Evolutionary Economics and Social Complexity Science 15

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Microfoundations of Evolutionary Economics

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The Japanese Association for Evolutionary Economics (JAFEE) always has adhered to its original aim of taking an explicit "integrated" approach. This path has been followed steadfastly since the Association's establishment in 1997 and, as well, since the inauguration of our international journal in 2004. We have deployed an agenda encompassing a contemporary array of subjects including but not limited to: foundations of institutional and evolutionary economics, criticism of mainstream views in the social sciences, knowledge and learning in socio-economic life, development and innovation of technologies, transformation of industrial organizations and economic systems, experimental studies in economics, agent-based modeling of socio-economic systems, evolution of the governance structure of firms and other organizations, comparison of dynamically changing institutions of the world, and policy proposals in the transformational process of economic life. In short, our starting point is an "integrative science" of evolutionary and institutional views. Furthermore, we always endeavor to stay abreast of newly established methods such as agent-based modeling, socio/econo-physics, and network analysis as part of our integrative links.

More fundamentally, "evolution" in social science is interpreted as an essential key word, i.e., an integrative and /or communicative link to understand and redomain various preceding dichotomies in the sciences: ontological or epistemological, subjective or objective, homogeneous or heterogeneous, natural or artificial, selfish or altruistic, individualistic or collective, rational or irrational, axiomatic or psychological-based, causal nexus or cyclic networked, optimal or adaptive, microor macroscopic, deterministic or stochastic, historical or theoretical, mathematical or computational, experimental or empirical, agent-based or socio/econo-physical, institutional or evolutionary, regional or global, and so on. The conventional meanings adhering to various traditional dichotomies may be more or less obsolete, to be replaced with more current ones vis-à-vis contemporary academic trends. Thus we are strongly encouraged to integrate some of the conventional dichotomies.

These attempts are not limited to the field of economic sciences, including management sciences, but also include social science in general. In that way, understanding the social profiles of complex science may then be within our reach. In the meantime, contemporary society appears to be evolving into a newly emerging phase, chiefly characterized by an information and communication technology (ICT) mode of production and a service network system replacing the earlier established factory system with a new one that is suited to actual observations. In the face of these changes we are urgently compelled to explore a set of new properties for a new socio/economic system by implementing new ideas. We thus are keen to look for "integrated principles" common to the above-mentioned dichotomies throughout our serial compilation of publications. We are also encouraged to create a new, broader spectrum for establishing a specific method positively integrated in our own original way.

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Preface to Microfoundations of Evolutionary Economics

This book explicitly provides microfoundations of evolutionary economics that have been absent thus far in evolutionary economics. The evolutionary economics continued to criticize mainstream neoclassical economics as insufficient framework of analysis, but it had no other choice than to use ideas and analytical tools of neoclassical economics implicitly or explicitly, because it lacked microfoundations of its own. It is clear that without microfoundations of its own, evolutionary economics will not become an academic discipline independent of neoclassical economics. Evolutionary economics needs theoretical foundations as fine and logically sure as Arrow and Debreu's model of competitive equilibrium (Arrow and Debreu, "Existence of an equilibrium for a competitive economy", *Econometrica* 22(3): 265–90, 1954) is, but it lacked this firm basis of analysis for a long time. This book was written in order to change this state of evolutionary economics. Although discovered by a series of studies that were not directly connected to evolutionary economics, the results we have obtained have a good chemistry with evolutionary economics and with Keynesian analysis of effective demand. We believe that our results serve as microfoundations for both evolutionary and Post-Keynesian economics.

Firstly, let me explain the reason why this book provides the microfoundations of evolutionary economics. Humans are a product of biological evolution and have many limitations as organisms. For example, we have limitations in life spans, boundedness of our rational reasoning and calculations (bounded rationality), limited range in perception and recognition (bounded or myopic sight), and limited ability in executing something planned. This is the very reason why our societies could have developed through our repeated learning and innovations. If humans were omniscient and omnipotent, our economy may have been totally different from that we have today. The limitations of human abilities are the basis of many institutions of our society. We are in a big economy which extends globally and comprises billions of people and millions of firms. We are incapable to collect relevant information and calculate solutions. One of the core issues in economics is the clarification of the mechanisms and the reasons how and why the economy as a whole functions quite well, although an enormous number of agents are acting with their limits in rationality and sight. The issue includes elucidating mechanisms that may exist in the actual economy and guarantee its smooth functioning. Of course, since the onset of economics approximately 250 years ago, the awareness of this issue has resided in the studies with a focus on the workings of the market. Adam Smith posed the problem but could not solve it except that he could barely suggest the existence of an invisible hand.

A model economy, which is studied through Chaps. 2, 3, 4, 5 and 6, forms the core of this book. It consists of many goods and services that are produced by different firms and exchanged between them. We assume a flow of final demands which are given exogenously. Our main concern is whether the economic system consisting of many producer firms with limited information (myopic sight) can follow this flow of final demands. Of course, it is impossible without conditions. Our main result is that the complex system of interconnected producers can follow the final demand flow as long as the average demand flow changes "slowly." What "slowly" means exactly is given in the main text, i.e., Chapter 2 and others. The economy we examine is very different from model economies that assume an auctioneer, and which form a long tradition in modern economics from Leon Walras to Arrow and Debreu. Our market participants, whether they are individuals or firms, conduct their activities based on their limited knowledge that they can obtain within their own perspectives. More concretely we assume that firms (or rather managers of firms) can only know the past series of sales flow of their products. In these processes, prices do not serve as mediator that brings equality of demand and supply for products. It is the producers that adjust their production flow in such a way that the supply of the product is almost equal to its demand. As firms cannot know the future demand exactly, the firms produce with an expectation, but we assume that this expectation is fulfilled in no way. Firms are obliged to hold product stocks or inventories and regulate them in order to avoid stockout situation as far as possible and keep the inventories as small as possible. As these objectives often contradict, there are no optimal solutions to these inventory control problems. We suppose firms follow rule-of-thumb solutions by adjusting the parameters of the adjustment rules. The adjustment system based on quantity changes without mediating price changes is referred to as *a quantity adjustment process (or economy)* in this book.

When prices are not primary mediators which bring equality of demand and supply, what functions do prices assume? Prices are determined in principle by producers (and by suppliers in case of the distribution industry). Price setting may have various rules but the principal method is *full-cost pricing*. In other words, the price of a product is determined as the unit cost of the product multiplied by a markup factor, namely 1 + markup rate m. In this book, we do not enter in the question how this markup rate is determined nor in the question why firms adopt this pricing policy. This is a widely observed custom and we have already a huge literature (see, for example, Frederic S. Lee, *Post Keynesian price theory*, Cambridge, Cambridge University Press, 1998). We can prove that these prices are stable in the sense that a change of demand compositions cannot influence the prices. If firms are producing by a competitive production technique, the firms cannot change to other production techniques as long as the final demands are satisfied by those productions.

This is in sharp contrast with Arrow–Debreu model. Contrary to the generally accepted (mis)understanding, Arrow–Debreu model does not guarantees the stability of prices. It only proves existence of a system of prices in which no agents want to change their behavior. The price system may stay constant at a given point of time when the market is open, but it may change in the next period when the next market takes place. Existence of futures market only proves that demand and supply of goods that will be delivered in the future are in equilibrium in the present market (Shiozawa, *Reflections on Modern Economics* [in Japanese], Tokyo, Nihon Keizai Shinbunsha, 1983, Section 2.2). In the Arrow–Debreu model, no conditions that guarantee this stability between periods are posed and there is no guarantee that prices remain stable between the present and the next periods. Chapter 2 of this book proves that prices remain constant as long as two conditions are satisfied: (1) there is enough labor power and material stocks that makes possible to produce as net product the final demands, and (2) the set of production techniques remain invariant and the markup rates remain constant. The first condition is normally satisfied if we assume that the final demands are backed by money gained one period earlier. Main arguments are obtained as what Shiozawa named *minimal price theorem*, which is in fact the dual version of Samuelson's nonsubstitution theorem. It is custom that the latter theorem is introduced as having too restricted conditions, but Shiozawa shows that it can be extended to sufficiently wide class of economies. The stability of prices provides a good base for change of production techniques which is one of main research agenda for evolutionary economics.

The main focus of this book is however everyday adjustment processes under this stable price system. If a firm can obtain enough amount of demand for its product, i.e., if the demand exceeds profit-loss point, it can get a profit. Although firms can work on markets in order to increase the demand by advertising and other marketing activities, the production unit is obliged to follow the change of the demand flow for the product. Chapters 3, 4, 5 and 6 describe and analyze in detail what happens in the interactive network of inputs and outputs. We are interested in the process how the final demand is transmitted to upstream firms through input–output relations in such a way that the total network of firms can produce final demands without causing stockouts too often. As it is already pointed out, our results are affirmative in the sense that total system of production network can follow final demands when their average moves slowly. In addition, the remarkable fact in our research is that the complex network of quantity adjustment does not necessitate unrealistic capabilities for the part of decision makers. This is the reason why we claim that our results provide the microfoundations for evolutionary economics. The new findings have the most important significance for the economics of the market economy, because this is probably the first result after Arrow and Debreu's model. It means we have found that "a social system moved by independent actions in pursuit different values (Arrow and Hahn, *General Competitive Analysis*, 1971, p.1)" can work *without* assuming the unrealistic capabilities for economic agents.

Secondly, a special mention must be added on the fact that this book examines an economy which is composed of many products. In the model, the number of products can be as big as we want. It is difficult to know the exact number of commodities (goods and services) that exist in the real world, but it surely exceeds tens of millions. It may count hundreds of millions. This bigness of number of products is an important characteristic of the modern economy. However, many standard economics models observe the single-good economy. In such an economy, there is no need of coordinating different goods. Majority of macroeconomics ignores the problems which may arise from the multiplicity of commodities. It is extremely strange that they simply assume there are no such problems. Our results in this book provide how this complicated coordination problems are solved in the real economy and where obstructions may occur. With our results, macroeconomic principle of effective demand obtains a new foundation. When firms follow the demand flow expressed for their products, the whole system of input–output links adjusts itself to produce the final demands as net production provided that each of the latter satisfies certain restrictions made explicit in this book. This provides a new foundation for Keynesian economics, because the principle of effective demand gets a new formulation based on behaviors of individual firms. Shortly stated, the principle can be reformulated at the product level. If products are differentiated by firms that produced them, the principle simply means that firms produce as much as products sell. This is what Shiozawa named *Sraffa principle* (Shiozawa, *The Revival of classical theory of values,* London, Routledge, 2015, and others). There is a strong parallelism between the firm-level principle and the economy-wide principle relative to demand and production (See Fujimoto, "Preface to Special Issue Evolution of Firms and Industries," *Evolutionary and Institutional Economics Review*, 9: 1–10, 2012).

As everybody knows, Keynes' concept of effective demand was deleted from new Keynesian economics which adopted microfoundations based on neoclassical general equilibrium theory. Its macroeconomic framework is now *Dynamic Stochastic General Equilibrium* (DSGE) model. Post-Keynesians rejected such microfoundations and they were right. But they are obliged to remain minor because they could produce no alternative theory. The present book has a power to change this state of the art, as it provides a powerful tool of analysis based in realistic human behaviors. We have not included post-Keynesian economics in the title of this book, because we believe that evolutionary economics is more comprehensive than post-Keynesian economics and the first comprises the latter as a part when a suitable analytical framework is given. Our book provides such a framework.

Thirdly, I would like to point out that, in any research field, we can built from the beginning no universal theory that can explain all the phenomena that might be relevant to the field. We should start from what can be studied with a firm base. In the economics science, the same dictum applies. It is worth emphasizing that the model economy we studied in this book only applies to the real or production economies. Evidently, it should not be applied to financial economies. We need another theory for them. We make no judgment on whether Walrasian economics is applicable to financial economies. It is well known that Walras got his image of market from Bourse de Paris (*Eléments d'économie politique pure*, 1900). No matter whether it is applicable to financial market or not, production economies and financial economies are so different with each other. We should not assume that two economies can be formulated in the same manner at the moment. The trouble with Walrasian economics started from this confusion. To avoid repeating similar mistakes again, we want to emphasize that the theory, described in this book, applies only to the production economies until some new theory appears that can unify both real and financial economies.

Fourthly, a simple note should be added on the history of our studies on quantity adjustment processes which culminated in our book. More than 30 years ago, Shiozawa was concerned why quantity adjustment process based on agents with shortsighted perspectives, or myopic agents, can function without no big troubles. The main focus of his study was on analyzing the microscopic structure of the process, run by agents with limited abilities, which was to progress step-by-step while excluding any kind of equilibrium mechanism. However, the conclusion obtained by the study of Shiozawa ("The Micro Structure of Kahn-Keynes Process (In Japanese)," *Keizaigaku Zasshi* 84(3): 48–64, 1983) was negative in the sense that the whole process of adjustment was divergent, implying that the rule-based adjustment was not sufficient to make the process to follow after the change of final demand. It meant that either some kind of price adjustment was necessary or some other adjustment rules were in reality adopted.

Taniguchi was interested in the path of economy. The starting point of his study was the "Traverse" by Hicks (*Capital and Time*, 1973). The study of "Traverse" focuses mainly on capital adjustment, and the unique point of his analysis was that the study was constructed by process analysis. Through this study, Taniguchi encountered Shiozawa's study on the microscopic structure where production was adjusted. Taniguchi ("On the Traverse of Quantity Adjustment Economies" [in Japanese], *Keizaigaku Zasshi,* 91(5): 29–43, 1991) conducted a computer-based numerical analysis to avoid suffering from the mathematical difficulties that Shiozawa faced in his study. As a result, Taniguchi discovered that a quantity adjustment economy, which consists of individual entities having their own shortsighted perspectives within a narrow range around themselves and over a short period of time in the past, has a robust convergent structure.

Morioka started his study on quantity adjustment economies with the study of *Economics of Shortage* (1980) by Kornai. He came to be interested in the analysis of the production and transaction processes in the market. Afterwards, through the study of the iteration processes of production and transactions in the markets of a capitalist economy, he explored the framework of the background theory and deepened his consideration on the history of economic doctrines. He then succeeded in showing through mathematical analysis that the quantity adjustment process can be stabilized by moderate averaging of past demands in the demand forecast formation. These achievements were published in his book *The Economic Theory of Quantity Adjustment* (in Japanese, Nihon Keizai Hyoronsha, 2005). Shiozawa later called these discoveries by Taniguchi and Morioka *the Taniguchi-Morioka theorem*.

As described above, the studies made by these three economists are separated in time and interest. Those reports were written only in Japanese, while there were no similar studies published in English as far as we know. This is the first attempt to introduce our results to English-speaking world. Through the publication of this book, we hope that the originality of our studies will be admitted and the book will get proper appreciation.

Fifthly, the followings are brief descriptions on each chapter. Readers can see how this book is organized. Chapter 1, written by Yoshinori Shiozawa, provides a theoretical perspective of evolutionary economics. First, the author discusses how our rational capability is limited, how often intractable problems exist in our lives, how restricted the range of influence of our actions is, and finally, what this implies for economics. Bounded rationality is the basis of all evolutions of economic entities of various categories, which include behavior, commodity, technology, institutions, organizations, systems, and knowledge. Because of bounded rationality, any existing entities are not optimal at any time. This is the main reason why evolution is ubiquitous and occurs successively and incessantly. Second, the author explains that the core structure of human behavior is If-Then behavior or Cognitive-Directive (CD) transformation. The author examines in detail this structure and shows how the skill of an experienced worker is built. The process analysis as an analytical framework and the concept of the micro-macro loop are also explained. This chapter is not only appropriate as an introductory chapter of this book but also a comprehensive introduction to evolutionary economics in general. It provides readers with signposts that guide them to the microfoundations of evolutionary economics.

Chapter 2, written also by Shiozawa, provides contents directly related to the quantity adjustment economy. First, a set of postulates that show how our market economy works are introduced, and the separation of price and quantity adjustment is discussed. Second, *the minimal price theorem* is proved, at first for a simple case. The theorem is then extended to various cases including fixed capital cases and the existence of labor heterogeneity, which are normally treated as the situation that the theorem does not hold. Our basic understanding on price and quantity adjustment is that they are in principle independent with each other. Thus, a change of quantities does not affect prices and vice versa, except for special cases. *The minimal price theorem* justifies the basic independence of price and quantity adjustment, because in a normal case, firms produce with the production technique which gives the minimal unit cost among alternative production techniques. This understanding, our core message, is drastically opposed to the standard price theory that assumes prices and quantities are simultaneously determined at the intersection point of the demand function and the supply function. In addition, this chapter refers to how the essence of *the minimal price theorem* can be extended to international trade economy. The economy here treated is very wide, because it is an m-country, n-commodity economy where input trade is permitted. In the final section, it is explained how the quantity adjustment process can be formulated. It gives an introduction to the quantity adjustment processes, which are main theme of the following chapters.

Chapter 3 provides the basic framework and key concepts of the economic theory of quantity adjustment and is written by Masashi Morioka. First, general characterizations of the capitalist system such as a demand-constrained economy are clarified, and the author argues that this aspect of capitalism has a profound relevance to the long-term changes of technologies and products through incessant innovations. Second, inventory shortage (stockout) avoidance behaviors by individual firms that are faced with the uncertainty of demand as a consequence of sales competition are formulated. In this way, quantity adjustments in the capitalist economy as a dynamic process generated by interactions of firms that repeat inventory shortage avoidance behaviors are outlined. In addition, Morioka describes the historical overview of earlier contributions to the analysis of the quantity adjustment that have taken the form of attempts to construct a dynamic and multisector model of the multiplier theory by Kahn–Kalecki–Keynes. This chapter introduces a quantity adjustment economy to the researchers who are unfamiliar with it. This chapter is also helpful for reading the following chapters.

Chapter 4 by Morioka includes the basic setting of the model; the author analyzes a multisector dynamic model of the quantity adjustment process in which firms determine production and material orders based on inventories and demand forecasts under fixed prices and final demands. Special attention is paid to the roles of the demand forecast by using a moving average of past demand, and the dynamic properties of the process generated through interactions among sectors are investigated. This chapter also contains a series of theorems on the stability conditions that thoroughly elucidate how the stability of the process is affected by the input structure, the extent of averaging, and the relative scale of buffer holdings. It is also shown that moderate averaging of past sales in the demand forecasts formation is indispensable for quantity adjustment stability. Otherwise, the big transition matrix would have eigenvalues outside of the unit circle. Moreover, the mechanism of stabilization through averaging in the demand forecast is closely examined. This chapter is the theoretical core of a quantitative adjustment economy in this book. Since the main parts are described with mathematical precision, it is suitable to help researchers to investigate this chapter in greater depth.

Chapter 5, also written by Morioka, provides extensions or generalizations of the model given in Chapter 4. First, the following three modifications are discussed: (1) the existence and change of work-in-process inventories, (2) the partial or delayed adjustment in the decision of production amounts, and (3) the multiplicity of firms within a single sector. Analysis of the modified models shows that these modifications do not bring fundamental change to the properties of the adjustment process. Delayed adjustment has the same effect as averaging the demand. Second, the author examines the process accompanied by occurrences of the stockout of materials and products. The stockout of a raw material causes a reduction in the production amount to the level that corresponds to the input of this raw material, and the stockout of a product causes a rationing of sales among buyers. Disturbances caused by stockout can be absorbed by buffer inventories within a certain limit. Finally, two cases that relate to the mid- and long-term changes of the final demand are investigated. It revealed that despite the temporary fluctuations, in due time, the quantity adjustment processes can follow the movement of the final demand.

Chapter 6, written by Kazuhisa Taniguchi, gives the numerical experiments of the nonlinear quantity adjustment processes based on inventory control, which is referred to as the (S, s) policy. First, the author describes the features of a contemporary society that is characterized by an enormous number of different kinds of commodities. To theoretically contemplate an economy with this many kinds of commodities, the concepts of vector space and nonlinearity are explained. Second, the (S, s) inventory control policy theory developed by Scarf ("The optimality of (S, s) policies in the dynamic inventory problem," In Kenneth J. Arrow and Samuel Karlin and Patrick Suppes, *Mathematical Methods in the Social Sciences 1959*, Stanford University Press, 1959) is explained. Since Scarf's model focuses on one kind of goods, it does not consider the movements of the entire economy. The author discusses this crucial point with respect to Scarf's model. Third, the quantity adjustment economies based on the (S, s) policy model as a whole economy are shown. The mathematical solutions of the one kind of goods and two kinds of goods models are shown, and the results of the more than three kinds of goods model are discussed, which are different from the one kind of goods and two kinds of goods models. Finally, certain results obtained by numerical experiments that were conducted by the author are explained, and the effects of the number of commodities are discussed.

Chapter 7 is also written by Taniguchi. The author considers buying and selling transactions and arbitrage based on *the Principle of Exchange* (Shiozawa, "The Present State of Complexity Economics" [In Japanese], in Shiozawa (Ed.) *The Present State of Economics*, Volume 1 History of Economic Thought, Tokyo; Nihon Keizai Hyoronsha, 2004, pp. 53–125) and the equivalence relation. Since money has emerged and price can be observed objectively, buying and selling can be conducted by referring to objective indexes. In this instance, "evaluation" has to be explicitly distinguished from prices. It is important for executing buying and selling transactions that there be a different "evaluation" formed by each buying party and selling party. Arbitrage is defined as the use of the differences in exchange rates to earn a profit. Presenting specific cases with respect to these phenomena, this chapter considers the stability and instability of prices in financial markets and product markets based on the formation of "evaluations" and the function of arbitrage. This chapter does not discuss the quantitative adjustment economy but considers buying, selling, and arbitrage as a process based on *the Principle of Exchange*. This chapter gives, we hope, the microscopic foundations of the exchange (buying and selling) economy from evolutionary point of view.

Last but not least, I want to express my deep thanks to two of my co-authors Yoshinori Shiozawa and Masashi Morioka. Shiozawa first tried to penetrate into the hard rock of quantity adjustment processes and consistently has emphasized the importance of the problem. Without his eventually failed work, we (Morioka and I) would have had no chance to attack the problem. Morioka built a firm and concrete foundation for the quantity adjustment process research by his astonishing result in estimating the Frobenius root of a large matrix which seemed for Shiozawa and me

an impossible attempt. Owing to his great mathematical achievement, scholars in the field of quantity adjustment processes as well as effective demand analyses will be able to develop their researches with a firm basis.

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Osaka, Japan
January, 2019

Kazuhisa Taniguchi

Contents

Chapter 1
Microfoundations of Evolutionary Economics

Abstract An evolutionary point of view is the best way to understand the economy and its development. This is *the central dogma* of evolutionary economics. In this chapter on the foundations of evolutionary economics, we discuss (1) why this dogma is supportable, (2) why most of economic entities evolve, (3) what are the defects of standard (or neoclassical) economic theories, and (4) ideas to reconstruct economics in an evolutionary way.

The main task of this chapter is to find the basic form of human behavior. Human being is an entity whose capability is strictly limited in (1) sight, (2) rationality, and (3) execution. How such an entity can effectively behave in a large economic system which is a network which extends worldwide. The question should be investigated from two sides. One is the structure of our behavior. We contend that all routine behavior is composed of C-D transformations or if-then rules. The other is the system characteristics which can be summarized by (1) stationarity, (2) loosely connectedness, and (3) ample margin of subsistence. Only in such a system, routine behavior is a powerful instrument of human knowledge. This two-sidedness requires the economic methodology to be reorganized from the micro-macro loop approach.

Keywords Bounded rationality · Structure of the human behavior · Micro-macro loop · If-then rule · C-D transformation · Semiotics

1.1 Introduction

Evolutionary economics lacked theoretical foundations: no theory of value, no theory of behavior, no proper tool of analysis, and no proof of how an economy works. There were some brief comments on how a market economy works and how it evolves, but few attempts had appeared[1] that try to build a theoretical foundation. Although the work of Nelson and Winter (1982) was a great achievement and helped

[1] New contributions such as Markey-Towler (2018) are now appearing.

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to resurrect evolutionary economics, later development was quite poor. Evolutionary economics pretends to criticize neoclassical mainstream economics, but in many of its arguments, implicitly or explicitly, it has imported the reasoning and results of neoclassical economics. Lacking a theoretical microfoundation defining the nature of human economic behaviors that is consistent with its own distinct worldview, it cannot become a differentiated branch of economics free from the neoclassical mode of thinking. This chapter and the book intend to fill this gap in the state of evolutionary economics.

An evolutionary point-of-view is the best way to understand the economy and its development. This is *the central dogma* of evolutionary economics. In this chapter, we examine the foundations of evolutionary economics and discuss (1) why this position is supportable, (2) why most economic entities evolve, (3) what are the defects of standard (neoclassical) economic theory, and (4) the ideas that are central to the reconstruction of mainstream economics according to the evolutionary view of human behavior.

The central dogma of evolutionary economics can be justified in various ways. The most conspicuous fact supporting it is that many of the important entities of the economy change or evolve. We can cite at least seven categories of such entities: (economic) behavior, commodities, technology (including production and design techniques), institutions, organizations, systems (e.g., various kinds of artificial systems, including market systems), and knowledge.[2]

An economic entity is very complex in itself. Although it is a result of human development, its overall complexity exceeds our capacity to fully understand or control completely. This observation raises the possibility of these economic entities being subject to evolutionary change. Take an example of *commodity*. A simple commodity such as a drinking cup, in its present form, is fruit of the accumulation of a huge set of human knowledge: knowledge about clay soil, the potter's wheel, techniques of treating clay, glaze-making, design, the baking oven or kiln, know-how of temperature keeping, and so on. At many points in the production process of each cup, there are also some uncontrollable factors. The present process of cup production is a crystallization of innumerable trials and errors. It incorporates elements necessary to achieving the intended output as well as those intended to ameliorate the effects of factors which cannot be completely controlled.

The seven categories identify major economic entities, each of which has a different mode of evolution. *Economic behavior* can be changed by a decision of an individual, whereas an *institution* is not changed by an individual. Even if it is a simple custom, it is required to have wide support socially that is passed from generation to generation. *Technology* is a huge network of scientific and nonscientific knowledge. It is transmitted by apprenticeships, schools, organizations, and experience. It is partially supported by a workers' skill but develops

[2] I cited four of seven categories in Shiozawa (2004). I added three others in the General Introduction to a handbook edited by Japan Association for Evolutionary Economics (2006). Seven categories are not listed for classification purpose. They are not exclusive or comprehensive.

through scientific research. The Internet is a new system that has quickly become an institution. Although its basic concepts are a result of human design, the present form of the network evolved autonomously, and no one person can completely control it. *Organization* is a new kind of human group that works as a purposeful entity. The evolution of actions, from being those of person to being those of an organization, can be compared to the transition from unicellular to multicellular organisms. *Systems* also evolve and their mode of evolution changes or evolves. When machines were typical systems, systemic evolution only occurred as a result of new design. Internet had a new property as being an evolvable system (a system open to evolution). We have observed conspicuous spontaneous development of Internet system in these 30 years. *Knowledge* may be created by a person, but a new creation is only possible with the support of long accumulated knowledge. It forms the third domain different from the objective and subjective world.[3] Openness is one of the key factors for the development of human knowledge.

The evolutionary paths taken by particular economic entities take widely varied forms. Despite this variety, we can discern three significant moments during any evolutionary process. They are *retention*, *mutation*, and *selection*. In evolutionary biology, the same moments are termed replication, mutation, and selection. The reason why we don't use the term "replication" is that many economic entities are not easily replicated or copied. Retention is a more fundamental concept than replication, because some essential features must be retained when something is replicated. However, exact analogy between the two sciences is not important. Economic evolution has its own characteristics, proper to itself. Our task is to clarify how economic entities evolve and to elucidate why they evolve.

As we have hinted above, the ubiquitous nature of evolution in an economy comes from the subtle relationship between the *complexity of our problems* and our own set of skills and *capabilities*. In Sect. 1.2, we explain how our most fundamental capabilities are bounded and how widely intractable problems are constantly percolating into our lives. Neoclassical economics, based on the maximization principle, ignores these facts, because maximization generally requires an extremely high capacity for rationality, as we will show in Sect. 1.2.1. Many economists are aware of this fact, but they cannot reformulate their frameworks of thought because they cannot abandon the maximization principle. Neoclassical economists do not know how to formulate intentional human behavior without applying the analytical framework of maximization.

Section 1.3 starts from a simple commonsense observation that we human beings are myopic, in the sense that we are short-sighted, with regard to future events. We are also myopic in the sense that we know little about the present states of different industries, areas, and activities that may be influencing the outcomes of our own actions. The third limit to our capabilities is in the limited spatial range of influence of our direct physical actions. How can an animal with these three limits (bounded rationality, myopic sight, and limited influence) behave and survive in a

[3] Karl Popper (1976, Chap. 38 World 3 or the Third World) called this the World Three.

complex world? This is the main question of Sect. 1.3. There, we present a new framework of human behavior involving patterns of actions or routine behaviors. Routine behaviors comprise 99% of our behaviors, but they each function only in a specific environment. It will be clarified that the reality of human behavior is extremely different from its conception in neoclassical economics.

Section 1.4 gives an overview of the environment created by our economic activities. Three important conditions are discussed. They are the *stationarity* of the economic process, *loose connectedness* of the system, and *slackness of subsistence* for economic agents.

Section 1.5 discusses a proper method of economic analysis. In Sect. 1.5.1, some special features of process analysis, as applied in the social sciences, are discussed: in particular, the micro-macro loop. Identifying this more precisely, although the macroeconomic process is generated by individual human actions, in aggregate these form an environment of habitual human behaviors which in turn sustains performance at the individual level. When this occurs, we can observe a kind of coevolution of macroeconomic processes and the micro behaviors of which they are comprised. This is the *micro-macro loop*. We give two instances of the micro-macro loop and consideration of the methodological questions it raises.

Section 1.5 is a preparatory section for Chap. 2. An economy is a network of routine behaviors conducted by myopic agents who see a very small part of the total economy. A great enigma in economics is why these myopic agents with bounded rationality can generate a roughly stable economy and also adapt to the changes in it. To solve some parts of this enigma is the main object of our book. We know that the market economy is a spontaneous ordering. Even if it is, it is necessary to understand how this comes about and how it works.

Readers who are not interested in the methodological aspects of evolutionary economics can go to Chap. 2 directly. They can read it independently of methodological arguments. As a market economy is a series of exchanges that are concluded by mutual agreements, the theory of prices or exchange value is crucial for any concrete understanding of the economic process. The value theory we present in Chap. 2 is in the tradition of the classical theory of value, especially that of Ricardo (Shiozawa 2016a). Readers will see how this classical theory of value can be reinstituted in modern economics in a form which competes with the modern mathematical version of general equilibrium theory. Chapter 2 is an introduction to the research to be deployed in subsequent chapters.[4]

[4]I have argued repeatedly in Japanese almost all topics treated in this Chapter (Shiozawa 1990, 2006 and others that I do not add in the reference list).

1.2 Ubiquity of Intractable Problems

Humans gained the capacity to accumulate a wide range of voluntary motor skills and can control their deployment of these actions by intelligence. Most of our actions having economic effects are taken as a result of our decision-making, and these decisions are based on our intelligence. Why should we prefer to think that there has been, and continues to be, evolution in these behaviors, instead of in our use of rational decision-making? The answer lies in considering the question of our mental capacity in relation to the difficulty of the problems we want to solve.

1.2.1 Bounded Rationality

Take as an example utility maximization, which is the most common situation that many economists suppose occurs. Let N be the number of commodities and u be the utility function. If a positive price vector $\boldsymbol{p} = (p_1, p_2, \ldots, p_N)$ and a positive budget B are given, then the problem is formulated as

$$\begin{aligned} &\text{maximize } u(x_1, .x_2, \ldots, x_N) \\ &\text{under the condition that} \\ &p_1x_1 + p_2x_2 + \cdots + p_Nx_N \leqq B \text{ and } x_1, x_2, \ldots, x_N \geqq 0. \end{aligned} \tag{1.1}$$

When a solution or maximizer (x_1*, x_2*, ..., x_N*) exists, it is usually assumed that consumers choose a basket of goods **x*** = (x_1*, x_2*, ..., x_N*). Then we can define the demand function by

$$D(p_1, p_2, \ldots, p_N) = \left(x_1{}^*, x_2{}^*, \ldots, x_N{}^*\right).$$

There exists no problem, at first glance. Few people ask how this solution is obtained. Of course, a solution exists if utility function u has some good property such as continuity (Weierstrass theory on bounded closed set). However, the mathematical existence and the obtainability of a solution are quite different. As Neumann and Morgenstern (1953) stated, a wide range of alternating move games such as chess and the game of Go have the property that either the first player or the second player has a winning strategy.[5] If that strategy is easily identified, then these games have no fun, because the game is determined before we play. Mathematically

[5] The theorem can be stated as follows: if G is a two-person, open, alternating game and is determinable within a bounded number of moves, either the first or second player has a strategy by which one can win the game whatever the other plays. Chess and Go have a possibility of a draw (no game, stalemate in the case of chess). In that case, the theorem can be modified to assert that the first has a strategy to win or the second player has a strategy by which he or she does not loose (can gain the game or lead the game to draw). This theorem can be proved as a simple exercise of symbolic logic.

a winning strategy exists, but there is no way to find it (even by using a computer). This fact makes these games highly intellectual games and gives computer scientists a challenging task to beat professional players.

We are in the same situation as in the above games when we want to maximize a utility function under a budget constraint. Commodities are ordinarily sold by units. If a maximal solution (i.e., a combination of commodities) contains quantities that are not integer, that solution is not realizable as a basket of purchased items. If we restrict all solution variables to be integer, the maximizing problem (1) with a most simple linear function u is equivalent to a famous problem called the (unbounded) knapsack problem. It is known that this problem is NP-hard. This means that there is no algorithm that can compute the solution in a polynomial time relative to the size N of the instance (unless $\mathbf{P} = \mathbf{NP}$).[6]

A simple (but not perfect) explanation why the problem requires such a long computing time is given by restricting x_i to be either 0 or 1. Then the problem (1) reduces to knowing the subset of set $\{1, 2, \ldots, N\}$ that has the maximal value satisfying the budget condition. The set of all subsets counts 2^N. If we are to check all possibilities, it is normal that the computer requires a computing time proportional to 2^N.

In a worst case, the computing time may require a time that is proportional to 2 raised to power N. This is a very serious problem. For example, if the problem for less than 10 commodities is solved by a computer in one thousandth of a second (or a millisecond), a problem which involves 80 commodities requires computing time of about 36 billion years, which is almost the double the time that elapsed since the Big Bang until now (Shiozawa 1990, §9 and 10 or Shiozawa 1999, Table I.). However, 80, as the number of commodities, is comparatively small if we assume the problem is to make a purchase in a convenience store. A standard convenience store stocks more than 1500 items in the shop.

It is also necessary to correctly understand the meaning of the knapsack problem being NP-hard. It does not exclude that many instances of the problem can be solved rapidly. We have many algorithms which work for special subclasses of the knapsack problem. For example, if all prices are the same, the maximal solution is the top M/p commodities that have the highest utility. The combined meaning of the fundamental conjecture and the theorem that the knapsack problem is NP-hard is that there is no algorithm that solves all instances of the problem within a polynomial time.

For practical purposes, an approximate solution will do. Some approximation algorithms are very rapid. George Dantzig, the founder of linear programming, proposed an algorithm called a greedy algorithm. It seeks to find the most cost-effective set of commodities. This algorithm ends in a computing time that is proportional to the third order of N. It is not difficult to solve the problem for in instances with N more than 1000. This algorithm is guaranteed to achieve at least half of

[6]The class **P** and **NP** are defined in Sect. 1.2.3. The proposition $\mathbf{P} \neq \mathbf{NP}$ is the most basic conjecture of computing complexity theory but not yet solved.

the theoretical maximum for any given instance. We also know an approximation algorithm that has a polynomial computing time and is guaranteed to attain the value $(1-\varepsilon)\ m$, where m is the maximum and ε is any positive real number.[7]

However, this does not change the point very much. In economics we solve the maximization problem (1.1) with the purpose of defining a demand function. What we need for that is the solution, i.e., the maximizer (x_1*, x_2*, ..., x_N*), and not the maximal value u(x_1*, x_2*, ..., x_N*). Let a solution be given by an approximate computation, and let it be (x_1^{a}, x_2^{a}, ..., x_N^{a}). If approximation is good enough, this may approximate the utility value u (x_1^{a}, x_2^{a}, ..., x_N^{a}) to the maximum utility value u(x_1*, x_2*, ..., x_N*), but we cannot say that the solution (x_1^{a}, x_2^{a}, ..., x_N^{a}) is close to (x_1*, x_2*, ..., x_N*) (see Shiozawa 1999, 2016b).

At the very basic core of neoclassical economics, there is this problem. It ignores the fact that human agents have a limited capacity for calculation. When it assumes that consumers calculate, it assumes, for all individual consumers, an infinite capacity to calculate. Human beings evolved an intelligence that is incomparably greater than other animals. However, much greater that may be, human intelligence is bounded and not perfect. Neoclassical economists ignore this basic fact.

They ignore this, either because they are simply thinking that the human capacity for computing is infinite or because they do not think that this raises a serious problem for their formulation. A prominent Japanese economist once declared that he continues to assume the maximization hypothesis, because in his opinion, economics loses all effective formulation for the behavior of consumers, if once he abandons this hypothesis. It is severely neglectful for a scientist to employ a mathematical formulation of consumer behavior for the sake of personal convenience, even though he knows very well that it is impossible that consumers behave in the manner it describes.

A general problem arises. H.A. Simon named it the problem of *bounded rationality*. In the above, we examined consumers. Simon thinks that a similar problem exists for business firms. He once declared: "If there is no limit to human rationality, administrative theory would be barren. It would consist of the single precept: Always select that alternative, among those available, which will lead to the most complete achievement of your goals" (Simon 1997, p.322). Simon contributed enormously to the recognition of the universal importance of bounded rationality. It really deserves a Nobel prize for economics. However, he made two

[7]This does not mean that any approximation problem is tractable. The Unique Games Conjecture postulates that the problem of determining the approximate value of a certain type of game, named a unique game, has NP-hard algorithmic complexity. Subhash Khot presented this conjecture in 2002. He was given the Rolf Nevalinna Prize at the World Mathematicians Congress in 2014. It is reported that Khot and his collaborators got new results in 2018, which is strong evidence for many mathematicians in this field that the conjecture is true. If the conjecture is true, even to find whether a given number is sufficient to satisfy the conditions of a problem requires more than polynomial time even if the number is not the best (or minimum) number. It means that there does exist a problem which is NP-hard even if only to find an "approximate" solution of any accuracy. See Trevisan (2012) and Klarreich (2018).

small mistakes. First, he compared economics and management science as parallel sciences and admitted that each has its own characteristics. By this unnecessary concession, he renounced the chance to reconstruct (or at least to propose to reconstruct) economics on the basis of bounded rationality. Secondly, his focus on rationality was too narrow to open a way toward the formulation of a general theory of purposeful human behaviors.

We give such a formulation in Sect. 1.3. Before attacking this problem, let us make a detour to consider the complex nature of our world.

1.2.2 Solving a Problem and Computing Complexity

Evolution of economic behavior depends much more on intelligence and learned behaviors than on hereditary characteristics. The major forces that drive change in our behaviors are rational computation, together with learning from previous decisions of self and others. Of course, the basic economic behaviors associated with physiological survival remain within a wide range of human hereditary characteristics. However, they have since evolved enormously under social influences. Behavioral evolution occurs for economic reasons and is not determined by human hereditary characteristics so long as new acquired and learned behaviors remain within the range of our physical possibilities. What then are the reasons that make evolution inevitable for almost all economic entities? To understand the true nature of an economic entity's evolution, it is necessary to consider two conditions. One is the limits of our capabilities. The other is the complexity of the decision-making.

There is no absolute criterion that determines something is complex or not. It depends on our capacity. When we got computers, many once unsolvable problems have now become solvable. The mathematics of optimization is developing everyday. Computing capacity is expanding rapidly. Despite all these manifest facts, it is ironical that mathematics is also revealing that a class of "unsolvable" or "intractable" problems exists and will persist in every corner of optimization. The class is called NP-hard. This is a very important concept in understanding the nature of the complexity that we encounter in the real world. Before entering into the discussion of NP-hard, and of computing complexity in general, we need to complete some preparations.

A problem is a set of infinitely many *instances* with an integer called *size* of the instance (there may be many different ways to measure the size of an instance). For example, a linear equation of N unknown variables is

$$\begin{aligned} a_{11}x_1 + a_{12}x_2 + \cdots + a_{1N}x_N &= b_1 \\ a_{21}x_1 + a_{22}x_2 + \cdots + a_{2N}x_N &= b_2 \\ \cdots \\ a_{N1}x_1 + a_{N2}x_2 + \cdots + a_{NN}x_N &= b_N. \end{aligned} \tag{1.2}$$

An instance of the problem (1.2) is given, when we specify all a_{ij} and b_i. The size of this instance is, for example, N. We know that (1.2) is solvable when the determinant of the matrix of coefficients a_{ij} is not 0.

Consider an algorithm for solving (1.2). An *algorithm* is a predetermined procedure of calculation to solve the problem. How much time does it take before we get a solution? The computing time depends naturally on computing speed. In the complexity theory of computing, we normally count the number of elementary arithmetic procedures. For example, in the case of linear equations, we count the necessary number of four operations (plus, minus, multiplication, and division). This number depends of course on the design of algorithms available and varies depending on the goodness of those algorithms. Take as an example the Gaussian elimination method. A standard procedure requires

$$\left\{4N^3 + 9N^2 - 8N\right\}/6$$

operations. In this case, computing time is given by a polynomial of the size N. When we are interested in the growing length of the computing time, only the highest order term of the polynomial is relevant. In that case, we often say that the computing time is of order N^3, or use a mathematical abbreviation O (N^3).

Some problems can be calculated very rapidly (if we use a computer and a good algorithm). For instance, if a sorting problem is to sort any set of integers in increasing order, then this sorting process ends by steps that are proportional to $N \log_2 N$. This means that to sort an instance of 10,000 numbers requires about 23 times more steps than sorting 1000 numbers. Many effectively soluble problems can be solved at orders 2, 3, or 4. For example, the multiplication of two matrices, or a system of linear equations, can be solved at O(N^3).

Another example of a rapid algorithm is linear programming, or LP. LP covers a wide range of practical problems, and we can say that it is the most useful mathematical tool that is applicable to problems of large scale.[8] The classical simplex method runs normally in polynomial time, e.g., O(N^3), but in some cases computation enters into an eternal cycle, and in some others, it requires an exponential order of time (or O(2^N)). The Karmarkar method (a variation of the interior method) eliminated these troubles, and it is now assured that the program runs in O(N^α) for any LP problem, where α is a constant between 3 and 4. In some cases, a seemingly difficult problem can be reduced to an LP problem, in which cases a problem can be solved rapidly. The reduction is drastic. The classical assignment problem is an example. With an enumeration method, computation requires $N!$ steps of a simple routine. Kuhn (1955), based on the works of Birkhoff and von Neumann, proved that it can be solved as an LP problem and the computation time can then be reduced to O(N^3).[9]

[8] In some cases, we can solve problems with 1000 unknowns or more.

[9] Pak (2000) is a good illustration how LP works in the case of the classical assignment problem.

However, the lesson we should learn here is not that some problems can be solved rapidly by computers. The lesson we should learn is that there are many intractable problems. They are *intractable*, not because there is no algorithm that solves the problem, but because it takes too long a time for the computation (many years or many thousands of years). With the arrival of computers, study of the "goodness" of algorithms became urgent and important. The needs of this research led to the establishment of computational complexity theory.

1.2.3 NP-Hard Problems or Really Intractable Problems to Solve

Computational complexity theory is a part of mathematics that studies questions of how complex a problem is. *Complexity* is measured in two major ways: time complexity and space complexity. The first gives an estimate of the necessary number of operations. The second gives an estimate of the necessary memory space, or the number of places for arguments. We have seen that the time complexity of problem (1.2) is $O(N^3)$. To the astonishment of many mathematicians, computational complexity theory revealed that there are many intractable problems among the problems that we encounter in economics and industry. The NP-hard problem is one of them. To define this concept also requires some preparation.

A decision problem, in computation theory, is a problem that can be answered yes or no. The class of problems **P** is the class of decision problems that has an algorithm whose computing time is bounded by a polynomial function of the size N. In a rough description, a problem in **P** is somehow "tractable" because we can solve it in a polynomial time. Of course, even if a problem is soluble in polynomial time, it does not assure that we can effectively solve the problem. If the degree of the polynomial is as large as 6 or 7, an instance of a large size becomes difficult to solve. However, here we are concerned with those problems which are far more difficult. The majority of computer scientists believe that an NP-hard problem necessitates more computing time than any polynomial order $O(N^M)$.

A verification problem of a decision problem is the problem to verify that when a candidate of the solution is given (e.g., by chance), it is really a solution. The class of decision problems **NP** (meaning nondeterministic polynomials) is the one whose verification problem can be solved in polynomial time. Note that **P** is a subclass of **NP**, because an instance of **P** has an algorithm by which we can determine if the problem is "yes" or "no" in polynomial time.

An interesting subclass of decision problems is *NP-complete* problems. A decision problem H is NP-complete when any instance of a NP problem can be reduced to an instance of H within polynomial time. It is astonishing to know that there are such problems. In 1971, Stephen Cock proved that a problem called 3-SAT has such a property. 3-SAT is a special case of problems when we want to know if there is a set of truth values which makes a given logical formula true. Cock's result opened a new era of computational complexity theory.

After one NP-complete problem was discovered, many problems came to be known as NP-complete. An easy way to prove it was to show that we can reduce a problem to a 3-SAT problem.[10] An example of the NP-complete problem is the *subset sum problem*. Suppose we are given a set of integers of N elements. The problem is to determine if there exists a nonempty subset T such that elements of T sum up to zero. For example, if $S = \{-13, -8, -4, 2, 5, 7, 19\}$, there exists a subset $T = \{-8, -4, 5, 7\}$ which sums to zero. Then the decision problem is affirmative. Evidently this is a NP problem, because it is easy to verify (in polynomial time) that $-8-4+5+7=0$. If such a subset T is given, the verification ends with at most $N-1$ times of additions and subtractions. However, it is not easy to determine if there is a subset whose elements sum up to zero. To answer this problem by checking all possible subsets requires computing time proportional to 2^N.

When NP-complete problems were known, a new problem arose: $\mathbf{P} = \mathbf{NP}$? Since 1971 this problem has been the most challenging problem for mathematicians and computer scientists. Many challenged the problem, but no one has ever succeeded. The Cray Mathematics Institute selected this problem as one of seven Millennium Prize Problems (Cook 2000). It is promised that US$ 1,000,000 will be given to the person who is first to find a correct solution (i.e., to prove $\mathbf{P} = \mathbf{NP}$ or show $\mathbf{P} \neq \mathbf{NP}$). Although this decision problem is not yet solved and nobody knows how to approach the problem, the majority of researchers in this field believe that $\mathbf{P} \neq \mathbf{NP}$. Thousands of NP-complete problems were found since the 1970s, but there is no known algorithm which runs in polynomial time. This is one of the reasons why the majority of researchers in this field believe that $\mathbf{P} \neq \mathbf{NP}$.

A problem is called NP-hard, when it has an associated NP-complete decision problem. An optimization problem usually has its associated decision problem.[11] For example, the knapsack problem we have examined above is a maximization problem. The associated decision problem of a knapsack problem is the question: "Is there a 0–1 vector $\mathbf{x} = (x_i)$ which satisfies the constraint condition and whose total utility is higher than a given value?" We said that the knapsack problem is NP-hard. It is, because its associated decision problem is NP-complete. In the same way, there are as many NP-hard optimization problems as there are NP-complete decision problems which are associated with an optimization problem. Recall that an NP-complete problem is a decision problem by definition and NP-hard problems are not necessarily decision problems. This is the main difference between NP-complete and NP-hard problems.

One of most famous NP-hard problems is the traveling salesman problem. It is to find a traveling route that passes all cities in a given list and requires the least

[10] In an exact expression, this means that an instance of problem H can be reduced to an instance of 3-SAT problem in polynomial time. We use this abbreviation from now on.

[11] Optimization in mathematics and economics means to obtain a maximal or minimal solution. In engineering, optimization often means simply improvement.

cost. We cannot say that the traveling salesman problem is important in real life. However, it is intuitively understandable, and this is the reason why it is presented so often. But, there are many other problems which we do often face in real life. They are the scheduling problems. Scheduling problems appear frequently in business and industry. A *schedule* is an assignment of a set of personnel, machines, and other resources to a specific task or duty over a specific interval of time. Making a schedule is a part of everyday work for a manager.

As they appear in the most varied situations, they have many variations and have many different names. For example, they are called job-shop scheduling problems, nurse scheduling problems (or nurse rostering problems), optimal staffing problems, weighted assignment problems, general assignment problems, and others.

A job-shop scheduling problem is an optimization problem when we are given N jobs of varying time lengths, which need to be scheduled on M identical or different machines. Jobs may have sequence-order constraints. For example, job J2 should be placed after the job J1 is finished. We can take as optimizing objectives various target functions: the time span in finishing all jobs, the total cost of operating machines, the number of machines used, the time of delivery of the finished goods, and so on. We do not enter into the details of these problems, but many problems we want to solve in many of the most common situations turn out to be NP-hard.[12]

Although they are a common planning task for managers, most scheduling problems are NP-hard and intractable, if we really want an optimal solution.

Before ending this long detour into NP-hard problems, it is necessary to add one more remark. It is important to know that an NP-hard problem has many instances that can be solved in a reasonable length of time. As I have noted above, when I first introduced the knapsack problem, being an NP-hard problem does not mean that no instances can be solved rapidly. On the contrary, it is known that many (or even the majority of) instances of a NP-hard problem can be solved quite rapidly, even if they are of a large size. However, it is not well known how computing time is dispersed. A possibility is that the computing time of instances of the same size makes a landscape similar to the absolute value of a function of a complex variable. Imagine a rational function defined on a complex plane. They are finite for all points except for several poles. If the points approach to a pole, the computing time increases without limit and exceeds any predetermined one. Instances whose computing time is less than a predetermined time will be a large area with some holes. For a fixed maximum computing time, the holes become bigger and may cover almost all the area when the size of instances becomes bigger.

This fact has a serious consequence for neoclassical economics. It is based on the basic assumption that demand and supply functions exist and that they represent actual human economic behavior. Therefore, the above result implies that a demand

[12]To discern if a given problem is NP-hard or not is a delicate mathematical problem. It is hard for non-specialists to tell that this problem is NP-hard and that problem is not NP-hard. A minor modification of the problem may change NP-hard problem to a problem which can be solved in polynomial time.

function defined on the maximization assumption cannot represent actual people's demand behavior. As I have pointed out, the computing time easily exceeds any practical scale of time when the maximum computing time is proportional to 2 raised to N the number of commodities. A demand function can represent an economic agent's behavior only for an extremely small economy that counts at most a few tens of commodities.

The ubiquitous nature of NP-hard problems indicates that formulating economic behavior by a maximization principle is a bad characterization, be it a personal or organizational one. Then, how is our intellectual behavior organized? This is the question we must pose and solve. We will do it in the next section.

1.2.4 Some Economic Consequences of the Ubiquity of NP-Hard Problems

NP-hard problems appear everywhere. They are ubiquitous. Does this mean that we should abandon the rational pursuit of better solutions? By no means! In economic situations, no exactness is required. You may not attain an optimum by computation. Except in a very fortunate situation, you are obliged to satisfy by a nonoptimal feasible solution (a solution which satisfies all constraint conditions).[13]

What matters in an economic situation are the feasible solutions that you can obtain. They may result in different values for the objective function. However, you can compare their values, and if you find one solution that is the best of all, then it is sure you will choose that solution.[14]

The best solution you get is the best among the feasible solutions you can compare. That best solution may have a value which is far from the optimal value, and you may not know what that optimal value is. You cannot compare the solutions you obtained with the optimal solution. Theoretically speaking, or in the eyes of God, the value of your solution may be very bad. Your solution may give you a value that is one half of the optimal value. You can inquire in what situation you are, theoretically, but it will be a difficult mathematical problem to solve.

You can continue the search for better solutions, for example, by consuming more computing time. However, you may lose the chance to get your profit by postponing your decisions. Because of bounded rationality and the ubiquity of NP-hard problems, the majority of any existing entities are not optimal. This creates the opportunity for improvement and is the reason why evolution takes place successively and incessantly.

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[13]Taking this fact more positively, H.A. Simon named it the *satisficing principle*.

[14]Solutions may have different effects on other aspects that are not taken in consideration. If you are a manger of a firm, you cannot ignore these points. In the above, we assumed that these side effects are all indifferent. The same remarks apply to many later discussions, but we do not repeat the same caution.