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Economics and Econophysics

What is econophysics? If it is just the use of physical methods to investigate economic problems, In what way is econophysics different, if at all, from orthodox mainstream economics? If it is really different from mainstream neoclassical economic thought, Is econophysics just another nonmainstream, or heterodox, approach to economic problems? Can econophysics contribute to the understanding of economic phenomena in a different way than economics itself, no matter if this understanding comes from the orthodox or heterodox traditions? Answering these questions form the subject of the present chapter. The next sections will present a discussion on the similarities and differences between economics and econophysics from the methodological and practical viewpoints. For the benefit of readers not entirely familiar with physical terminology, there will be first a very short summary about the origins of modern physics followed by a similarly short overview on the history of economic thought.

1.1 Physics

Physics as a modern science started with the scientific revolution which occurred during the European cultural movement known as the Renaissance. The works of well-known names of that time, like Nicolaus Copernicus (1473–1543), Galileo Galilei (1564–1642), and Johannes Kepler (1571–1630) were fundamental in establishing physics as we know it today. Their contributions spanned the proposal of the heliocentric planetary motion, due to Copernicus, the discovery of the three laws of the planetary motion, due to Kepler, and the law of the falling bodies, due to Galileo, who also made some important contributions to astronomy like the discovery of the sunspots, the biggest four natural satellites of the planet Jupiter, the ring system in the planet Saturn, and the lunar mountain system. Afterwards, the most important advancements in physics are associated with Isaac Newton (1642–1727), whose three laws of motion and his law of universal gravitation

https://doi.org/10.1017/9781316136119.004 Published online by Cambridge University Press

established what is now known as *Newtonian physics*, *Newtonian mechanics*, or *classical mechanics*. *Thermodynamics*, which macroscopically deals with problems related to heat and temperature, and *electromagnetism*, which studies electric charges, both static and in movement, and magnetic phenomena, as well as the propagation of perturbations in the electric and magnetic fields, the electromagnetic waves, are physical theories whose developments occurred mainly during the eighteenth and nineteenth centuries. The main physicists associated with these theories are Sadi Carnot (1796–1832), James Watt (1736–1819), Michael Faraday (1791–1867), and James Clerk Maxwell (1831–1879). These three major theories, classical mechanics, thermodynamics, and electromagnetism are collectively known as *classical physics*.

During the period lasting from approximately 1870 to 1930, physics underwent a scientific revolution. Starting from results already developed by Maxwell himself, Josiah Willard Gibbs (1839–1903) and Ludwig Boltzmann (1844–1906) used statistical reasoning to describe thermodynamics as a consequence of statistical properties of large ensembles of particles, that is, at a microscopic level, creating then new theories known as *statistical mechanics* and *statistical thermodynamics*. At the same time, contradictions between classical mechanics and Maxwell's electromagnetic theory led Albert Einstein (1879–1955) to propose in 1905 a solution which became known as the *special theory of relativity*. The famous $E = mc^2$ equation comes from this theory. Concurrently, the inability of Maxwell's theory to describe some aspects of the electromagnetic radiation, the blackbody radiation, and the behavior of the fabric of the physical world, the atoms, led Max Planck (1858–1947), Niels Bohr (1885–1962), Erwin Schrödinger (1887–1961), and Einstein himself to establish the basis of a new theory to describe the micro world, the *quantum mechanics*. The use of statistical reasoning was also applied to quantum mechanics and the collection of statistical methods to describe physical systems, classical or quantum, is now known as *statistical physics*.

By the end of 1915, Einstein presented a new theory of gravitation which he had been working on during the previous ten years that went much beyond Newton's one and entirely revolutionized the way physics described the gravitational phenomenon. This theory became known as the *general theory of relativity*, whose conclusions included the very unexpected result, verified empirically, that light beams are deflected by the mass of celestial bodies. The physical theories which appeared from late nineteenth to early twentieth centuries, that is, statistical physics, both relativity theories and quantum mechanics, are now known as *modern physics*.

The paragraphs above are just an extreme summary of approximately the last 450 years of the history of physics and cannot do justice to dozens of other physicists whose names were omitted in the text above, but made very important

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contributions to physics. Several of them were in fact honored with their names becoming physical units used in our everyday life, this being the case for André-Marie Ampère (1775–1836), Andres Celsius (1701–1744), Heinrich Rudolf Hertz (1857–1894), James Prescott Joule (1818–1889), William Thomson, Lord Kelvin (1824–1907), Georg Simon Ohm (1789–1854), Blaise Pascal (1623–1662), and Alessandro Volta (1745–1827), to name just a few. Others like, for instance, Louis de Broglie (1892–1987) and Paul Dirac (1902–1984) made groundbreaking theoretical contributions to quantum theory and both were recipients of the Nobel Prize in Physics.

Nevertheless, our purposes here are not to present a brief history of physics, but to establish the terminology of physical theories to nonphysicists, show the time frame when they were advanced, associate these theories with a handful of names more or less well known to nonphysicists and to state that although at about 120 years ago physics went through a scientific revolution, the previous classical theories were not abandoned. There was no methodological rupture in physics or any kind of dismissal of previous results simply because classical physics agrees with empirical results which are strongly anchored in well-tested experiments. In fact, several technologies used in our everyday life, from electric power to airplanes, are based on the results of classical physics.

What modern physics established were the limitations of classical physics and worked out, both theoretically and experimentally, the new theories to describe physical phenomena placed beyond the scope of classical physics, like the physical laws of the micro world, how bodies behave at speeds approaching the speed of light, and the dynamic connection between space and time. There were naturally new concepts which contradicted classical physics, but physicists worked out the domains of validity of classical and modern physics, including the ranges where those concepts are applicable or not, and nowadays physics works well with both sets of theories in an integrated way.

It must be noted, however, that during these last 450 years several theories and models were effectively abandoned because either their predictions were not validated by experiments or new concepts which described these empirical results rendered those previous theories obsolete. This is, for instance, the case of the caloric theory to explain heat transfer, replaced by the mechanical theory of heat, and the geocentric Ptolemaic epicycles, replaced by Copernicus' heliocentric system to describe the orbits of the planets, to name just two of several superseded physical theories.

At this point it is important to mention the influence of classical Greek philosophers in the development of physics. Several of them discussed topics which are now considered within the scope of physics, like Democritus (460–370 BC), who advanced the ancient theory of atoms, and, especially, Aristotle (384–322 BC),

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who discussed the movement of bodies. For the purposes of this discussion one should present one result of the *Aristotelian physics* as examined by Galileo in his famous book titled *Dialogues Concerning Two New Sciences* (Galilei, 1638).

Aristotle claimed that a heavier body would fall faster than a lighter one under the influence of gravity. Galileo refuted this assertion simply because he made the experiment and found that two bodies of the same shape, but different weights, would fall at the same acceleration and reach the ground at the same time if they are released from the same height, a result contrary to Aristotle's conclusion. In other words, in this instance Aristotle's reasoning was deductive and logical, but empirically false. Galileo even questioned if Aristotle ever made the experiment himself (Galilei, 1638, pp. 62–64).

Here we arrive at the methodological essence of the Galilean approach to physical phenomena. No matter how logical and convincing a reasoning can be, it can only be considered scientific if it is subjected to empirical validation, either experimentally or observationally. Until that happens, it is just conjecture waiting to be tested, proved, or disproved. This concept is at the heart of the *scientific method* inaugurated by Galileo, implying that science is an activity whose theories must be constantly checked against observation and/or experimentation and modified accordingly.

After Galileo, the term *Aristotelian physics* became synonymous with *pseudoscience,* that is, presupposed statements assumed as true, but which were never subjected to empirical testing and validation. Hence, *metaphysics*, another word originated from Aristotle's works, is a type of inquiry having nonempirical character, i.e., statements assumed as valid which lead logically to other statements which are also assumed as valid, but never subject to empirical testing and whose final conclusions cannot be considered as having any relationship whatsoever with the real world. That can only happen if they are empirically tested.

Actually, to label Aristotelian physics as pseudoscience is historically unfair to Aristotle, since this only focuses on what was changed in our physical view of the world by the Renaissance's scientific revolution rather than what was *not* changed by this same revolution. Several physical concepts advanced by Aristotle remained after Galileo and became essential building blocks to very important modern concepts in physics. For instance, this is the case of motion as a process, from potential to actual, from where the modern concepts of potential energy (Aristotle, 2012b, pp. 652–655) and dynamics originated. What did not remain were his models, like the geocentric view of the World and the concept of *natural place*, to which objects would seek when moving (Aristotle, 2012a, pp. 913, 1074). Nevertheless, one can even find similarities between definitions and results arising in modern physical theories and the Aristotelian concept of natural place (e.g., Neves, 2018), showing that some fragments of Aristotle's physical models are still with us.

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In addition, at Aristotle's time the possibilities of doing experimental physics by means of arithmetic operations with physical measurements were rather limited. One of the main obstacles was the very cumbersome and arithmetically impractical numeral system adopted by the ancient Greeks, where arithmetic operations and the representation of very large numbers varied from hard to nearly impossible, this being specially due to the fact that their numerals did not include the number zero (Ifrah, 2000, ch 16, pp. 327, 333). Galileo, on the other hand, was already in possession of the arithmetically very practical modern Indo-Arabic numerals, where the essential concept of the number zero was already well established, allowed unlimited representation of very large numbers and made their arithmetic operations practical. Nevertheless, although historically unfair, the use of the term 'Aristotelian physics' to mean pseudoscience has remained to this day within the physics tradition.

1.2 Economics

1.2.1 Antiquity and the Middle Ages

Aspects of what constitutes economics as we know it today can be traced back to texts from antiquity which dealt with the justice in the exchange of goods and acquisition of wealth by means of unfair gain in commerce. During this time and the Middle Ages the economic discussion was dominated by Aristotle's ideas about the moral limits of commercial activity, since this was considered as an unnatural way of acquiring wealth. In addition, Aristotle discussed the role of money as a means of exchange, measure of value, and as a stock of value for future transactions (Backhouse, 2002, chs. 1–2).

Scholastic philosophy of the thirteenth century derived from Aristotle's theory of "just wage," which was defined as the wage that would give the worker a standard of living adequate to his social condition. Similarly, there were a just price theory connected to the cost of production through the exchange of equivalents. Included in the cost of production is a fair and moderate profit, enough for the merchant's family and charity (Screpanti and Zamagni, 1993, section 1.1.1).

The sixteenth century saw *mercantilism* dominate economic thought. Its main concerns were no longer the administration of the household, but of the state, no longer the enrichment of the individuals, but of the nation and the merchant class. The goal was the use of state power to build industries and increase the trade surplus by means of exports, leading then to the accumulation of money. The interests of the merchant class were identified with the interests of the collectivity, a situation which meant that economics was no longer domestic, but political (Screpanti and Zamagni, 1993; Backhouse, 2002).

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It must be mentioned that many mercantilists were in fact more interested in promoting higher-productivity economic activities through policy interventions; that is, they were focused on solving real-world problems, especially policy proposals on how economically backward countries should develop their economies in order to catch up with the more advanced ones. This focus started a viewpoint in economics that is today known as the *developmentalist tradition* or *development economics*. Developmentalist theories are still being advanced and refined today, although policy practices under this tradition can be traced as far back as the fifteenth century (Chang, 2014, pp. 96–99).

1.2.2 Political Economy

The seventeenth century witnessed the birth of *political economy*, the name by which the study of economic matters became known until the end of the nineteenth century (see Section 1.2.4) and which shows the close connection between economics, politics, social sciences, and philosophy.

William Petty (1623–1687) produced the first texts generally accepted as belonging to political economy, and his book *Political Arithmetick*, written between 1671 and 1676, but published after his death (Petty, 1690), reflected his aspiration at providing an empirical base for economics in which pure speculative reasoning must be avoided, and qualitative arguments ought to be replaced by rigorous ones relying on number, weight, and measure (Screpanti and Zamagni, 1993, p. 36). This was a very good start because if we see Petty's work from the perspective of the early twenty-first century, the time of writing, what he had in mind was really a kind of Newtonian physics of society (Ball, 2004, pp. 3–4).

The next important contribution for the development of political economy came from the French school of thought known as the *physiocrats*. Prominent among the members of the physiocratic school was François Quesnay (1694–1774), whose main contribution was the *Tableau Économique* (Economic Table), published in 1758. The *Tableau* is basically a model that sees the economic system as a cycle of deep interdependence and interrelationship among the various productive processes, that is, all parts of the system function according to a certain natural law. Economic exchange is then represented as a circular flow of goods and money among all economic sectors. Related to this interdependence is the idea of equilibrium, which we would today call *macroeconomic equilibrium* (Screpanti and Zamagni, 1993, section 2.1.2).

According to the *Tableau*, the system is moved by the surplus produced by farmers, considered as the productive class. The landlords formed the distributive class, consuming the surplus created by the productive class and starting the circulation of money and goods among the economic sectors of the nonproductive

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class (manufacturing industry). The circulation is closed by returning part of the surplus to the productive class. Hence, one can find in the *Tableau* three important economic concepts: production, distribution, and accumulation. The accumulation occurs when the production increases by higher quantities of surpluses which are then returned (invested) into production (Delfaud, 1986).

Classical political economy, or the *classical school of economics*, is a term associated with a group of five very influential economists of the eighteenth and nineteenth centuries: Adam Smith (1723–1790), Jean-Baptiste Say (1767–1832), Thomas Malthus (1766–1834), David Ricardo (1772–1823) and John Stuart Mill (1806–1873). Their studies inherited the physiocratic method of viewing the economic system as circulatory in nature, treating this system as a whole and seeing it as being dynamically characterized by three main phases: production, distribution and accumulation (Delfaud, 1986). They, nevertheless, studied in much more detail these three phases of the cycle.

Smith saw the system as a cumulative mechanism operated in a sequence leading to a virtuous circle of growth: division of labor, enlargement of the markets, and increase in labor productivity. The division of labor triggers the growth process and the accumulation drives it. He discussed a theory of *income distribution* among the three basic social classes, capitalists, workers, and landlords, differentiated by the productive resources they hold, respectively, capital, labor, and land, and the way they spend their income, respectively, profits, wages, and rents.

Smith also provided an explanation for the values of goods, which are measured by the quantity of human labor they are able to command, that is, the wage equivalent or the labor that can be bought with it. For Smith, positive growth rate occurs when labor commanded is higher than the amount of labor used to produce it, leading then to a surplus required to sustain capital accumulation. He also distinguished market price, the real price of a good at a certain moment, from natural price, the normal rates of remuneration for capitalists, workers, and landowners. Smith thought of this system as stable, unique, and in equilibrium, since there would be an *invisible hand* where individuals would serve the collective interest exactly because they would be guided by self-interest. However, these three properties of the economic system, stability, uniqueness, and equilibrium, which would justify Smith's conjecture of an invisible hand, remained unproved, and are a source of much debate to this day (Screpanti and Zamagni, 1993, section 2.2).

The other classical political economists discussed the economic system by also using its three phases, production, distribution, and accumulation, as the basis of their analysis. Regarding production, Ricardo discussed Smith's theory of value by arguing that the exchange value must incorporate not only labor, but the tools used in their production, whereas Say argued that the use value implies a certain *utility* that satisfies needs and wants. Mill viewed labor as determining the supply while

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utility governs the demand. On distribution, Malthus and Ricardo talked about a 'natural salary' due to the costs of production of labor, since labor is seen as a commodity as any other. But Malthus stated that if the birth rate increases, the natural salary is reduced to the bare minimum subsistence level. For all classical political economists, profit is at the center of the capitalist dynamics as it provides the accumulation.

Therefore, from Smith to Mill the engine of the economic system is the cycle accumulation–profit–accumulation. Say tried to show that general excess supply is impossible, so arriving at the famous *Say's law* according to which supply always creates its own demand (Delfaud, 1986; Screpanti and Zamagni, 1993).

1.2.3 Marxian Economics

Karl Marx's (1818–1883) contributions are well known to be far-reaching, but here we are not interested in the social and political doctrines associated with his name, Marxism, but only in his contributions to political economy, that is, *Marxian economics*, which in fact has a close relationship to the classical political economists, particularly Ricardo's political economy. His conclusions were based on the labor theory of value, the theory of surplus, and an analysis of the behavior and relationship of social classes, issues already discussed by Smith.

On *(i)* production, Marx viewed capitalism as a *dynamic system* where money (M) and commodities (C) are exchanged in the C–M–C cycle which characterizes a simple commodity production, that is, where commodities produce money which then produces commodities. The M–C–M' cycle is, on the other hand, the dominant form of circulation in capitalism, the part of the system's dynamics that renders the creation of value as long as $M' >$ M. Thus M' is the final capital whereas M is the invested capital. The difference between M' and M is the *surplus value* or unpaid labor (Delfaud, 1986). Note that Say's law states that a sale is always followed by a purchase of equal amount, or everything that is produced is consumed. This means no interruption in the C–M–C cycle and, therefore, there is no overproduction, a point which Marx strongly criticized in Ricardo (Sweezy, 1942, pp. 136–138).

On *(ii)* distribution, Marx basically reduced the partition of the produced value in wage share and profits, where the latter is further divided in interests and rent. Finally, on *(iii)* accumulation he noted that capitalist production grows on *cycles of booms and busts*. In a boom, profits increase and unemployment decreases as the workers are capable of obtaining better jobs and higher wages due to manpower shortage to feed the growing production. This boom is, nevertheless, followed by a bust inasmuch as less unemployment reduces the profit margin, whose recovery is achieved by a higher unemployment and a reduction of workers' bargaining power. Smaller salaries lead to an increase in the profit margin which leads to new

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investment and then a new boom starts, being followed by another bust, and so on (Marx, 1867, ch. 25, section 1). It follows from this reasoning the concept of *labor reserve army*, a large group of unemployed workers willing to accept lower wages in exchange for a job, whose existence is essential to avoid wages going too high and profits too low.

1.2.4 Neoclassical Economics

The above paragraphs show that the analytical approach started by the physiocrats was continuously developed until Ricardo and Marx. However, by the end of the nineteenth century the economic thought suffered a methodological rupture in which distinct social classes such as workers, capitalists, and landowners, treated in circular flow according to a process of production–distribution–accumulation, were no longer considered as fundamental concepts. A new form of economic analysis stopped using collective, or aggregate, social classes as their main economic agents, and replaced them with individual economic agents such as consumers and producers. The classical approach of treating the economic system as a whole was also replaced by a reasoning that emphasized the supposed equilibrium of the system from a theory of value expressed in terms of utility and scarcity (Delfaud, 1986), where classical physics concepts such as energy conservation and equilibrium thermodynamics were used as essential metaphors for the establishment of this new approach to economics (Mirowski, 1989, p. 222; Drakopoulos and Katselidis, 2015).

Utility is defined as the ability to increase pleasure and decrease suffering, measured indirectly by means of the market behavior. This also defines the *indifference curves*, representing the same level of utility (satisfaction) between different bundles of goods to which a consumer has no preference, or is indifferent. Thus, economics becomes domestic in the sense that it deals with the maximization of the household's welfare or the profits of the firm, and the focus is on the allocation of given resources. This new emphasis on the micro level originated the term *microeconomics*. And the hypothesis of a decreasing *marginal utility*, where the reasoning is focused on the last available element of a certain good, the margin, gave rise to the term *marginalism* to this approach. The idea is that once a person has more of a certain good, this person's marginal utility decreases. The rupture was so strong that even the name of the discipline was changed, from political economy to *economics*. Although there were predecessors, the main names associated with this *marginalist revolution* are Léon Walras (1834–1910), William Stanley Jevons (1835–1882), and Carl Menger (1840–1921). The theoretical system they created became known as *neoclassical economics* (Screpanti and Zamagni, 1993, section 5.1).

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The works of Walras, Jevons, and Menger were published in the early 1870s and from this time onward neoclassical economics became hegemonic, pushing in effect the classical political economic way of thinking to the background, at least in the Western world. The reasons for that are various, but the inability of political economy in solving several theoretical problems is certainly among them. In this respect, one can cite that the labor theory of value, which states that value is created by labor, did not withstand criticism because of the development of Western Europe industrial economies did not lead to labor-intensive industries being more profitable than capital-intensive ones, as predicted.

In addition, the classical income distribution was viewed as inadequate because it was based on a theory that operated under the supposition that wages are forced down to the subsistence level by means of Malthus' population mechanism, something which was not observed due to the real increase of wages, although Marx had not adopted this approach in his theories. Nevertheless, many other results of classical political economy could not be dismissed so easily, like the economic role played by social classes, the concepts of circulation, surplus, labor reserve army, and the analysis of the economic system as a whole, to name just a few. In addition, as we shall see below, the fact that the neoclassical theory also has several cracks and critical flaws, meant that this rupture effectively led to long-lasting divisions and infighting among several economic schools of thought.

Despite all this, the neoclassical economics imposed itself and became the new orthodoxy by the turn of the nineteenth to the twentieth century. This coincides with the professionalization of economics, as from that time on economists became full-time university professors whereas previously they were a mixture of entrepreneurs, administrators, businessmen, public servants, politicians, and independent scholars. In particular, Walras' *general equilibrium theory* became an essential pillar of the neoclassical utilitarianism. In this theory, individuals are well informed, each well aware of his own choices, self-interested, each thinks about himself and, rationally, each tries to maximize his goals. This combination would systematize and organize production and distribution of income in a supposedly efficient and mutually beneficial way. There are several names associated with this period, which lasts until approximately the 1930s, but for the purposes of this very limited survey two names suffice: Alfred Marshall (1842–1924) and Vilfredo Pareto (1848–1923).

Marshall's ideas focused on the concepts of industry, group of firms producing the same good, and the *representative firm*, an average firm possessing the essential features of the industry. He concentrated on the equilibrium conditions of a single productive sector. He proposed mathematical methods to solve this problem, known later as *partial equilibrium analysis*, in which a part of the economy is studied in

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isolation. He studied mathematics and physics, being a Maxwell's student, before becoming an economist and his ideas were influenced by biology and Charles Darwin's (1809–1882) theory of evolution (Screpanti and Zamagni, 1993; Backhouse, 2002). This is particularly clear in his theory of the firm, viewed as progressing through a life cycle similar to an individual. They start young and vigorous, but, after reaching maturity, they become old and, eventually, replaced by new and more efficient firms.

Marshall's economic theory was based on the theory of supply and demand. Price is entirely determined by demand. There would be a demand price p_d, the maximum price at which demand reaches a certain level, and a supply price p_s, the minimum price that leads the sellers to offer a quantity equal to that certain level. Disequilibrium occurs when either $p_d > p_s$ or $p_d < p_s$. In the first case the seller would increase the supply by an increase in production or decrease of stocks, whereas the second case works the other way round (Screpanti and Zamagni, 1993). In both cases the system would, after a period of transition, reach equilibrium. Thus, his analysis was of *comparative statics* where two states of equilibrium are compared after the adjustment. Although this method used differential calculus, neoclassical economics lost the classical interest in long-range dynamics. One must also note that comparative statics does not offer a method of studying motion, or dynamics toward equilibrium, nor the process of change itself. In addition, if the economic system is not in equilibrium, the conclusions reached by this method would be in doubt.

Pareto is known for the income distribution law he found empirically. According to it, income is distributed among the richest individuals in a decreasing power-law, a result which is approximately the same for many countries and possibly all times. He also made contributions to the theory of the rational consumer, redefining the utility of a good from its ability to satisfy needs to an expression of preferences and, hence, individual choices. He also arrived at a concept known as *Pareto efficiency*, which is a certain state of allocation of resources where it is impossible for an individual to be better off without at least one individual being worse off.

1.2.5 Keynesian Economics

The 1920s was a period where several capitalist economies experienced a great boom, followed by a bust that started with the *Great Crash* of 1929 and lasted until World War II. These events inevitably caught the attention of the economists, as it became clear that the then dominant theories were inadequate to explain the level of economic instability and depth of the economic bust. Somehow, the changes in

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the level of economic activity were related to money and finance. In addition, it was easy to note a connection between the financial activities that led to the boom and subsequent collapse of the American stock market and the unprecedented depth of the economic depression that followed.

Some economists turned back to classical theories of political economy, especially Marxian, to try to understand the events. Others went another way, and revisited the neoclassical theories in a critical light in order to find answers capable of explaining the real world. Among the latter we find the most influential economist of that period, and arguably of the twentieth century: John Maynard Keynes (1883–1946).

Keynes was among a group of economists who returned to the problem that gave rise to classical political economy: *macroeconomic dynamics*. The term *macroeconomics* seems to suggest a split between the two approaches to economics: the global, or macro, and the partial, the elementary, or micro. However, Keynes followed an intermediate line between these two approaches to economic problems. From the global approach of production–distribution–accumulation, Keynes kept the cycle viewpoint as given by production–income–expense. Nevertheless, this circularity does not occur among social classes, but by means of macroeconomic functions such as consumption, investment, employment. From this viewpoint Keynes concluded that there is more disequilibrium than equilibrium in an economy.

From the neoclassical approach, Keynes kept elementary behaviors like the decision to produce, consume, save, or invest. These, however, are no longer individual behaviors, but aggregates which articulate themselves in specific ways. The system is dynamic since it does not try to explain the equilibrium state of production and employment, but its variation process. The Keynesian dynamic process is triggered by the decision of the producers to employ a certain volume of production, which requires a certain level of employment, according to expected sales since from the producer's viewpoint it is not at all certain that there will be a demand for produced quantity. Therefore, businesses use their experience to predict their sales and profits, not supported in a potential demand based on the globally distributed income, but on the *effective demand* that comes from real-world expenses of the economic agents. From this point, Keynes determined the components of global demand, consumption, and investment, and then consequences for the variations in income, employment, and prices (Delfaud, 1986).

1.2.6 Contemporary Economics

By Keynes' time and afterwards the economic thought had been dividing itself even further in several schools of thought. Some of them are known by the names of their

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respective predecessors or founders, whereas the very names of others define their approach to economics: post-Keynesian, neo-Ricardian, neo-Marxian, institutional, ecological, behavioral economics, etc.

One can basically consider the neoclassical orthodoxy as the present *mainstream economic theory*, and this includes the interpretation of Keynes, theories within the neoclassical equilibrium context, the *IS–LM model* as initially proposed by John Richard Hicks (1904–1989), although it has been argued that this model leaves out the most important dynamic aspects of Keynes' theories (Backhouse, 2002). The other schools are called *heterodox*, including the *post-Keynesian*, formed by those who view Keynesian theories as basically incompatible with neoclassical theory since it essentially disregards economic dynamics, a viewpoint shared by the neo-Ricardians and neo-Marxians.

The *neo-Ricardian school* has its source in the work of Piero Sraffa (1898–1983), who sought to perfect the classical economics theory of value, as originally developed by David Ricardo and others, whereas *neo-Marxians* consider Michał Kalecki (1899–1970) as one of their prominent representatives as he based his theories on the classical class analysis and the physiocratic circular flow of production and income.

Institutional economics considers sociopolitical factors and economic history as being at the core of the evolution of economic practices. That is, it argues that one needs to study the social rules, or institutions, that affect, and even shape, individuals. Institutional economics has Thorstein Veblen (1857–1929) as one of its key founders.

Development economics focuses on helping economically late starters to catch up with more advanced economies (see p. 8 above). The *Schumpeterian school* is based on Joseph Schumpeter's (1883–1950) original thoughts on the role of innovations by entrepreneurs as the driving force of capitalism. Expanding upon Marx's emphasis on technological development, he argued that capitalism develops by the creation of new products and new markets such that successful entrepreneurs acquire temporary monopolies through innovation. Thus, no firm, however entrenched it may appear, is safe from the process of "creative destruction" provided by new technologies.

The *Austrian school* was started by Carl Menger, Ludwig von Mises (1881–1973), and Friedrich von Hayek (1899–1992), who argued that government intervention in the economy leads to the loss of fundamental individual liberty. They say that the free market is the best economic system because there are so many things in the world that are unknowable that it is best to leave everyone alone.

Ecological economics places sustainability at the center of its approach to economic thought, whereas *behavioral economics*, especially originated in the works of Herbert A. Simon (1916–2001), discusses psychological aspects on the

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economic decisions of institutions and individuals, how people are not always rational and self-interested, how they misinterpret information, how they miscalculate probabilities, and how their emotions distort their decisions. So, the main constraint on our decision-making is our limited ability to process the information we have, rather than the lack of information.

This classification of the contemporary schools of thought in economics is not at all comprehensive or unanimous. Different authors provide different views on this matter and advance different classifications, foundational concepts, and authors, as well as interplays among the different theories. It is not the aim of this work to delve into such matters, but the interested reader can find a recent discussion on the different approaches to economics in Chang (2014, ch. 4 and references therein).

The above sections provide only a very small overview of just a few general aspects of economic thought, leaving out many names who played important roles in its development. Some of them will be discussed in the next chapters. Nevertheless, it is clear that economic thought cannot today be viewed as integrated. There are basically three levels of analysis: (1) socioeconomics, the main concern of which is the process of economic distribution among social classes; (2) microeconomics, the analysis of which is based on the behavior of economic agents according to some proclaimed "fundamental laws" about the allocation of resources in a universe of scarcity; it uses a deductive and abstract logic which dominates empirical validation; (3) macroeconomics, which uses some observable and measurable macro quantities, called *economic aggregates*, to try to determine the global economic activity and its tensions like unemployment, inflation, price indices, savings, international trade, and finance (Delfaud, 1986).

From a physicist's viewpoint, this lack of integration due to differing interpretations of what constitutes the core of the theoretical approach to economics somehow resembles the situation in which physics found itself before Newton, a time when there were different interpretations of Aristotle's teachings if we see Galileo as the most crucial critic of Aristotle's physics. It is completely unlike the situation between classical and modern physics. The latter does not at all consider classical physics outdated or rejects its concepts. On the contrary, classical and modern physics complement each other as their respective domains of validity are well determined.

In addition, as we shall see next, classical physics has not stopped developing after the appearance of modern physics. So, such a division between orthodox and heterodox theories simply does not exist in physics. Even theories which seem incompatible with one another, like modern field theory and general relativity, are unashamedly used when necessary, not uncommonly by the same physicist, and all physical theories, classical and modern, are generally taught at undergraduate

https://doi.org/10.1017/9781316136119.004 Published online by Cambridge University Press

and graduate university courses. This is why the division between orthodox and heterodox theories, commonly accepted in economics, is inapplicable in econophysics as we shall discuss in detail in the next section.

As a final comment, one needs to be fair here and acknowledge that one can find economists who also do the same; that is, discuss economic problems using different, sometimes incompatible, theories and compare the different answers provided by them. For instance, Marglin (1984) used the neoclassical, neo-Marxian, and neo-Keynesian approaches to discuss growth and distribution. Another example is Chang (2014), who also often uses several different theoretical approaches to discuss economic problems. Nevertheless, such pluralistic approach to economic problems seems to be the exception rather than the rule among contemporary academic economists.

1.3 Econophysics

As seen in the previous section, economics as it stands today does not seem to possess an integrated set of concepts from where economic systems can be studied, let alone more or less well-defined domains of validity for their various approaches to economic phenomena. Even the definition of what constitutes an economic science varies according to the economic school of thought one chooses as reference.

But, as econophysics is a new area, it will sooner or later provide its own definition of what constitutes economics, economies, and economic systems. However, it is usually better to avoid definitions based on strict logical sentences when discussing specific research areas, since statements of this sort are often either too restrictive, leaving out important issues which should somehow be included in the definition, but are not, or too wide such that everything can be included and, so, ends up defining nothing. Thus, the best initial approach is to start by determining the set of problems actually discussed in a certain area and then seek later a definition based on the domain, or subject matter, defined by these problems.

So, if we follow this practical way of establishing a certain scientific domain, that is, by means of first a list of problems associated with a certain collection of phenomena followed by the methods used in their study, economics can be seen as well defined, since it does have its own circumscribed phenomenological domain of study and collection of methods to analyze the problems within this domain, no matter if those methods come from different schools of thought and are not integrated. A list of economic problems includes the following: dynamics of markets, self-regulating, in equilibrium or anarchy; static and dynamic determination of prices, wages, rents, interests, profits, capital movement, and production; dynamics of economic growth and economic cycles; evolution of industries and firms in terms of technology and revenue; financial movements; stock and labor

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markets; dynamics of economic agents defined as classes or consumers and producers; money dynamics; institutional economic agents like the State; environmental influence in production; distribution and accumulation of income and wealth; value of use and exchange; international commodities markets and trade.

This is clearly an incomplete list which will certainly change in time, as it has already changed since Aristotle's first thoughts on this matter. Thus, when physicists began studying economics, they started with the set of problems already identified by economists. However, the method is not the same since they used the methodology of physics. So *econophysics* cannot be similar to economics simply because although the object of study is the same, the methodology is not (see below). Although there are methodological influences, if econophysics uses the methods of economics, or its mathematically idealized branch of *econometrics*, it is no longer econophysics, but simply economics. This responds to one of the questions posed at the beginning of this chapter.

Interfaces between physics and other disciplines are not new. The nineteenth century witnessed the appearance of various interdisciplinary applications of physics which are still with us today, like *astrophysics*, *biophysics*, and *geophysics*. In those fields, physical concepts and methods were so successfully applied to problems of astronomy, biology, and geology that in various situations there is no longer a clear distinction between the original discipline and its physical counterpart, inasmuch as those successful applications either deeply transformed the original discipline or created entirely new research subfields.

Trying today to make a distinction between the two faces in these interfaces is in some situations almost a bureaucratic task, often accomplished by simply labeling a certain set of problems as belonging to one or the other as a result of simple historical nomenclature inertia. In other situations, such a distinction became almost unnecessary, this being the case, for instance, of astronomy and astrophysics, often referred to the two names used together or, when isolated, one implying the other, especially after the introduction of science-oriented artificial satellites and interplanetary probes. Sometimes the distinction comes only from the specific instrument used to investigate the problem, this being the case of astronomy and space science, respectively ground-based telescopes and artificial satellites. Even so such a distinction becomes entirely blurred when one deals with astronomical objects beyond the solar system. So, in view of these successful experiences of physics interfacing with other disciplines, it should come as no surprise when physicists moved into the social sciences.

To answer another question posed at the beginning of this chapter, in historical terms econophysics emerged in the mid-1990s when physicists started to systematically use concepts, methods, and analytical tools typically applied in the analysis of physical systems to study economic problems. Note again that, although the

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problems come from economics, the method of analysis comes from physics. Therefore, it is not surprising that the name came from a natural derivation from the other interdisciplinary applications of physics mentioned above.

Econophysics is somewhat closer to its "sister" discipline of *sociophysics*, which appeared a bit earlier (Galam, 2004, 2012), than its older "brothers" born in the nineteenth century. Sociophysics focuses on the use of physical methods, particularly of statistical physics, to study social problems. As an example, criminal activity can be modeled statistically by seeing it as a feature emerging from collective social behavior, similar to punishment whose effectiveness is statistically modeled in order to provide measurements allowing to keep the crime rate within acceptable limits (see, e.g., Iglesias et al., 2012, and references therein).

One methodological aspect, however, unites all physical disciplines: the fact that they are empirically based sciences whose foundations are strongly anchored in measurable quantities, experimentally or observationally. As we shall see below, that does not mean a smaller role for theoretical studies; on the contrary, in the end even theoretical concepts require some metric, that is, they have to translate themselves into measurable quantities.

If a theory cannot translate itself into tools and results that can be objectively measured in order to provide evidences for its conclusions, even if this is a future endeavor to be made by an yet unknown technology, the theory is said to be *not even wrong*, in the sense that it has not even reached the stage where it could be disproved. This assessment about a theory or model is attributed to the theoretical physicist Wolfgang Pauli (1900–1958), one of the pioneers of quantum physics and the 1945 Nobel Physics laureate, who used to qualify in decreasing order of importance the work of his colleagues in less than polite terms such as "wrong," "completely wrong," or "not even wrong". The last one meant that the theory was so ill defined and incomplete that it could not be used to make a firm prediction whose failure would show it to be wrong (cited in Woit, 2006, preface). Although purportedly scientific, a not-even-wrong theory is such that it fails at some fundamental level and due to that it is considered as bad science or not science at all.

In summary, if one seeks a distinction between present-day economics and econophysics, one should look at the viewpoints taken by these two areas to approach, study, and solve economic problems. Some recent analyses of the themes studied by econophysicists have already clearly showed such differences in the sense that econophysics approaches economic problems from a very different set of theoretical viewpoints and assumptions as taken by economists. The list of these themes includes topics such as statistical econophysics and the kinetic theory of gases when applied to economic agents or the principles of complex systems dynamics when we start modeling economies as complex systems (see Schinckus, 2010, 2013; Jovanovic and Schinckus, 2013; Drakopoulos and Katselidis, 2015;

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and references therein). Such distinction goes beyond the description of economic issues by means of specific themes and physical theories, reaching the very heart of the epistemology of physics.

However, at this point we are directed to another question: what exactly is this physical viewpoint, this physical approach to problems? This has already been partially answered in Section 1.1 when we discussed the scientific method inaugurated by Galileo. But, the epistemological discussions in physics did not stop with Galileo. Particularly rich are the debates and reflections on philosophy of physics that occurred at the end of the nineteenth century, by the time of the marginalist revolution in economics, and continued throughout the early twentieth century when the modern physics revolution took place. Several well-known eminent physicists of the past participated in this debate such as, among others, Einstein, Planck, and Werner Heisenberg (1901–1976), another key pioneer of the quantum theory who advanced the uncertainty principle, a fundamental concept needed to understand quantum systems. But here we shall focus on the ideas of the physicist who in this author's views superbly synthesized this epistemology: Ludwig Boltzmann.

1.4 Physics, Reality, and the Natural World

Any scientifically minded person living in the early twenty-first century may find it hard to believe that there was a time not too far back when several physicists did not accept the concept of the atom. This was, however, the situation in the physics by the end of the nineteenth century when the atom concept was facing a growing number of opponents, like Wilhelm Ostwald (1853–1932) and Georg Ferdinand Helm (1851–1923), who considered the atomic picture of the world outdated (Cercignani, 1998) and proposed its replacement by the concept of energy conservation and its derivatives. They believed that this energetic viewpoint was the only way of correctly describing the physical world. Boltzmann feared that such a purely energetic representation of the physical world would lead physics to become dogmatic (Videira, 1995) and then passionately engaged himself in intense debates with many other eminent scientists of his time, like Hermann von Helmholtz (1821–1894), Heinrich Hertz, Ernst Mach (1838–1916), Pierre Duhem (1861–1916), Henri Poincaré (1854–1912), and Max Planck, as well as Ostwald and Helm (Boltzmann, 1974; Ribeiro and Videira, 2007).

The issues under discussion revolved around the aims and methods of theoretical physics, the importance of the hypotheses in physics, how a physical theory is built, if one must always start from empirically known facts or one could freely use scientific ingenuity and creativity to build them, or, yet, if the physical theories should describe, instead of explaining, nature. This last point meant putting aside the old ideal of reaching the final causes of natural phenomena.

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Boltzmann sought in those epistemological discussions to assure the survival of his favorite theories, as well as guaranteeing a place for the other ones. The ability of some theory in predicting new phenomena does not make it capable of predicting its own future and, even less, of science. At the same time, if a theory had already produced good results it should not be abandoned. Recognizing the scientific limits of a theory does not mean that it should be excluded from science. The main reason that motivated Boltzmann in trying to better understand the process along which science develops is probably his conclusion that a theory is incapable of predicting its own future. Boltzmann's interpretation of Darwin's theory of evolution gave him the basis from where he was able to reach some important conclusions.

For Boltzmann a scientific theory is nothing more than a *representation* of nature (Boltzmann, 1974; Cercignani, 1998; Ribeiro and Videira, 1998, 2007).

1.4.1 Theoretical Pluralism

By being representations, scientific theories cannot aim to know nature in itself, since such a knowledge would explain why the natural world phenomena show themselves to us the way we observe them. Therefore, such ultimate knowledge is, and will ever be, unknowable, which means that a scientific theory will never be complete or definitively true. This point of view in fact implies the existence of *limits of knowledge*, since it redefines the concept of *scientific truth* by means of the notion that there is indeed a *weak* identification between the researched object and theory, because this identification cannot be (1) unique, (2) complete, and (3) is temporarily limited.

The consequences of these points are as follows: (1.1) the same aspects of the natural world can be represented by more than one theory, often in competition among themselves for the preference of the scientific community; (2.1) as they are representations, or images of nature, the scientific theories will never be able to describe all aspects of natural phenomena, since such a complete knowledge is unreachable; (3.1) a scientific theory can one day be replaced by another. It is the possibility of replacement of one theory by another that defines and constitutes the scientific progress (Ribeiro and Videira, 2007).

Boltzmann's ideas about theories as representations are clearly explained in a passage from the entry "model" he wrote for the 1902 edition of the *Encyclopedia Britannica*:

> Models in the mathematical, physical and mechanical sciences are of the greatest importance. Long ago philosophy perceived the essence of our process of thought to lie in the fact that we attach to the various real objects around us particular physical attributes – our concepts – and by means of these try to represent the objects to our minds. Such views were formerly regarded by mathematicians and physicists as nothing more than unfertile

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speculations, but in more recent times they have been brought by J. C. Maxwell, H. v. Helmholtz, E. Mach, H. Hertz and many others into intimate relation with the whole body of mathematical and physical theory. On this view our thoughts stand to things in the same relation as models to the objects they represent. The essence of the process is the attachment of one concept having a definite content to each thing, but without implying complete similarity between thing and thought; for naturally we can know but little of the resemblance of our thoughts to the things to which we attach them. What resemblance there is lies principally in the nature of the connexion, the correlation being analogous to that which obtains between thought and language, language and writing. … Here, of course, the symbolization of the thing is the important point, though, where feasible, the utmost possible correspondence is sought between the two … we are simply extending and continuing the principle by means of which we comprehend objects in thought and represent them in language or writing.

(Boltzmann, 1974, p. 213)

The conclusion that natural phenomena can be represented by many different theories, even in opposition to one another, constitutes the core of Boltzmann's philosophical thinking, his most important epistemological conclusion, and is usually called *theoretical pluralism*. This clearly follows the thesis that all scientific theories are representations of nature.

As a representation, a scientific theory is initially a free creation of the scientist, who can formulate it from a purely personal perspective where preferences for a certain type of mathematical language, theoretical options, metaphysical presuppositions, and even the dismissal of some observational data, can enter into its formulation. That occurs when the theory is being devised. Nevertheless, for this theory to become part of science, it needs to be confronted by the experience, with empirical facts. If it is not approved in this crucial test the theory must be reformulated, or even dismissed. Boltzmann stressed that inasmuch as all scientific theories are, to some extent, free creations of scientists, scientific work is impossible without the use of theoretical concepts, which originates from the fact that the creation of any scientific theory is impossible simply from the mere observation of natural phenomena because any theory requires some mental acts.

Theoretical pluralism also implies that the *same* natural phenomenon can be described by different theories, since any theory is a construction, an image of the natural external world, and nothing more. According to Boltzmann one cannot do science in any other way. Either it is a representation, a construction, or the theory is not scientific. In Boltzmann's words:

Hertz makes physicists properly aware of something philosophers had no doubt long since stated, namely that no theory can be objective, actually coinciding with nature, but rather that each theory is only a mental picture of phenomena, related to them as sign is to designatum … From this it follows that it cannot be our task to find an absolutely correct theory but rather a picture that is, as simple as possible and that represents phenomena as

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accurately as possible. One might even conceive of two quite different theories both equally simple and equally congruent with phenomena, which therefore in spite of their difference are equally correct. The assertion that a given theory is the only correct one can only express our subjective conviction that there could not be another equally simple and fitting image.

(1974, pp. 90–91)

Since theories are images of the natural world, Boltzmann also noted that all have some explanatory power. In addition, a good theory is achieved by being carefully crafted by scientists, in a process similar to Darwin's natural selection. His words on this illustrate this connection very clearly.

Mach himself has ingeniously discussed the fact that no theory is absolutely true, and equally hardly any absolutely false either, but each must gradually be perfected, as organisms must according to Darwin's theory. By being strongly attacked, a theory can gradually shed inappropriate elements while the appropriate residue remains.

(Boltzmann, 1974, p. 153)

Theoretical pluralism synthesizes the fact that as the complete, or final, knowledge of nature is impossible, a theory can only be better than another. Hence there cannot be any ultimate, or final, scientific theory. Theoretical pluralism is the necessary mechanism which prevents science from risking stagnation. Also within this perspective, *truth is provisional*. In fact, *it can only be provisional* since any theory can only aim to be a temporary explanation of what one chooses, or is able, to observe and experiment in the natural world. A scientific theory is indeed an approximation achieved by different means, that is, by different theoretical constructions, and when it is formulated it is already doomed to disappear, to be replaced by another theory. The always present irony is that no one can precisely predicts when that will happen, unless one takes a dogmatic attitude (see below).

Boltzmann's theoretical pluralism in fact redefines the notion of scientific truth. This is so because since Galileo's times scientists have been accepting the notion of truth as the complete correspondence between models and observations, between theories and empirical facts. Let us call this relationship as the *strong correspondence principle*. Nevertheless, since according to Boltzmann all scientific theories are representations of natural phenomena, and, hence, they are not capable of determining what really constitutes nature, truth in modern science can no longer be thought of as searching to determine nature itself. Therefore, this strong concept of correspondence ought to be replaced by the *weak correspondence principle*, which in turn enables scientists to choose one theory among other possible ones, inasmuch as more than one theory, or model, may represent the same group of natural phenomena and/or experimental data.

At this moment Boltzmann advances another definition of scientific truth, which may be called the *adequacy principle* (Ribeiro and Videira, 2007). According to

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him, theory A is more adequate than theory B if the former is capable of explaining more intelligibly, more rationally a certain set of natural phenomena, than the latter. The following two passages state this point very clearly.

> [L]et me choose as goal of the present talk not just kinetic molecular theory but a largely specialized branch of it. Far from wishing to deny that this contains hypothetical elements, I must declare that branch to be a picture that boldly transcends pure facts of observation, and yet I regard it as not unworthy of discussion at this point; a measure of my confidence in the utility of the hypotheses as soon as they throw new light on certain peculiar features of the observed facts, representing their interrelation with a clarity unattainable by other means. Of course we shall always have to remember that we are dealing with hypotheses capable and needful of constant further development and to be abandoned only when all the relations they represent can be understood even more clearly in some other way.
>
> *(Boltzmann, 1974, p. 163)*

> We must not aspire to derive nature from our concepts, but must adapt the latter to the former. We must not think that everything can be arranged according to our categories or that there is such a thing as a most perfect arrangement: it will only ever be a variable one, merely adapted to current needs. Even the splitting of physics into theoretical and experimental is only a consequence of the two-fold division of methods currently being used, and it will not remain so forever.
>
> *(Boltzmann, 1974, p. 166)*

1.4.2 Scientific Realism

One can derive several important consequences of Boltzmann's epistemological theses (see Ribeiro and Videira, 2007, section 3), but for the purposes of this chapter I shall present just a few of them.

First, besides being a good representation, in the sense of being an adequate description of the natural phenomena, theories can gain the preference of the scientists by means of their *predictive* abilities. Once some theoretical prediction is confirmed empirically, our knowledge about nature increases quantitatively due to the weak correspondence principle. A correct prediction is always formulated in the context of a specific theoretical picture, so by being able to predict unknown phenomena a theory shows its explanatory power, as it is not only able to describe the already known "pieces," but it is also capable of going even further to show the existence of other still missing pieces that are necessary for a deeper and more organized understanding of nature. If a theory gets ahead in the preference of the scientists due to its predictive abilities, it is more likely to be developed and even of incorporating several elements of the less preferred theories. After some period of time, the gap between them may become so large that it may no longer be worth working with the less preferred theories, which are then put aside and, eventually, forgotten.

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Second, theoretical pluralism does not necessarily mean competition among different theoretical constructs, but often means complementarity since all theories possess some explanatory power. Thus, all theories say something about the natural processes that go on in nature as they all use the same or similar set of natural problems they seek to explain. This implies that the emergence of different theories for similar sets of natural phenomena is far from being a problem, but in fact contributes to our better understanding of nature. And if those different theories have elements that contradict each other, observation or experimentation associated to the their internal logic and consistency provide us the mechanisms which allows us to discard the inappropriate elements of the emergent theories while the appropriate elements remain.

When Boltzmann advanced the thesis of theoretical pluralism, he also had the goal of fighting *dogmatism*. While orthodoxy and skepticism are important to science as they preserve the scientific knowledge obtained on solid bases until new theories prove to have enough empirical validation and internal consistency, if they become too deep rooted the scientific community may end up avoiding any change in the established theories, which become dogmatic. If such a situation is not effectively challenged, the scientific debate ceases to exist. Therefore, dogmatism works against scientific progress. Boltzmann believed that once theoretical pluralism was accepted and entirely absorbed into the research practice, it would forbid that, once proposed, a theory could be excluded from the scientific scenario, meaning in practice the extinction of dogmatic tendencies (Ribeiro and Videira, 1998).

Another important point is that under Boltzmann's epistemological views one cannot confuse *reality* with *real*. Reality is the set of mental pictures, or images, of the natural world created in the human brain, whereas real is the nature itself, the external natural world, whose ultimate knowledge is, and will ever be, unknowable. So, nature constitutes what is real, being outside our brains, the real world, but reality is the collection of mental pictures created in our brains by its interface with what is real, with nature. Another way of putting it: reality is a projection of the real, the external natural world, into our internal mental world of observations, perceptions, and measurements. Since reality connects our brains with what is real, this means that *reality is realistic*. But as reality is made of internal mental pictures, or images of nature, which change with time, one can only conclude that reality changes and evolves.

To accept the above set of philosophical presuppositions advanced by Boltzmann, actually means adopting the philosophical position of *scientific realism*. This signifies that all theories must be empirically tested. However, to make an observation or perform an experiment is impossible without the supporting context of a theory in some form or shape, which means that facts are never theory-neutral, that is, they are never free of contamination from one or other theory. So, to reach

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workable theories, to formulate laws of nature, scientists rely on both intuition, which means theorizing, and the constant checking of those intuitions against experiments and facts that come from those theories. This is a highly convoluted process, prone to errors, advances, and retreats, which occurs in the slippery and treacherous ground called research practice. As Einstein (2002, p. 44) put it, "There is no logical path to these laws; only intuition, resting on sympathetic understanding of experience, can reach them."

Finally, testing a theory is not as straightforward as can be initially thought. This is because any theoretical application is built upon a whole series of *auxiliary assumptions* or hypotheses. So, to prove a theory false, or to reach a conclusion about the *falsification* of a theory, one must have to falsify all its auxiliary assumptions. In practice this means that when faced with possibly falsifying data, scientists tend to blame those auxiliary hypotheses and tinker with them before abandoning the entire theoretical structure, which implies that a test is often inconclusive. In addition, because theories are representations of the real, all are intrinsically imprecise and, to some extent, falsifiable (Kuhn, 1996, p. 146). These points taken together explain why it is often so difficult to dethrone a certain theory. Facts only are not enough as one can always tinker with the auxiliary hypotheses and claim that they can be satisfied by revising old, or introducing new, auxiliary hypotheses.

What actually leads to the replacement of a theory is the accumulation of problems in the old theory together with the appearance of a new one, a better theory in the sense of the adequacy principle discussed above (see also Kuhn, 1996, p. 206). This often requires a generational change, as famously remarked by Max Planck, the winner of the 1918 Nobel Prize in Physics: "a new scientific truth does not triumph by convincing its opponents and making them see the light, but rather because its opponents eventually die, and a new generation grows up that is familiar with it" (1950, pp. 33–34). Hence, theories must be constantly checked against old and new empirical facts, and only time will tell if, and until when, they survive this process.

Bearing this point in mind, we must also include in this epistemological discussion the *testability principle*: the main requirement of a scientific theory is that it should be in some way testable against existing or new empirical facts. In other words, to be useful a theory must be vulnerable, since its testing means unwrapping auxiliary hypotheses that often are hidden at first (Baggott, 2013, p. 20).

To conclude this section, the paragraphs above are just a general presentation of epistemological concepts adopted in practice by most physicists. This epistemology was inherited from various eminent physicists of the past and goes as far back as to Galileo, but came mostly from the physicists who were active participants in the modern physics revolution that occurred at the turn of the nineteenth to the

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twentieth century. They shared Boltzmann's ideas and saw their work in physics as natural extensions of their philosophical positions. Some of them actually expressed themselves in philosophical matters, this being particularly the case of Einstein, Poincaré, and Heisenberg. As a consequence, twentieth-century physics was overwhelmingly influenced by their philosophical positions, influence which is still present in the early twenty-first century.

1.5 Economics, Reality, and the Real World

Let us now turn back to economics and discuss it under the epistemological perspective presented in the previous section. Since this discipline also calls itself "economic science," we are entitled to ask whether or not scientific realism has also been adopted in economics. In this respect, the first point worth mentioning is that the lack of an integrated economic theory, as discussed in Section 1.2, cannot be seen as a problem since theoretical pluralism states that the same set of scientific questions can be described by different theories. So having a collection of classical and neoclassical theories, or orthodox and heterodox approaches to economics, is in fact an asset to the discipline. Some have criticized economics because it became self-referential in the sense that it moves by its internal problems. Again, this is not really an issue since any scientific discipline is fundamentally moved by its own internal dynamics.

However, clear indications of an abnormal condition would be if theories are no longer systematically validated by empirical testing or if there is a concerted attempt to put one of these various approaches to economic problems as the *only* legitimate starting point for addressing economic questions and try to suppress the others, especially in teaching. Both situations would certainly stem scientific progress, and the second one clearly characterizes a dogmatic attitude that can only be viewed as anti-scientific.

Unfortunately, this seems to have happened at least partially in economics. Recent evidence of the lack of pluralism within economics is the appearance of the post-autistic economics (PAE) movement, initiated by a group of Parisian economic students who, in June 2000, circulated a petition calling for reform in their economic curriculum. They complained about the narrowness of their university economic education, the one-sided way of addressing economic questions and asked for a broad spectrum of analytical viewpoints, more efforts to support theoretical claims with empirical evidence and interdisciplinary dialogue. Their petition was quickly followed by similar petitions from economic students in several other countries, which were then also supported by a no small number of economists worldwide. The speed in which the PAE movement has spread, gathering worldwide support in less than two years, surprised everyone involved

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and clearly showed a deep dissatisfaction with the way economics is taught in several of the world's universities.[1]

Actually, the very existence of two seemingly watertight approaches to economic questions, an orthodox as opposed to a heterodox one, and the fact that the neoclassical economics viewpoint is considered "mainstream," a situation that in practice relegates the alternative theories to the sidelines of economic thought, indicates that the problems felt by the students who started the PAE movement – lack of theoretical pluralism and empirical grounding in economics, one theoretical viewpoint elevated as the one solely capable of providing concepts and tools to analyze economic phenomena and bring understanding to real-life economic issues, especially in its research modus operandi – are not a recent occurrence. Classical political economy certainly has theoretical problems, but according to theoretical pluralism the existence of open problems, puzzles, or limitations is not enough for the abandonment of an empirically sounded theory, especially because certain ways of addressing economic problems are unique to this theory, like the economic influence of social classes and the central role of the economic surplus.

The abnormalities in economic thought indicated above are in fact a manifestation of what may be considered as the deepest epistemological predicament in economics: the effective divorce between theory and empirical evidence. There is a tendency to assume that the main theoretical problems in economics are solved only theoretically, by a logical dispute between different theoretical visions, and not by referral to empirical data and results. This is a kind of Aristotelism, in the pseudoscience sense (see p. 6 above), that goes against everything that physics has stood for since the time of Galileo, as it treats experimental and observational data almost with contempt. It does not lead to the creation of a theoretical reality, but of a theoretical illusion.

In other words, such a divorce between theoretical thought and empirical evidence does not create a reality in the sense of being an interface between our internal mental pictures and the real external world, but an illusion made of a group of mental pictures unrelated to the real world. Therefore, even models which might have been initially inspired by empiricism, but which in turn are not systematically put to test, produce conclusions which quickly escalate into the surreal world of theoretical illusions. What happens then is a complete inversion of what scientific realism stands for, because those who are imbued with these theoretical illusions assume then that reality *must* follow them.[2] So, anything empirical becomes just

[1] See www.paecon.net/HistoryPAE.htm (accessed September 28, 2018) for a brief history of the PAE movement.
[2] Ribeiro and Videira (1998) named this phenomenon *scientific dogmatism*, which occurs when scientists become unreasonably overconfident that their theories are true in the sense that nature does follow them. By doing so, these overconfident researches confuse reality with what is real, theory with the external world, representations with nature.

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an attempt to reinforce these illusions and what does not fit into them are labeled *externalities*; that is, exogenous facts that do not belong to the phenomenon, but are outside it, which is just a fallacious way of stating that the model is unable to address those real-world facts.

This means that to talk about externalities is in fact a refusal to grant scientific defeat. But, when researchers are in scientific denial, that is, are incapable of admitting their failure to come up with realistic representations of the real world, the process of force-fitting empirical data, and not using data to seek hypothesis validation, becomes the norm, resulting in an entirely upside-down "scientific" methodology which then becomes the supposedly "natural" way of doing things (see examples on p. 38 below).

Physicists embodied by the scientific method quickly detect these abnormalities in mainstream economics and, more generally, in the way economics is actually practiced nowadays (see, e.g., Blatt, 1983, pp. 4–8; Roehner, 2002, sections 1.3–1.4; Bouchaud, 2008, 2009; McCauley, 2009, chs. 1–2; Sinha et al., 2011, pp. 1–5; Buchanan, 2013; Cristelli et al., 2014; Sylos Labini and Caprara, 2017), a situation that can only lead to the conclusion that the present-day academic economics is epistemologically sick. Physicists, however, were not the first to identify this illness, it was the economists themselves. There is a large literature on this (Blaug, 1998; Keen, 2009b, 2011a; Hudson, 2012; and references therein), but for the purposes of this chapter only a few relatively recent examples will be presented.

Let us start with Paul Ormerod, who advanced the following viewpoint regarding those matters.

> An internal culture has developed within academic economics which positively extols esoteric irrelevance. Despite new emphasis in some of the very best work being done … on confronting theory with empirical evidence, a relatively low status is given to applied work, involving the empirical testing of theories, in contrast to pure theoretical research … Contemporary orthodox economics … method of analysis is isolated from the wider context of society, in which the economy operates, and … its methodology, despite the pretensions of many of its practitioners, is isolated from that of the physical sciences, to whose status it none the less aspires.
>
> *(Ormerod, 1997, pp. 20–21)*

Mark Blaug was also very critical of the teaching in economics:

> Economics as taught in graduate schools has become increasingly preoccupied with formal technique to the exclusion of studying real-world problems and issues … Economics has increasingly become an intellectual game played for its own sake and not for its practical consequences. Economists have gradually converted the subject into a sort of social mathematics in which analytical rigor as understood in math departments is everything and empirical relevance (as understood in physics departments) is nothing … [General equilibrium theory] has become a perfect example of … "blackboard economics," a model

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that can be written down on blackboards using terms like prices, quantities, factors of production, and so on, but nevertheless is clearly and even scandalously unrepresentative of any recognizable economic system … It is high time that economists re-examine their long-standing antipathy to induction, fact-grubbing, and fact gathering before, and not after, we sit down to theorize.

(1998, 12–14, 30)

Blaugh also noted that "the rot goes back to" John Hicks and even Joan Robinson (1903–1983), works that respectively appeared in 1939 and 1933, concluding that "Modern economics is sick" (1998, see also n. 6).

Steve Keen also voiced similar thoughts regarding his education in economics:

[W]hat I had initially thought was an education in economics was in fact a little better than indoctrination. More than a decade before I became an undergraduate, a major theoretical battle had broken out over the validity of economic theory. Yet none of this turned up in the standard undergraduate or honours curriculum … There were also entire schools of thought which … were ignored unless there was a dissident on the staff … Why has economics persisted with a theory which has been comprehensively shown to be unsound? … The answer lies in the way economics is taught in the world's universities.

(Keen, 2001, preface)

Years later, after the 2008 economic crisis began, he added that "neoclassical economists were about the only ones who were ill equipped to see it coming" and that "as a means to understand the behavior of a complex market economy, the so-called science of economics is a melange of myths" (Keen, 2011a, preface to 2nd ed.).

Backhouse (2002, ch. 11) discussed how the mathematization of economics starting in the 1930s actually led to a separation between economic theory and economic applications, and this also led to a divorce between theoretical and empirical research. Lionel Robbins (1898–1984) provided the intellectual basis of such an approach by arguing that the main economic theses could be obtained without knowing much more than just that resources are scarce, which suggested that a theory could be sought in a way highly independent from the empirical world. This meant that theoreticians could ignore the empirical works since the task of testing theories falls on econometrics. This point is also shared by Hudson (2010), and Mandelbrot. The latter stated the following in this respect.

Compared to other disciplines, economics tends to let theory gallop well ahead of evidence. I prefer to keep theory under control and stick to the data I have and the mathematical tools I have devised.

(Mandelbrot and Hudson, 2004, p. 229)

Chang (2010) pointed out the absence of economists in the governments of East Asia during the miracle years when their economies boomed, roughly after the 1950s, and advanced as possible explanation that "economics taught in university

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classrooms is too detached from reality to be of practical use." In addition, he argued that "modern economy is populated by people with limited rationality and complex motives, who are organized in a complex way, combining markets, (public and private) bureaucracies and networks." He concluded that "Economics does not have to be useless or harmful. We just have to learn the right kinds of economics" (Chang, 2010, pp. 244, 250–251).

Hudson (2012, p. 116) argued that neoclassical economics came to being not because there was some kind of understanding that the limits of validity of classical political economy had been reached, in a similar way modern physics came to being to extend classical physics, but as a kind of reaction movement whose purpose was to change the topic from the social implications of the classical theory a view somewhat shared by Screpanti and Zamagni (1993, pp. 149–155). Hudson systematically referred to neoclassical theory as "post-classical" to emphasize its "anti-classical" nature, or even as "junk economics" to emphasize its unrealistic underlying assumptions. He strongly criticized the way mathematics is used in economics:

> To mathematize economic models using obsolete or dysfunctional concepts hardly can be said to be scientific, if we define science as the understanding of how the world actually works … Many economists are trained in calculus and higher mathematics without feeling much need to test their theories quantitatively. They tend to use mathematics less as an empirical measuring tool than as an expository language, or simply as a decoration to give seemingly scientific veneer to their policy prescriptions … The main criterion of success in modern economics is its ability to maintain internal consistency in the assumptions being made. As in science fiction, the trick is to convince readers to suspend their disbelief in these assumptions … *What modern economics lacks is an epistemological dimension.*
>
> *(Hudson, 2012, pp. 163, 168, 172, 175, emphasis added)*

Häring and Douglas (2012) went further and argued that it was the influence of the powerful that changed and distorted theoretical economics so that it ignored critical empirical facts. Their analysis aimed at focusing on this issue:

> [We] examine how we got from an economic science that treated relative economic power as an important variable and regarded the resulting income distribution as a core issue of the discipline, [changed] to a science that de-emphasizes power and does not want explicitly to deal with distributional issues.
>
> *(Häring and Douglas, 2012, p. 1)*

> [T]hese external influences have, over the decades and centuries, created a science that is strongly biased in favor of negative viewpoints regarding issues like creating equality of opportunity … [and] neglecting or even denying the influence of power and the tendency of market economics toward the concentration of wealth, power and opportunity in a minority.
>
> *(Häring and Douglas, 2012, p. 45)*

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Mirowski (2013) discussed "the economic crisis as a social disaster, but simultaneously a tumult of intellectual disarray." His major thesis was that "most economists did not understand the economy's peculiar path prior to the crisis, and persisted in befuddlement in the aftermath," a situation which he considered as a "catastrophic intellectual failure of the economics profession at large" (Mirowski, 2013, pp. 15, 18).

Finally, Gallegati (2018) voiced similar criticisms, stating that "the economic theory taught in almost all universities around the world is axiomatic and seems inadequate to explain the real world," adding that "the real problem lies … in the fact that the dominant economic theory does not contemplate a major crisis." He concluded by criticizing mainstream neoclassical economic theories not because the lack of use of advanced techniques, but because "it just uses the wrong ones" (Gallegati, 2018, pp. 17, 19, 20).

Concluding this section, it must be noted that the above-discussed epistemological sickness afflicting economics is not unique to this discipline. Physics is not immune to it, as various authors have indicated that certain branches of modern theoretical physics have fallen ill of the same disease (Woit, 2006; Baggott, 2013; Unzicker and Jones, 2013, and references therein). These authors strongly criticized some physicists working on some problems of theoretical physics under the same epistemological position as modern economics was criticized above, i.e., that replacing experimentation, observation and testing with theorizing means giving up the scientific method (see also Ellis and Silk, 2014).

There is also a dangerous tendency to think of results coming from computer simulations made with equations used in domains where their empirical validity is not well established, or coming from untested theories, to be seen as if they were empirical results, rather than, at best, just general indications of the possible behavior of the phenomena under study. In this respect it is worth remembering the criticism made by the well-known Soviet physicist Lev Davidovich Landau (1908–1968) to his colleagues who worked on cosmological problems in the 1960s and at that time already had lots of speculative theories about how the universe evolved, but very little empirical facts coming from astronomy. He stated that "cosmologists are often in error, but seldom in doubt." Considering that the temptation to substitute empirical results for logical reasoning seems very hard to resist in the present-day academic economics, a situation which may well explain the recent failures of mainstream economics regarding its inability to see the 2008 crisis coming, one may paraphrase Landau and state that a great deal of academic economists appear to be mostly in error, but never in doubt.

The modern physics revolution that started in the late nineteenth century was overwhelmingly influenced by physicists with strong philosophical backgrounds, this being particularly true of those in the German-speaking world. One of the many

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tragedies of Nazi Germany was the destruction of several academic institutions in physics and mathematics which kept this philosophical tradition alive for centuries, and this destruction contributed to a slow decline of the philosophical influence in physics as it developed in the second half of the twentieth century. Hence, the above critique of the ways certain branches of theoretical physics have been developing lately are just a consequence of this loss of philosophical tradition. Thus, historical perspective suggests that both physics and economics would greatly benefit from the return of some philosophical education.

1.6 Econophysics and the Empirical World

We can now discuss the final question posed at the beginning of this chapter, of whether or not and in what way econophysics can contribute to the improvement of our understanding of the economic phenomena. To better answer this question we should briefly look first at the works made by a few econophysicists before the term econophysics was coined and the area created, that is, before 1995. The short list below of earlier econophysicists is not at all comprehensive, but is enough for the purpose of showing some important real cases of the different viewpoints taken by those physicists when approaching economic problems.

1.6.1 Before 1995

The first true econophysicist in the sense we understand the term today was Louis Bachelier (1870–1946). He was in fact a trained mathematician, but discussed the Brownian motion five years before Einstein and applied it in the study of finance in his PhD thesis entitled "Théorie de la spéculation" and finished in 1900. His PhD supervisor was Henri Poincaré and his work basically provided the foundations of mathematical finance. The results obtained by him became essential to this topic, although their seminal importance went largely unrecognized for several decades (Courtault et al., 2000; Mandelbrot and Hudson, 2004, ch. 3).

Frederick Soddy (1877–1956) was a physicist who, in the first two decades of the twentieth century, worked on radioactive decay problems and whose outstanding achievements earned him the 1922 Nobel Prize in Chemistry. Afterwards he turned to economics and wrote a book summarizing his findings where he advanced the proposition that "[t]he production of Wealth, as distinct from Debt, obeys the physical laws of conservation and the exact reasoning of the physical sciences can be applied" (Soddy, 1926, p. 294). He distinguished between real wealth and virtual wealth, the former being the means of production, machinery, buildings, tools, etc., whereas the latter is made of money and debt. For him, real wealth is subject to the laws of physics whereas debt is subject to the laws of mathematics since debt

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does not decay with time and is not consumed in the process of living. Since debt is basically financial claims on real wealth, it tends to expand more rapidly than the production of real wealth available to pay for the virtual wealth. Although he seems to have been entirely ignored by academic economists of his time and for several decades afterwards, perhaps because they were focused on building the theoretical edifice of neoclassical economics and Soddy was very critical of various prevalent concepts of this theory, his ideas seem to be making a recent reappearance (Martin Hattersley, 1988; Daly and Rufus, 2008; Zencey, 2009; Hudson, 2012, p. 416).

Matthew F. M. Osborne (1916–2003) was a physicist who worked on several problems of applied physics, like the hydrodynamics of migrating salmon, before turning his attention to the stock market and finance. His book on these topics clearly exemplifies how a trained physicist views economic and financial problems, using both real cases found in the history of physics and issues from philosophy of science, to discuss the usability of mathematical axioms and their limitations when applied to empirical sciences (Osborne, 1977, sections 3.3–3.5).

Of particular relevance to the issues raised in this chapter is his discussion about the theorem proved by Kurt Gödel (1906–1978), which states that any domain defined by a set of axioms will always raise questions which cannot be decided within that predefined axiomatic domain. Hence, there will always exist a finite range of experience and understanding where our ideas work, which means that we "can understand the theory best when [we] find out where those boundaries are. So Gödel's theorem puts a limit on the power of logic itself" (Osborne, 1977, p. 112).

Osborne also confronted the idealized supply-and-demand functions found in elementary textbooks of orthodox microeconomics, the so-called Marshallian cross diagram (see, e.g., Gregory Mankiw, 2009, p. 77), with real-life examples (Osborne, 1977, sections 2.3–2.4; see also McCauley, 2009, section 2.4) and concluded that "it is indeed very difficult to extract from real data what a real life supply and demand curve is like," although it must be noted that some of his real-life supply-and-demand curves had some resemblance to the idealized version, but not in the way economists portray it. He also noted that "supply and demand are both altered by [a] transaction and that there is an asymmetry of information in who has knowledge of the other demand and supply functions" (Osborne, 1977, pp. 18, 25–27).

Echoing Boltzmann in some sense, Osborne voiced what social scientists do not seem to have learned:

> [I]t is an incorrect procedure that data should be made to fit the theory. ... As a result [social scientists] very often won't even undertake an investigation and collect data unless they have some sort of a theory or model to fit the data to. This is not the way significant

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discoveries are made, ... [which is] probably an explanation ... of why economics is called the dismal science, but that doesn't prevent economics from being important.

(1977, p. 19)

John Markus Blatt (1921–1990) was an Austrian-born physicist specializing in nuclear physics and superconductivity, who in the 1970s turned his attention to economics. His writings on this subject showed that his economic interests were mainly focused on the dynamics of economic phenomena. He considered the trade cycle as the most striking example of dynamics in economic systems and devoted his first book to this subject, critically surveying the most important dynamic economic theories (Blatt, 1983). He criticized neoclassical comparative statics analysis by stating that "it is by no means true that *all* dynamic behaviour can be understood best, or even understood at all, by starting from a study of the system in its equilibrium state" since there are systems whose important and interesting features are essentially dynamic (Blatt, 1983, p. 5). Echoing Boltzmann's discussion on dogmatism (see p. 25 above), Blatt argued:

[T]he main enemy of scientific progress is *not* the things we do not know. Rather, it is the things which we think we know well, but which are actually not so! Progress can be retarded by a lack of facts. But, when it comes to bringing progress to an absolute halt, there is nothing as effective as incorrect ideas and misleading concepts.

(1983, p. 6, emphasis in the original)

[T]he theory of [Blatt's] book ... *is* directly relevant to something equally prevalent, namely the creation of economic myths and fairy tales, to the effect that all our present-day ills, such as unemployment and inflation, are due primarily to the mistaken intervention by the state in the workings of what would otherwise be a perfect, self-adjusting system of competitive capitalism. This system was in power in the nineteenth century. It is well-known that it failed to ensure either common equity ... or economic stability ... [T]he failure of stability was no accident, but rather was, and is, an inherent and inescapable feature of the freely competitive system with perfect market clearing. The usual equilibrium analysis *assumes* stability from the start, whereas the equilibrium is highly unstable in the long run. The economic myths pushed by so many interested parties are not only in contradiction to known history, but also to sound theory.

(1983, p. 8; emphases in the original)

In collaboration with Ian Boyd, his PhD research student at the time, this dynamic approach was further advanced. They argued that

the essential features of the observed trade cycle of a laissez-faire system cannot be understood in purely real terms. Rather, it is necessary to include the psychological variable of "confidence" with its major effects on credit conditions, and thence on the "real" economy.

(Boyd and Blatt, 1988, p. 1)

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They also proposed a model of trade cycle incorporating an investor confidence variable as a major element with a usable definition that relates it to what they called "horizon of uncertainty" which is "the time interval over which the typical investor is prepared to place at least some trust in his, or other peoples', predictions of the future" (Boyd and Blatt, 1988, p. 4). As we shall see in later chapters, Blatt's approach to the dynamics of economic systems will significantly influence our discussions.

When in the mid-1990s the term econophysics was coined, formally defining and establishing this new research field (Eugene Stanley, 2008), physicists started to join in in growing numbers and as a result a flurry of econophysics research activity came about. This inevitably also led other physicists to voice similar criticisms to mainstream economics. Some of them have already been mentioned and others will be reviewed as needed in the next chapters.

Nevertheless, considering the brief presentation above, quite apart from Bachelier who basically created the field of finance, both Osborne and Blatt did not dismiss conventional economic theories, but looked at them from a physicist's viewpoint and in doing so they basically disagreed with several, if not most, of the prevalent neoclassical assumptions and results because they compared those results and assumptions with empirical facts. Note that both of them were trained physicists and their criticisms of neoclassical economics are essentially similar to the above discussed epistemological sickness of academic economics (see p. 29 above). As a consequence, those authors stood in a position highly critical of mainstream economics, on par with the previously examined criticisms made by economists themselves, but that does not mean that they were in favor of all results of classical political economy or dismissed entirely the neoclassical theoretical body. In fact, recent research in econophysics has stressed the need to be careful of criticizing orthodox economics, because neoclassical equilibrium theories were initially based on a reasonable attempt to understand the economic phenomena (Doyne Farmer and Geanakoplos, 2009).

In summary, physicists criticizing the foundations of neoclassical economics is not at all a new phenomenon. For several decades various physicists working independently on economic problems have been voicing criticisms that varied from serious reservations to flat-out rejection of most mainstream economics theoretical premises and conclusions under similar grounds: that they were reached without following basic scientific methodology. This translates into the absence of empirical foundations for those theories, a fact which inevitably led to the creation of several myths and illusions rather than sound scientific theory, results, and conclusions.

So, from this assessment of mainstream economic theory it is not difficult to understand why, prior to the 2008 financial crisis, the economics profession was

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so misguided in its evaluation of macroeconomic stability, misguided to such an extent that Robert Lucas, the 1995 winner of the Nobel Prize in Economics, wrote:

> [M]acroeconomics ... succeeded [in solving the] central problem of depression prevention ... for all practical purposes ... for many decades.
>
> *(Lucas, 2003)*

The former chairman of the Federal Reserve, the central bank of the USA, also strongly underestimated economic volatility because it was thought it had been tamed, or "moderated," by the supposed achievements of economic theory (Bernanke, 2004). As it turned out, economists were taken aback when the crisis started (Colander et al., 2009; Kirman, 2009; Krugman, 2009).

But, now that we are aware of the important limitations of neoclassical equilibrium theories, we can start the hard work of laying new foundations to go beyond.

1.6.2 Methodology

Considering what has been set out so far in this chapter, it is clear that the first, and perhaps major, contribution of econophysics to economics is epistemological, that is, to bring the scientific methodology that proved so successful for centuries in physics to the economic mainstream in order to bring to economics its missing epistemological perspective, as mentioned above by Michael Hudson. Again, this viewpoint is not really new (Roehner, 2002; McCauley, 2009; sections 3 of Moura and Ribeiro, 2009, 2013, and references therein) and some economists have also reached at a similar conclusion (Drakopoulos and Katselidis, 2015). Inasmuch as the previous interfaces of physics with other disciplines proved so successful, e.g., astrophysics, geophysics, and biophysics, there is a good chance that econophysics will follow suit.

1.6.2.1 Epistemology

The epistemological perspective that ought to be brought by econophysics may be divided into three major aspects. First and foremost, it is mandatory to *bring empirical testing and validation of economic theories and models to the forefront of economic analysis*, meaning that theories and models must propose some metric for their quantitative testing. In other words, *models and theories must be made vulnerable to empirical scrutiny*. It is preferable that this metric comes with the proposal of the model, but there is also room for theoretical work where such metric proposal may come later. If that does not happen, the theory or model are destined to fall into Pauli's not-even-wrong category and should not deserve much attention until someone somehow makes them testable.

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Second, *research in economics must look at the data with as little theoretical preconceptions as possible* in order to try to discover patterns, regularities, processes, structures, and interrelationships that may indicate where theories can be built. The aim must be to define a problem arising during empirical research and then devising or selecting a theory capable of solving it. This entails data-oriented studies based on appropriate metrics where the number of possible free parameters must be kept to the bare minimum during the theory-building process, and can only increase once the theory is well tested and validated. The opposite path, that is, hypothesizing the key theoretical roles and then looking for evidence to test the hypothesis will, most likely, lead to the process of data being force-fitted into models during the data analysis process, a situation equivalent to putting the scientific method upside down. Such path very rarely produces functioning theories, even in physics, because it fails to consider multiple competing, and often equally consistent, hypotheses.

A striking example of such upside-down way of thinking within economics comes from the following statement allegedly expressed by Edward C. Prescott, the 2004 Nobel Prize Winner in Economics: "If the model and the data are in conflict, the data must be wrong" (cited in Farmer, 2016, p. 49) This statement reportedly appeared in defense of a research programme that advocated the use of data "selectively to judge a theory," called "calibration" (Farmer, 2016, p. 49). William F. Sharpe, the 1990 Nobel Prize Winner in Economics, also expressed a similar viewpoint.

> I've been amazed at how little you can trust any empirical results, including your own. I have concluded that I may never see an empirical result that will convince me that it disconfirms any theory. I'm very suspicious. If you try another time period, another country, or another empirical method, you often will get different results. Fischer Black,[3] in a wonderful talk that was published toward the end of his life, explained why theory is much more important than empirical work.
>
> *(Bernstein, 2005, p. 43)*

Bearing in mind the epistemological viewpoints expressed above, such statements indicate lack of understanding of the history of sciences, that science evolves through a process that intertwines theory with experimentation and/or observation. So, real science does not place theory above experimentation or empirical evidence, theory above the data. Or the other way round. A cursory study of the history of science shows abundantly clear that the best scientific theories are the ones that survive once they are compared to data that were not previously "selected." By selecting data to judge a theory one can prove anything right. Data, of course, can

[3] Fischer Sheffrey Black (1938–1995).

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be wrong, but one cannot distrust empirical data due to that, but work toward better data. And inasmuch as models are representations, a result produced by a model does not necessarily mean that it will be present in the real world.

These statements express a view that puts theory above empirical validation, which is very far from being the most productive way of doing science. If Galileo had done that 400 years ago it is very possible that physics would still be Aristotelian and we would have missed all technological results brought about by the applications of classical and modern physics, from airplanes to smart phones.

Another example of such upside-down way of thinking was presented by Roger E. A. Farmer, who argued that "all models are wrong ... [because this] is the definition of a model" (Farmer, 2016, p. 49). Under the epistemological perspective advanced here all models do have some explanatory power and, so, they are correct to some extent. But, by being representations they have limitations, sometimes so severe that it is best to put the model aside and produce a new one. So, all models are both right and wrong to some extent, and the task of science is exactly to find these limitations, conclude which models are more adequate representations of the real world and, if inadequate, throw them away and propose better models.

Finally, *theoretical pluralism must be taken by heart in economics research*, which means that there cannot be an a priori dismissal of any school of economic thought, orthodox or heterodox, neoclassical economics or political economy. At the present state of affairs all of them have something to contribute to the understanding of economic phenomena, but all of them need to be empirically scrutinized through the modern economic databases available worldwide for most, if not all, countries in order to see if their theories and models stand the test of experience and observation. No author, however important to political ideology, can be left out of such close scrutiny and only through this process will we see if their ideas reflect how nature operates and, therefore, truly belong to science, or if those ideas belong someplace else.

If the epistemological perspective proposed above were actually absorbed into economics research practice it will probably bring about a change of paradigm in economics, in fact a possible scientific revolution in the Kuhnian sense (Kuhn, 1996). Nevertheless, transformation processes of this sort do not come about easily, since evidence from the history of sciences suggests that paradigmatic shifts in scientific disciplines do not happen smoothly, being usually resisted at every corner. And although various econophysicists and a few economists believe that this is the only way out of the present intellectual crisis of academic economics, it remains to be seen whether or not its current practitioners will learn from this crisis and change the profession or if the discipline will eventually have to be taken over by scholars originated from different areas like, among others, physics.

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Whatever outcome this changing process in economics brings, there are a few practical developments resulting from the three methodological points above that are worth some brief comments.

1.6.2.2 Theoretical Physics

Despite the warning words above about following a path that starts from pure theoretical speculation, it must be mentioned that Einstein's general relativity theory advanced in 1915 was in fact developed by following this speculative theoretical path. That was so because Einstein proposed a theory that was not suggested by data, but arose from pure theoretical reasoning based on his views about some theoretical inconsistencies of Newtonian mechanics and his desire to extend his special relativity theory advanced a decade earlier.

Notwithstanding, to the general astonishment of the physics academic establishment of the time the theory was validated by astronomical observations almost immediately afterwards. Since then, it has been subjected to intense observational and experimental scrutiny, especially after the dawn of the space age, using (unselected) data of all kinds, from gravitationally bound binary stars to the GPS navigational system, to name just two among many, and survived the test of time by consolidating its empirical validation one test after another, in addition to having opened up an entirely new theoretical view of the physical world, a situation that helped to elevate its theoretical and experimental importance to new levels, although at the time of writing some competing gravity theories have not yet been entirely ruled out by solar system experiments and gravitational waves measurements (Moskvitch, 2018; Sakstein, 2018).

This was, however, a rare case, perhaps the only one, of a successful physical theory built that way: proposed without a clear set of experimental facts that suggested the need of a new theory and only afterwards being tested and successfully validated empirically. For this reason, it cannot be considered a role model of scientific investigation, especially if we remember that Einstein himself tried very hard, but failed, to repeat his own feat in the last four decades of his life when he devoted himself to finding a physical theory unifying gravitation, electromagnetism, and quantum theory (Pais, 2005), a task that to this day continues to elude theoretical physicists.

So, although this speculative path for proposing scientific theories might sometimes work, its success rate as measured by an a posteriori empirical validation can be considered as exceedingly rare even in physics. Nevertheless, its impact on economics might had been considerable, because one may speculate that since Einstein's achievements in theoretical physics coincided temporally with the consolidation of neoclassical economics, it is possible that economists might have misunderstood the role of theoretical reasoning by failing to recognize the

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uniqueness of Einstein's achievements and to note his subsequent inability in repeating his own previous triumphs using pure theoretical reasoning. The net result of these failures was the entirely unwarranted claim that theoretical reasoning is more important than empirical verification of theories.

1.6.2.3 Scientific Method

The systematic application of the scientific method creates in practice a virtuous circle where theoretical and experimental approaches occur in parallel and complement each other, inasmuch as they progress in a reciprocal feedback that in fact constitutes two sides of the same coin. This is why physics is both an experimental and theoretical science. However, experiments are characterized by a high level of controlability and reproducibility, whereas this is not possible when one deals with observations, which have a low or unpredictable level of reproducibility and no controlability. Nonetheless, both experiments and observations require some metric and measurement tools in order to allow the phenomena to be studied quantitatively.

Since economics deals with social issues, experiments in controlled conditions may be either unrealistic or undesirable on ethical grounds. Even if they are allowed by some ethical code, perhaps similar to what happens to testing of pharmaceutical compounds on animals and humans, due to its social nature the possible economic experiments may be too limited to be of a value. In this case, researches are left to no other option than to rely on observations, which put them on a par with astronomy as astronomical objects cannot be created or reproduced in a laboratory (at least not yet). The major difference is that observations are much less constrained than experiments and, thus, are subject to much larger margins of error.[4] But, they will have to do if experiments are either impractical or undesirable.

1.6.2.4 Probability Theories

Another important aspect to be considered is that scientists always work under a reasonable degree of subjectivity when performing scientific research. This is so because under the viewpoint that all theories or models are representations, or images, of the real world, by necessity they circumscribe and limit reality in one way or another as the scientist must necessarily pick and choose among various aspects of reality to be added into a model.

This is, of course, also valid when one sees nature through the lens of probability theory, that is, in statistical and stochastic modeling, which implies that in using a model based on probability theory to reach a conclusion about the possible outcome

[4] Errors in physical measurements will be discussed in Section 4.1.1.

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of an event, the calculated probability, even when accurately derived from theory, will in itself also provide a partial and incomplete answer about this outcome, since all models, probability theories included, are partial and incomplete representations of the real world.

Therefore, no probability calculation can be used as a kind of empirical measurement like, for instance, temperature, which is based on an objective physical way of interacting with nature. Perhaps the best way of describing this situation is to use the word *expectation* in the sense that we expect something to occur by means of a certain probability calculation. Even so, an event having, say, 99.9999% probability cannot be expected to have a sure outcome because this probability calculation is based on a theory which in turn is a necessarily limited, therefore incomplete, image of the real world. Due to this the expectations of small probabilities have even less meaning and we may take this reasoning to the point that very small probabilities may have almost no meaning at all in terms of expectations. This is, perhaps, what Nassim Taleb called "true randomness" because this whole discussion is really about the limits of knowledge in probability theory (2010, pp. 339–360), a point somewhat popularized by the well-known quote about "unknown unknowns," that is, things we do not know that we do not know (Rumsfeld, 2002).[5]

This point of view regarding probabilistic calculations leads us directly to *Bayesian statistics*. Currently there are two ways of defining probability: the *frequentist* definition assumes that probabilities represent long-run frequencies with which events occur. In other words, probability in *frequentist statistics* is only meaningful in the context of repeated experiments, or multiple trials, even if those repetitions are only hypothetical. The *Bayesian* definition assumes that probabilities are degrees of credibility that an event will occur. So, probability in Bayesian statistics is seen as a *measure of belief*, that is, it is something subjectively used to describe uncertainties because it quantifies our ignorance that something will happen. In other words, in the Bayesian view, probabilities are essentially linked to our degree of knowledge about an event (D'Agostini 2003, section 2.2; VanderPlas, 2014).

The Bayesian statistics is based on *Bayes' rule*, sometimes also called the *Bayes–Price–Laplace rule*, after Thomas Bayes (1701–1761), Richard Price (1723–1791), and Pierre Simon Laplace (1749–1827), those behind its original formulation,

[5] Two other manifestations of the limits of knowledge in physical theories are the existence of constants of nature and physical singularities. Constants of nature, like the gravitational constant, have no theoretical explanation since they usually appear in semi-empirical approaches to physical problems, are measured by careful experiments and then used as such. When a more elaborated theory is proposed to take into account some constant of nature, it comes with another constant of nature. Physical singularities imply the breakdown of a theory, where it is no longer valid. This is, for instance, the case of general relativistic results like black holes or the cosmological big bang.

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publication, interpretation, and early practical use.[6] The basic idea of this approach is to combine subjectively assessed *prior probability* of an initial belief with objectively attained data, so that an initial belief is modified by objective new information to produce a *posterior probability* of a newly revised belief. This methodology evolves because every time a new bit of information is added the posterior becomes prior of the new iteration and probabilities are recalculated. Hence, accumulation of data brings observers closer and closer to certitude and converge on the truth. In a sense, John Maynard Keynes summarized this process of belief evolution in a quotation attributed to him: “When the facts change, I change my mind. What do you do, sir?”[7]

When there is enough data and priors have similar or equal weight these two definitions tend to produce the same results (VanderPlas, 2014). But some real differences occur when one has little data, or several parameters, and a good amount of knowledge about the event so that one is able to have different weights to constrain priors.

This was the case, for instance, when one was hunting for a missing commercial airplane that crashed out of radar range on a remote part of the Atlantic ocean after encountering a severe electric storm during an international nocturnal flight from Rio de Janeiro to Paris and plunged to the depths of the sea in a region full of underwater mountains and turbulent water currents (McGrayne, 2011, pp. 252–256). In such circumstance a Bayesian will use every bit of information, old and new, however small, to update his/her belief at the plane’s location, even to the extent of using very tiny probabilities that a frequentist would discard as meaningless because their frequencies are irrelevant. For a Bayesian, every information is considered a valuable datum, no matter how tiny its implied probability. So, the hunt for the missing airplane would go on with every iteration increasing our knowledge about the probable location of the airplane’s debris until it was actually found after covering a small part of the area where the accident might have occurred.

At this point an important question arises. If probabilities are regarded as subjective measures of belief, then different people could look at the same information and reach different conclusions because they may use different subjective probabilities or priors. Would this not dismiss the whole Bayesian approach because science must be objective whereas priors are not? This argument has been raised again and again against Bayesian reasoning from those who think that science is, or has to be, entirely objective (McGrayne, 2011).

[6] See McGrayne (2011) for a detailed historical account of Bayes’ rule and its two centuries of controversy.
[7] There is some controversy if this is precisely what Keynes said, as it has been claimed that what he really stated is as quoted at page vi (see also Kay, 2015; Keynes, n.d.). Whatever the historical truth of the quote above, as well as the one paraphrased in the epigraph of this book, are now widely credited to him.

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Nevertheless, it is exactly this point which leads us to Boltzmann's epistemological views, because, as in science in general, probabilistic results cannot be considered as entirely objective, but as always having subjective elements, being therefore incomplete and subject to fail. Similar to theoretical pluralism, which states that there is no unique way of representing nature, there should be no unique way of assigning prior probabilities as they are, as with the proposal of any theory, always contaminated by subjective choices.[8]

So, similar to the way of proving a theory, experimentation updates our beliefs and determines more adequate prior and posterior probabilities until different opinions converge to the truth. In other words, it means learning from experience, which is the same as combining old knowledge with new. We shall return to this topic in Section 4.1.2 when discussing the concepts of risk and uncertainty in economics.

1.6.2.5 Mathematical Economics

The use of mathematics in economics is another point which deserves some thoughts. It has been known since Galileo's times that mathematical tools are essential to describe physical concepts, and new physical theories often require the development of new mathematical tools. As an example, the invention of the infinitesimal calculus by Newton and Gottfried W. Leibniz (1646–1716) in the seventeenth century was fundamental to the development of classical mechanics.

However, mathematical tools can only be effective as long as the scientific concepts they describe are equally effective representations of the real world. If they are not, even the most sophisticated mathematics will produce bad science or not science at all, sometimes dubbed *Cargo Cult Science*, in reference to the speech delivered by the famous physicist Richard Feynman (1918–1988), a recipient of the 1965 Nobel Prize in Physics, about methodologically inadequate, or false, science (Feynman, 1974). For this reason physicists have known for quite some time that it is a serious mistake to confuse mathematics with physics.

Feynman expressed very clearly this viewpoint in a series of lectures delivered at the University of Cornell in 1964:

> The mathematicians only are dealing with the structure of the reasoning, and they do not really care about what they are talking. They don't even need to know what they are talking about, or, as they themselves say, whether what they say is true ... If you state the axioms and say, such-and-such is so, and such-and-such is so, and such-and-such is so: what then? Then the logic can be carried out without knowing what the such-and-such words mean. That is, if the statements about the axioms are carefully formulated and complete enough, it is not necessary for the man who is doing the reasoning to have any knowledge of

[8] A note of caution is due here. Subjectivity does not mean conventionalism or arbitrariness (D'Agostini, 2003, p. 30).

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the meaning of these words, and [he] will be able to deduce in the same language new conclusions … In other words, mathematicians prepare abstract reasoning that is ready to be used if you will only have a set of axioms about the real world. But the physicist has meaning to all the phrases.

And there is a very important thing that the people who study physics that come from mathematics don't appreciate. Physics is not mathematics. And mathematics is not physics. One helps the other. But, you have to have some understanding of the connection of the words with the real world … to find out whether the consequences are true. And this is a problem which is not a problem of mathematics at all.

Mathematicians also like to make their reasoning as general as possible … [but the] physicist is always interested in the special case. He is never interested in the general case! He is talking about something! He is not talking abstractly about anything! He knows what he is talking about.

When you know what it is you are talking about … then you can use an awful lot of common sense … about the world … You've seen various things, [and] you know more or less how the phenomenon is gonna behave, whereas the poor mathematician translates into their equations, and [as] the symbols don't mean anything to him he has no guide, but precise mathematical rigor and care in the argument, whereas the physicist, who knows more or less how the answer is gonna come out, can sort of guess part way, and so go along rather rapidly.

The mathematical rigor of great precision is not very useful in the physics, nor is the modern attitude in mathematics to look at axioms. Mathematicians can do what they want to do. One should not criticize them because they are not slaves to physics. It is not necessary that just because [something] is useful to you they have to do it that way. They can do what they will. It is their own job. And if you want something else, then you work it out for yourself.

The [next] question is to what extent models help? … But, the greatest discoveries, it always turns out, abstract away from the model and it never did any good … The method of guessing the equation seems to be a pretty effective way of guessing new laws. This shows us again that mathematics is a deep way of expressing nature, and attempts to express nature in philosophical principles … is not an efficient way.

(1964, 44:15–50:40)[9]

In the same vein, Galam (2012) elaborated why "physics does not care about mathematical rigour":

While the use of modeling in physics has been tremendously powerful in establishing the field as an exact hard science, capable of building concrete and efficient experimental devices, its power comes from the empirical use of mathematics to describe real phenomena. This means that it is not the mathematical rigor that prevails but the capability to reproduce particular properties using some mathematics. It is exact opposite of what economists have been doing for decades, who focused on the mathematical rigor of their model rather than their ability to reproduce real features.

[9] This transcript of the passages of Feynman's exposition were made by this author from the recorded video lecture. See also Feynman (1967, pp. 55–57).

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> Another essential characteristic of physics is that all results obtained from the various models are aimed, sooner or later, at being tested against experimental data, even if it takes many years or decades or even centuries before being able to do so … Physics is a so-called hard science but it balances between the hard reality and the rich possibilities of inexact mathematics.
>
> *(2012, p. 27)*

So, like the authors' viewpoints cited above, one should not confuse economics with mathematics since economics is not mathematics. And mathematics is not economics. Therefore, bad economic theories, that is, those not connected with the real world, will produce bad results, regardless of their mathematical contents.

But, sophisticated mathematics can also conceal bad theories by making them obscure and arcane, and, so, rendering theoretical inadequacy and ineffectiveness more difficult to recognize. Hence, although economics deals with social issues, there is nothing intrinsically blameworthy in the use of mathematics in economics. If the results and predictions made by the economic theories are bad, this is a consequence of incorrect, inadequate, or inappropriate concepts formulated in mathematical language, which means that mathematical tools are not to blame for such a failure. Physicists learned from the experience of previous generations of physicists that if a theory systematically produces wrong results and predictions this means that our understanding of the problem is at fault, i.e., that there is something fundamentally wrong with our view of the phenomenon and its supposed theoretical description.

This point, nevertheless, leads to another question. Could the ineffectiveness of the use of mathematics in economics have something to do with the fact that economics deals with social issues whereas physics deals with physical quantities? This seems hardly the case. Human beings, either individually or interacting collectively in society, belong to nature as much as falling bodies and atoms. So, the difference between the natural and social sciences are a consequence of the use of different analytical tools to understand different aspects of nature. Therefore, inasmuch as the tools and concepts used to deal with classical mechanics are not the same as the ones applied to describe the atomic structure, from the viewpoint of physicists the real-world aspects of the collective human action and interaction must similarly entail specific implementations.

1.6.2.6 An Econophysical Definition of Economy?

Based on the reasoning expounded in the paragraphs above it may be now possible to tentatively propose a practical econophysical definition of an *economy*, as being 'an open system comprising the collective human interactions and interdependencies empirically observed in the dynamic environment created in societies by production, trade, accumulation, and distribution of value.' A similarly

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practical econophysical definition of *value* would be ‘the set of materials, services and energy produced, transported, traded, and consumed by society.’ Economics and econophysics are then the study of economies, or economic systems, which then requires appropriate concepts and mathematical tools to adequately describe modern economies. From this viewpoint the terms *economy* and *economic system* have the same meaning and can be used indistinctively.

The tentative definitions above of what is value and an economy open the way for applying new theories to understand the economic phenomenon. In this respect modern physics and applied mathematics may come to help, particularly due to the developments of classical physics and nonlinear dynamics that occurred during the second half of the twentieth century which led to the new theories that will be briefly set out below.

1.6.3 Recent Theories

Classical physics did not stop developing after the appearance of modern physics. Some of its validity domains were established by both quantum mechanics and relativity theory in the early twentieth century, but afterwards some problems of classical physics showed to have surprisingly new features when their nonlinear dynamic systems were more thoroughly studied. Together with branches of applied mathematics, like the mathematical theory of singularities and bifurcations, these new features gave rise to the theories of the three Cs: *catastrophe*, *chaos*, and *complexity*. Another important new development of classical physics is the *nonequilibrium thermodynamics*.

Although the origins of the three-Cs theories can be traced as far back as Poincaré at the end of the nineteenth century, they made their effective appearance approximately in the period from 1960 to 1990. They all presented new concepts and methods which are now seen as quite fitting to the study of the economic phenomena. In addition, despite the fact that classical physics provided essential inspiration for the establishment of neoclassical economics at the end of the nineteenth century (Mirowski, 1989), mainstream economics seems to have missed these new developments during the late twentieth and early twenty-first centuries, most likely because it remained stuck with the equilibrium, comparative statics, and linear systems paradigms for analyzing economic systems.

There were, nevertheless, some attempts to incorporate nonlinear dynamics ideas, particularly chaos theory, into economic analysis, but they seem to have been mostly isolated initiatives, only slightly touching mainstream economics, and, therefore, incapable of changing the prevailing twentieth century neoclassical economics paradigms.

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In addition, as we shall see in the next chapters, several of those initiatives suffered from the same limitations that hampered the development of mainstream economics in the sense that they remained basically theoretical, having rarely motivated, or generated, empirically verifiable studies capable of actually testing the proposed models with real-world economic data in order to generate results that in turn would be able to change, by improving or rejecting, those theories. As the concepts of these new developments of classical physics and nonlinear dynamics are important to the discussions of the next chapters, their most basic concepts will be very briefly presented below.

1.6.3.1 Catastrophe Theory

The theory of catastrophes is basically a combination of the mathematical theory of *singularities* with its applications in the study of a great variety of different processes and phenomena in all areas of sciences. Singularities are points where a certain mathematical object is not defined or where it behaves badly. For instance, the coordinate system of the geographical points on the surface of the earth have singular points at both the South and North Poles because at the South Pole the concepts of south, east or west become undefined. Similarly, on the North Pole there is no north, east, or west, but only south.

Since describing our world mathematically requires a delicate interaction between continuous and discontinuous, or discrete, phenomena, the importance of singularities come from their ability to describe how discrete properties can appear from continuous ones, inasmuch as most interesting phenomena in nature involve discontinuities. In this respect it is worth citing the late Soviet and Russian mathematician Vladimir I. Arnold (1937–2010):

> Singularities, bifurcations and catastrophes are different terms for describing the emergence of discrete structures from smooth, continuous ones . . . The word *bifurcation* means *forking* and is used in a broad sense for designating all sorts of qualitative reorganizations and metamorphoses of various entities resulting from a change of the parameters on which they depend. *Catastrophes* are abrupt changes arising as a sudden response of a system to a smooth change in external conditions.
>
> *(1986, pp. vii, 2)*

Hence, as pointed out by Saunders (1980), when catastrophe theory is applied to systems whose inner workings are unknown, it deals with discontinuous properties directly, without referring to any specific underlying mechanism. So, this makes catastrophe theory well suited for problems which the only reliable observations are of the discontinuities, rendering catastrophe theory capable of predicting qualitative behavior of systems without knowledge of their governing differential equations and their solutions. Both Saunders (1980) and Arnold (1986) provide readable

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introductions to catastrophe theory with several examples of applications to a wide range of fields.

1.6.3.2 Chaos Theory

Chaotic dynamics, or chaos theory, arose as a consequence of the limitations of Newtonian mechanics in a different domain than the one that led to the appearance of quantum mechanics. The classical view of the world was of a machine governed by a set of equations of motion discovered by Newton, whose solution would allow the exact prediction of the future state of a system described by these equations given a precise knowledge of the present state of all relevant forces. Such dynamic systems are called *deterministic* because they are governed by equations entirely determined by their initial conditions. For instance, the weather can be described by a set of differential equations, so under the old Newtonian mechanicist viewpoint it was thought that given information precise enough it would be possible to predict the weather for several months, or years, in advance. Therefore, it came as a great surprise when researchers realized this to be impossible.

The difficulty lies in the fact that these equations have properties such that unless we are able to specify the initial conditions with infinite precision, we eventually lose the ability to predict the system's future behavior. In addition, in many cases even with a good knowledge of the system's initial conditions its future behavior is random. And this randomness is generated by simple deterministic systems with only a few components. So, this feature is fundamental; gathering more information does not make this randomness disappear. Systems exhibiting such features became known as *chaotic* because they have elements of determinism, predictability, and unpredictability, even when they are discussed completely within the domain of classical physics.

This means that although the future was thought to be determined by the past, small uncertainties are so hugely amplified in chaotic systems that for all practical purposes they become unpredictable. Hence, chaotic systems are predictable in the short term, but unpredictable in the long term. Predictability is reduced in such a fundamental way that we can only talk about a *horizon of predictability* beyond which one can no longer predict the system's future behavior (Lighthill, 1986). This is the case of the weather, whose horizon of predictability is of about a week. In summary, the future of a chaotic system is only partially determined by the past, and this is restricted to within the horizon of predictability.

Thus, the essence of chaos, that is, of systems exhibiting extreme sensitivity to initial conditions, lies in the fact that small changes in these conditions can change entirely the future outcome of the system, a feature popularly known as the *butterfly effect*. On the other hand, since the motion of dynamic systems can be represented as points following orbits in what is called a phase space, chaotic systems were

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found to generate elegant geometrical patterns in this space, differently from the nonchaotic ones which generate simple curves. So, in a sense this result indicates that there is also *order in chaos*.

The geometrical patterns generated by chaotic behavior were also found to have interesting properties. First, there are points in the phase space where the orbits seem to concentrate and others where they avoid. These are respectively called chaotic *attractors*, or *strange attractors*, and chaotic *repellers*. Second, it was found that the orbits of strange attractors are *fractals*, that is, patterns so irregularly embedded in regular space, but whose dimension is noninteger.

In simple terms, the *fractal dimension* quantifies how "broken," or irregular, is a distribution, that is, how far a distribution departs from regularity. Because fractals usually arise from power laws, which in turn seem to be ubiquitous in nature, being present from the galaxy distribution (Ribeiro and Miguelote, 1998) to the stock markets (Peters, 1994), power laws came to be seen as powerful indicators of dynamic behavior of systems where the concepts above may apply, since the slope of the power laws indicate the fractal dimension of the distributions.

The history of how chaos theory appeared is fascinating, showing the interplay of different study areas and motivations, ranging from the meteorologist Edward Norton Lorenz's (1917–2008) first attempts of weather prediction using a small digital computer during the 1950s, until he realized this to be impossible in the long term and finally proposing the butterfly effect (see Palmer, 2008), to the contributions of various physicists and mathematicians such as Andrey Kolmogorov (1903–1987), Jürgen Moser (1928–1999), Vladimir Arnold and Benoit Mandelbrot, to name just a few among several others.

Another issue closely related to both chaos and catastrophe theories is that science proceeds under the assumption that experiments are generally repeatable. However, since infinite precision is impossible, no experiment can be repeated at exactly the same conditions in which it was previously performed. So, what science truly expects is that if an experiment is repeated under approximately the same conditions we will obtain approximately the same results. This property is known as *structural stability*. The issue here is that the system under study must be resistant to perturbations of the conditions of the experiment. Mathematically speaking, structural stability requires that a dynamic system does not change its qualitative behavior and nature if it suffers small perturbations. If it does, the system is said to be structurally unstable. This concept plays an important role in dynamic systems, especially the nonlinear ones, and shall be revisited in Section 6.1 in the context of a specific model.

1.6.3.3 Complexity

Complex systems theory, or simply complexity, is basically a conceptual framework which proposes that science is made of hierarchical levels where each level has

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its own fundamental laws. Such proposition challenges the reductionistic working hypothesis that chemistry and biology can in principle be completely reduced to physics, to the laws of quantum physics. So, complexity does not endorse the reductionistic claim that all animate and inanimate matter is thought to be ruled by the same set of fundamental laws uncovered through research on fundamental problems lying at the frontiers of science. In a well-known article, P. W. Anderson, the 1977 Nobel Physics laureate, wrote.

> The ability to reduce everything to simple fundamental laws does not imply the ability to start from those laws and reconstruct the universe. In fact, the more the elementary particle physicists tell us about the nature of the fundamental laws, the less relevance they seem to have to the very real problems of the rest of science, much less to those of society.
>
> *(1972, p. 393)*

He then defined the fundamental concept of *emergence* as follows.

> The behaviour of large and complex aggregates of elementary particles ... is not to be understood in terms of a simple extrapolation of the properties of a few particles. Instead, at each level of complexity entirely new properties appear, and the understanding of the new behaviours requires research ... as fundamental in its nature as any other ... At each stage entirely new laws, concepts, and generalizations are necessary, requiring inspiration and creativity to just as great a degree as in the previous one. Psychology is not applied biology, nor is biology applied chemistry.
>
> *(Anderson, 1972, p. 393)*

Finally, after mentioning Karl Marx's proposition that quantitative differences become qualitative ones, Anderson reasoned that a dialog in Paris in the 1920s sums this up even more clearly: "Fitzgerald: The rich are different from us. Hemingway: Yes, they have more money" (1972, p. 396).

From the above it is clear that the central concept underlying a complex dynamic system is that it is made of a large number of material objects reaching such a high degree of relatedness of its components that then genuinely novel properties and processes may emerge, properties which are not reducible to the material attributes of its components. Hence, emergence can be expressed by the thesis that *the whole is more than the sum of its parts*. Closely related to the concept of emergence is the one of *downward causation*, whose thesis is that *the whole determines the behaviors of its parts* (see also Ellis, 2015).

Complex systems are made of interacting objects, usually called *agents*, linked together by direct interactions or through subgroups, forming a complex *network*. But a complex system is made of parts that do more than just *interact*, as they are also *interdependent*, that is, they must be *cooperative*. One cannot separate the parts and continue having the same properties. So, it is the nature of the interactions of the agents within the network that defines the complex system.

To illustrate, complex agents can be cars in a traffic jam, pedestrians in a crowd, firms in an economy, banks in a financial system, people in society, computers on

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the Internet, electricity transmission nodes in a power grid, etc. (Strogatz, 2001). All these systems have emerging properties which only appear in a large aggregate of agents, being not present at the individual agent level. So, *they cannot be derived by microscopic dynamics*, that is, it is not possible to link the large scales, temporally or spatially, with the correspondent small scales of the micro-dynamics (Paradisi et al., 2015).

This viewpoint can be applied, for instance, to economic growth and innovation, as they can be considered as key features of an ecosystem with complex interactions involving intangible elements like good education, financial status, labor cost, high-tech industry, energy availability, quality of life, etc., elements which cannot be measured in monetary figures. The emphasis is then on the complexity and diversity of a country's export basket because this expresses the technologies and capabilities it is able to control, tap, and exploit. This complexity could then determine the level of national competitiveness as an emergent property in a dynamic way (Tacchella et al., 2012; Cristelli et al., 2013; Pietronero et al., 2013; Van Norden, 2016).

The Internet is another good example of an emergent property in the complex system of interacting computers, because it only makes sense to talk about the Internet, or the World Wide Web, once there is a large number of interconnected computers collectively interacting with each other or in subgroups, forming a complex network of computers. Thus, the Internet cannot be understood by looking at individual computers, or cannot be understood by means of the laws of electronic circuits or electromagnetism, although these are required for the understanding and construction of computers at the individual level.

Following the same reasoning, a society cannot be understood by only considering the behavior and psychology of individual human beings, however average, which means that *there is indeed such a thing as society*. Similarly, this conceptual framework tells us that an economy cannot be understood by simply reducing its behavior to the one of a "representative agent" or "representative firm." It is the collective that matters, or, better stated, the properties of the collective. Not surprisingly, some economic research has already reached similar conclusions (see, e.g., Kirman, 1992, 2010).

Each complexity level has its own unique properties and requires its own analytical tools. The transition of one complexity level to another requires different models, and each one needs to be placed in its own context of cause and effect. In addition, emergent phenomena usually appear in the absence of any kind of central controller or "invisible hand," showing a complicated mix of ordered and disordered behavior. Because local interactions between the components of an initially disordered system lead to the emergence of an overall coordination, complex systems are said to present *self-organization*. Besides, since complex

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systems are typically open in the sense that they influence and can be influenced by its surrounding environment, if the system responds to its environment by changing its behavior it is said to *self-adapt*, that is, it becomes an *adaptive system*. Finally, at the core of most real-world examples of complexity one can find *competition for some kind of limited resource*, such as energy, space, food, income, wealth, economic value. This last remark will be very useful in the next chapters.

The implications of complexity concepts to economics are fundamental. It essentially proposes that the understanding of economic dynamics cannot be achieved by means of a “representative agent” because complexity economics builds from the assumption that the economy is not necessarily in equilibrium, which means that economic agents constantly change their strategies and actions in response to the environment created by their mutual interactions, which can in principle be either predatory, or symbiotic, or a mixture of both.

Such an approach cannot be an extension of the neoclassical economics viewpoint (Kirman, 2010), which emphasizes stability, permanence, and reversibility due to its basic equilibrium hypothesis, but sees economics as being formed by structures that constantly change and rearrange themselves, creating patterns which in turn lead the interacting elements to change and adapt for survival in a sort of ecology where time becomes important as the created events are historical contingencies (Brian Arthur, 2014, and references therein). As we shall see below, this viewpoint is neatly connected to physical theories where systems in equilibrium are just a particular case of more general patterns, and are not particularly interesting ones.

1.6.3.4 Thermodynamics of Nonequilibrium

Nonequilibrium thermodynamics is the study of open systems far from equilibrium that can still be described in terms of macroscopic thermodynamic variables. This approach to thermodynamics was initiated by Ilya Prigogine (1917–2003), the 1977 Nobel Chemistry laureate, who started from the observation that an open system submitted to a gradient of temperature such that it reaches a nonequilibrium state which may be a source of order. This is, for instance, the case when water is contained between one hot plate below and another cold plate above, leading to the appearance of a macroscopically ordered structure of fluid patterns due to convection flows, called Bénard cells. To put the background theory in simple terms, this observation led to the realization that systems submitted to a continuous flow of energy reach a far-from-equilibrium stable thermodynamic state, and this stable state endows them with structures.

Thus, nonequilibrium and, particularly, far-from-equilibrium systems are a source of order as they evolve toward coherent behavior. These structures are radically different from equilibrium structures and can only be maintained in

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far-from-equilibrium conditions by means of enough flow of energy and matter. Due to this feature they are called *dissipative structures* (Nicolis and Prigogine, 1977).

In view of the fact that since Boltzmann's contributions to statistical thermodynamics in the nineteenth century it is known that high entropy is a measure of disorder, and since dissipative structures are stabilized by exchanges of energy with the outside world and, for this reason, have low entropy, the conclusion is that dissipative structures are ordered and are possibly entropy-reducing systems. In other words, *dissipative structures are a manifestation of self-organization in nonequilibrium systems*.

The results of nonequilibrium thermodynamics are in fact far-reaching. Life, for instance, is made of dissipative structures, since cells require a continuous flow of energy and matter to keep them functioning (Morowitz, 1968). Hence, biological systems are in a far-from-equilibrium state because if they achieve equilibrium the energy and matter flows come to a halt, which means death.

Another illustration is of a city that can only maintain itself as long as it has an inflow of fuel, food, and other commodities and an outflow of wastes and other products. This means that an economy, or its *production system*, can be seen as a dissipative structure where matter is changed into forms useful for human beings, kept in action by a constant energy flow in a manner akin to biological systems.

This connection between non equilibrium thermodynamics and economics is not trivial to be formalized in terms of specific mathematical models, but some authors faced the challenge and advanced this interface conceptually. For instance, Ayres and Nair (1984) argued that the laws of the conservation of energy and of the increase of entropy constrain processes by which raw materials are transformed in consumable goods, Georgescu-Roegen (1986) proposed that economic processes are entropic, and Pokrovski (1999, 2018) discussed the physical principles of economic growth from the viewpoint that economies are fundamentally based on the flow of energy and matter.

Finally, non equilibrium thermodynamics have aspects of all theories above, since it is nonlinear and presents elements of complexity, chaos, structural stability, and catastrophe. A technical approach to these issues is given by Nicolis and Prigogine (1989).

The summary above of some recent physical theories that are in principle applicable to economic systems form an assortment of concepts and ideas capable of opening new perspectives for the understanding of the economic phenomena and of providing avenues for fresh modeling approaches. Nevertheless, none of them will have any value if they do not produce new results and applications that can

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now or in the future be connected to the real world and validated by empirical findings. The way forward is, therefore, not to rely on purely logical premises of how economies would, or should, work, not to depend solely on mathematically constructed theories about idealized economies, but to piece together from empirical observations of the real world how economic systems actually work and build mathematical models using both intuition and ingenuity that are capable of describing and predicting the real-world economic phenomena.

https://doi.org/10.1017/9781316136119.004 Published online by Cambridge University Press