointly organized with Kenneth Arrow a meeting between physicists and economists at the Santa Fe Institute that resulted in several early attempts by physicists to apply the recently developed tools in non-equilibrium statistical mechanics and nonlinear dynamics to the economic arena (some examples can be seen in the proceedings of this meeting, *The Economy as an Evolving Complex System*, 1988). It also stimulated the entry of other physicists into this inter-disciplinary research area, which, along with slightly later developments in the statistical physics group of H. Eugene Stanley at Boston University, finally gave rise to econophysics as a distinct field, the term being coined by Stanley in 1995 at Kolkata. Currently there are groups in physics departments around the world who are working on problems relating to economics, ranging from Japan to Brazil, and from Ireland to Israel. While the problems they work on are diverse, ranging from questions about the nature of the distribution of price fluctuations in the stock market to models for explaining the observed economic inequality in society to issues connected with dynamical fluctuations of prices as a consequence of delays in the propagation of information, a common theme has been the observation and explanation for scaling relations (or power laws). Historically, scaling relations have fascinated physicists because of their connection to critical phenomena; but more generally, they indicate the presence of universal behavior. Indeed, the quest for invariant patterns that occur in many different contexts may be said to be the novel perspective that this recent incursion of physicists have brought to the field of economics, and that may well prove to be the most enduring legacy of econophysics.

1.1
A brief history of economics from the physicist's perspective

When physics started to develop, say with Galileo Galelei (1564-1642), there were hardly any science at a grown-up stage to get help or inspiration from. The only science that was somewhat grown up was mathematics, which is an analytical science (based on logic) and not synthetic (based on observations/ experiments carried out in controlled environments or laboratories). Yet, developments in mathematics, astronomical studies in particular, had a deep impact in the development of physics, of which the (classical) foundation was almost single-handedly laid down by Isaac Newton (1643-1727) in the seventeenth and early eighteenth century. Mathematics remained at the core of physics since then. The rest of "main stream" sciences, like chemistry, biology etc all tried to get inspiration from, utilize, and compare with physics since then.

In contrast, development in social sciences started much later. Even the earliest attempt to model an agricultural economy in a kingdom, the "physiocrats' model", named after the profession of its pioneer, the french royal physician Francois Quesnay (1694-1774), came in the third quarter of the eighteenth century when physics was already put on firm ground by Newton. The physiocrats made the observation that an economy consists of the components like land and farmers, which are obvious. Additionally, they identified the other components as investment (in the form of seeds from previous savings) and protection (during harvest and collection, by the landlord or the king). The impact of the physical sciences, in emphasizing these observations regarding components of an economy, is clear. The analogy with human physiology then suggested that, like the healthy function of a body requiring proper functioning of each of its components or organs and the (blood) flow among them remaining uninterrrupted, each component of the economy should be given proper care (suggesting rent for land and tax for protection!). Although the physiocrats' observations were appreciated later, the attempt to conclude using the analogy with human physiology was not.

Soon, at their last phase, Mercantilists, like Wilhelm von Hornick (1638-1712), James Stewart (1712-1780) et al, made some of the most profound and emphatic observations in economics, leading to the foundation of political economy. In particular, the observations by the British merchants (who traded in the colonies, including India, in their own set terms) that instability/unemployment growing at their home country in years whenever there had been a net trade deficit and out-flow of gold (export being less than import). This led to the formulation of the problem of effective demand: even though the merchants, or traders were independently trading (exporting or importing goods) with success, the country's economy as a whole did not do well due to lack of overall demand when there was a net flow of gold (the international exchange medium) to balance the trade deficit! This remains still a major problem in macroeconomics. The only solution in those days was to introduce tax on import: the third party (namely the government) intervention on individuals' choice of economic activity (trade). This immediately justified the involvement of the government in the economic activities of the individuals.

In a somewhat isolated but powerful observation, Thomas Malthus (1766-1834) made a very precise modelling of the conflict between agricultural production and population growth. He assumed that the agricultural production can only grow (linearly) with the area of the cultivated land. With time t, say year, the area can only grow linearly ($\propto t$) or in arithmetic progression (AP). The consumption depends on the population which, on the other hand, grows exponentially ($\exp[t]$) or in geometric progression (GP). Hence, with time, or year $1, 2, 3, \ldots$, the agricultural production grows as $1, 2, 3, \ldots$, while the consumption demand or population grows in a series like $2, 4, 8, \ldots$. No matter, how much large area of cultivable land we start with, the population GP series soon takes over the food production AP series and the population faces a disaster — to be settled with famine, war or revolution! They are inevitable, as an exponentially growing function will always win over a lineraly growing function and such disasters will appear almost periodically in time!

Adam Smith (1723-1790) made the first attempt to formulate the economic science. He painstakingly argued that a truely many-body system of selfish agents, each having no idea of benevolence or charity towards its fellow neighbours, or having no foresight (views very local in space and time), can indeed reach an equilibrium where the economy as a whole is most efficient; leading to the best acceptable price for each commodity. This 'invisible hand' mechanism of the market to evolve towards the 'most efficient' (beneficial to *all* participating agents) predates by ages the demonstration of 'self-organisation' mechanism in physics or chemistry of many-body systems, where each constitutent cell or automata follows very local (in space and time) dynamical rules and yet the collective system evolves towards a globally 'organised' pattern (cf. Ilya Prigogine (1917-), Per Bak (1947-2002) et al). This idea of 'self-organizing or self-correcting economy' by Smith of course contradicted the prescription of the Mercantilists regarding government intervention in the economic activities of the individuals, and argued tampering by any external agency to be counterproductive.

Soon, the problem of price or value of any commodity in the market became a central problem. Following David Ricardo's (1772-1823) formulation of rent and labour theory of value, where the price depends only on the amount of labour put by the farmers or labourers, Karl Marx (1818-1883) formulated and forwarded emphatically the surplus labour theory of value or wealth in any economy. However, none of them could solve the price paradox: why diamond is costly, while coal is cheap? The amount of labour in mining etc are more or less the same for both. Yet, the prices are different by astronomical factors! This clearly demonstrates the failure of the labour theory of value. The alternative forwarded was the utility theory of price: the more the utility of a commodity, the more will be its price. But then, how come a bottle of water costs less than a bottle of wine? Water is life and certainly has more utility! The solution identified was marginal utility. According to marginal utility theory, not the utility but rather its derivative with respect to the quantity determines the price: water is cheaper as its marginal utility at the present level of its availability is less than that for wine — will surely change in a desert. This still does not solve the problem completely. Of course increasing marginal utility creates increasing demand for it, but its price must depend on its supply (and will be determined by equating the demand with the supply)! If the offered (hypothetical) price p of a commodity increases, the supply will increase and the demand for that commodity will decrease. The price, for which supply S will be equal to demand D, will be the market price of the commodity: $S(p) = D(p)$ at the market (clearing) price. However, there are problems still. Which demand should be equated to which supply? It is not uncommon to see often (in India) that price as well as the demand for rice (say) increases simultaneously. This can occur when the price of the other staple alternative (wheat) increases even more.

The solutions to these problems led ultimately to the formal development of economic science in the early twentieth century by Léon Walras (1834-1910), Alfred Marshal (1842-1924) and others: marginal utility theory of price and cooperative or coupled (in all commodities) demand and supply equations. These formulations went back to the self-organising picture of any market, as suggested by Adam Smith, and incorporated this marginal utility concept, and utilized these coupled demand-supply equations: $D_i(p_1, p_2, \ldots, p_i, \ldots, p_N, M) = S_i(p_1, p_2, \ldots, p_i, \ldots, p_N, M)$ for N commodities and total money M in the market, each having relative price tags p_i (determined by marginal utility rankings) and demand D_i and supply S_i; $i = 1, 2, \ldots, N$ and the functions D or S are in general nonlinear in their arguments. These formal and abstract formulations of economic science were not appreciated very much in its early days and had a temporary setback. The lack of acceptance was due to the fact that neither utility nor marginal utility is measurable and the formal solutions of these coupled nonlinear equations in many (p_i) variables still remain elusive.

The major reason for the lack of appreciation for these formal theories was a profound and intuitive obsevation by John Maynard Keynes (1883-1946) on the fall of aggregate (or macroeconomic) effective demand in the market (as pointed out earlier by the Mercantilists; this time due to 'liquidity preference' of money by the market participants) during the great depression of 1930's. His prescription was for government intervention (in direct contradiction with the 'laissez-faire' ideas of leaving the market to its own forces to bring back the equilibrium, as Smith, Walras et al proposed) to boost aggregate demand by fiscal measures. This prescription made immediate success in most cases. By the third quarter of the twentieth century, however, its failures bacame apparent and the formal developments in microeconomics took the front seat again.

Several important, but isolated observations in the meantime contributed later very significantly. Vilfredo Pareto (1848-1923) observed that the number density $P(m)$ of riches in any society decreases rather slowly with their richness m (measured in those days by palace sizes, number of horses, etc of the kings/landlords in all over Europe): $P(m) \sim m^{-\alpha}$; for very large m (very rich people); $2 < \alpha < 3$ (Cours d'Economic Politique, Lausanne, 1897). It may be mentioned, at almost the same time, Joshiah Willard Gibbs (1839-1903) had put forward precisely that the number density $P(\epsilon)$ of particles (or microstates) with energy ϵ in a thermodynamic ensemble in equilibrium at temperature T falls off much faster: $P(\epsilon) \sim \exp[-\epsilon/T]$ (Elementary Principles of Statistical Mechanics, 1902). This was by then rigorously established in physics. The other important observation was by Louis Bachelier (1870-1946) who modelled the speculative price fluctuations (σ), over time τ, using a Gaussian statistics (for random walk): $P(\sigma) \sim \exp[-\sigma^2/\tau]$ (Thesis: Théorie de la Spéculation, Paris, 1900). This actually predated Albert Einstein's (1879-1955) random walk theory (1905) by five years. In another isolated development, mathematician John von Neumann (1903-1957) started developing the game theories for microeconomic behavior of partners in oligopolistic competitions (to take care of the strategy changes by agents, based on earlier performance).

In the mainstrem economics, Paul Samuelson (1915-) investigated the dynamic stabilities of demand-supply equilibrium by formulating, following Newton's equations of motion in mechanics, dynamical equations $\frac{dD_i}{dt} = \sum_i J_{ij} D_j(p_1, p_2, \ldots, p_N, M)$ and $\frac{dS_i}{dt} = \sum_i K_{ij} S_i(p_1, p_2, \ldots, p_N, M)$, with the demand and supply (overlap) matrices $\underline{J}$ and $\underline{K}$ respectively for N commodities, and by looking for the equilibrium state(s) where $dS/dt = 0 = dD/dt$ at the market clearing prices $\{p\}$ where $D_i(\{p\}, M) = S_i(\{p\}, M)$. Jan Tinbergen (1903-1994), a statistical physicist (student of Paul Ehrenfest of Leiden University) analysed the business cycle statistics and initiated the formulation of econometrics. By this time, these formal developments in economics, with clear impact of other developed sciences (physics in particular), were getting recognized. In fact, Tinbergen was the first recipient of the newly instituted Nobel prize in Economics in 1969 (for other sciences, they started in 1901; a delay by 68 years in 105 years' history of the prize!) and the next year, the prize went to Samuelson. Soon, the formal developments like the axiomatic foundations of utility (ranking) theory, and solution of general equilibrium theory by Kenneth Arrow (1921-), those of George Stigler (1911-1991), who first performed Monte Carlo simulations of markets (similar to those of thermodynamic systems in physics), or that of John Nash (1928-), giving the proof of the existence of equilibrium solutions in strategic games, etc, all were appreciated by awarding the Nobel prizes in economics (in 1972, 1982 and 1994 respectively). Although the impact of developments in physics had a clear mark in those of economics so far, it was not that explicit until about a decade and a half back.

The latest developments (leading to econophysics) had of course its seed in several earlier observations. Important among them was by Benoit Mandelbrot (1924-) when he observed in 1963 that the speculative fluctuations (in the cotton market for example) have a much slower rate of decay, compared to that suggested by the Gaussian statistics of Bachelier, and falls down following a power law statistics: $P(\sigma) \sim \sigma^{-\alpha}$ with some robust exponent value (α) depending on the time scale of observations. With the enormous amount of stock market data now available on the internet, Eugene Stanley, Rosario Mantegna and coworkers established firmly the above mentioned (power-law) form of the stock price fluctuation statistics in late 1990's. Simultaneously, two important modelling efforts, inspired directly from physics, started: the minority game models, for taking care of contigious behavior (in contrast to perfect rational behavior) of agents in the market, and learning from the past performance of the strategies, were developed by Brian Arthur, Damien Challet, Yi-Cheng Zhang et al, starting 1994. The other modelling effort was to capture the income or wealth distribution in society, similar to energy distributions in (ideal) gases. These models intend to capture both the initial Gamma/log-normal distribution for the income distributions of poor and middle-income groups and also the Pareto tail of the distribution for the riches. It turned out, as shown by the Kolkata group during the last half of 1990 to the first half of 2000, a random saving gas model can easily capture these features of the distribution function. However, the model had several well documented previous, somewhat incomplete, versions available for a long time. Meghnad Saha (1893-1956), the founder of Saha Institute of Nuclear Physics, Kolkata (named so after its founder's death), and collaborators, already discussed at length in their text book, in the 1950's, the possibility of using Maxwell-Boltzmann velocity distribution (a Gamma distribution) in an ideal gas to represent the income distribution in societies: "suppose in a country, the assessing department is required to find out the average income per head of the population.

They will proceed somewhat in the similar way ... (the income distribution) curve will have this shape because the number of absolute beggers is very small, and the number of millionaires is also small, while the majority of the population have average income." (section on 'Distribution of velocities' in A Treatise on Heat, M. N. Saha and B. N. Srivastava, Indian Press, Allahabad, 1950; pp. 132-134). This modelling had the obvious drawback that the distribution could not capture the Pareto tail. However, the accuracy of this Gibbs distribution for fitting the income data available now in the internet has been pointed out recently by Victor Yakovenko and collaborators in a series of papers since 2000. The 'savings' ingredient in the ideal-gas model, required for getting the Gamma function form of the otherwise ideal gas (Gibbs) distribution, was also discovered more than a decade earlier by John Angle. He employed a different driver in his stochastic model of inequality process. This inequality coming mainly from the stochasticity, together with the equivalent of saving introduced in the model. A proper Pareto tail of the Gamma distribution comes naturally in this class of models when the saving propensity of the agents are distributed, as noted first by the Kolkata group and analyzed by them and by the Dublin group led by Peter Richmond.

Apart from the intensive involvements of physicists together with a few economists in this new phase of development, a happy feature has been that econophysics has almost established itself as a (popular) research discipline in statistical physics. Many physics journals have started publishing papers in such an interdisciplinary field. Also, courses in econophysics are being offerred in several universities, mostly in their physics departments.

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