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No. 1

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主 論 文 題 名：

Nonlinearity, Bounded Rationality, and Heterogeneity: Some Aspects of Market Economies as Complex Systems

（非線形性、限定合理性、及び異質性：複雑系としての市場経済の諸相）

（内容の要旨）

This thesis pursues a nonlinear approach in considering both chaotic dynamical models and agent-based simulation models of economics, as well as their dynamical behaviors.

Chapter 1 deals with the following basic questions from the historical and methodological perspectives: what is nonlinear economic dynamics and how has it been developed? We first discuss how economic dynamics was formed in the 1930s and the extent to which it is closely related to the equilibrium paradigm, which is synonymous with the neoclassical paradigm. Then, by comparing two approaches in economic dynamics, namely exogenous and endogenous business cycle theories, we state that the exogenous business cycle theory relied on linear dynamical models and was suitable for the equilibrium paradigm, while the endogenous business cycle theory relied on nonlinear dynamical models and was the starting point of nonlinear economic dynamics. We state that the original standpoint of nonlinear economic dynamics was to make a clean break from the equilibrium paradigm and we should get away from it in order to pursue economic complexity.

Chapter 2 provides an introductory exposition of nonlinear discrete dynamics by presenting a one-dimensional nonlinear cobweb model. The model is a simple extension of the standard cobweb model. The new ingredients are an iso-elastic inverse demand function (i.e., an inverse demand function with constant price elasticity) and boundedly rational producers who gradually adjust their production toward the target levels based upon naive price expectations. Thus, the key parameters of the model are the price elasticity of demand and the production adjustment speed of producers. With the aid of mathematical analysis and numerical simulations, it is shown that for a large set of parameter values, the

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cobweb market exhibits observable chaos (a strange attractor) as well as topological chaos (a horseshoe) associated with homoclinic points. We detect chaotic behavior in a theoretically large and empirically relevant region of the price elasticities of demand and adjustment speeds. The faster producers adjust their production, and the more inelastic demand is, the more likely the market behaves chaotically.

Chapter 3 extends the one-dimensional model studied in Chapter 2 to include two different types of producers in order to investigate whether slight behavioral heterogeneity could be a factor that drastically changes the dynamical properties of a market. The two types of producers are naive optimizers and cautious adapters. A naive optimizer produces the profit-maximizing quantity instantaneously, while a cautious adapter adjusts his/her output toward the profit-maximizing quantity as a target. We obtain a two-dimensional model, which is more difficult to analyze because mathematical theories of higher-dimensional nonlinear dynamical systems are underdeveloped compared with those of one-dimensional systems. With the aid of mathematical analysis as well as numerical calculations, we show that a single agent may change the complexity of market behavior. In a market of naive optimizers, a single cautious adapter stabilizes the otherwise exploding market. In a market of cautious adapters, a single naive optimizer may destabilize the market. Without him/her, there exists at most one periodic attractor in the market. However, with him/her, many (and even infinitely many) coexisting periodic attractors may appear.

In Chapter 4, we take a moment to pause and reflect on the status quo and the future of nonlinear economic dynamics. Nonlinear economic dynamics originated in the 1930s, led into chaotic economic dynamics at the end of the 1970s, and continues today. However, research on nonlinear economic dynamics has thus far suffered from the serious restriction on mathematical analytics. We consider where nonlinear economic dynamics should be headed and state that it should aim to use computationally oriented research methods against the background of complex system theory. This statement underpins the studies presented in Chapters 5, 6, and 7. We finally point out that two fundamental directions exist in which research on economic complexity has been carried out: the econophysics approach and agent-

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based model approach. We concentrate on the latter approach in Chapters 6 and 7.

One of the important conclusions of Chapter 3 is that heterogeneity matters decisively in the complex behavior of a nonlinear economy when at least two different types of agents exist. The question then arises: what happens if there are many different agents in a nonlinear economy? Chapter 5 investigates such a problem by extending the one-dimensional nonlinear model studied in Chapter 2 to a high-dimensional nonlinear model to study multi-regional business cycle synchronization. Empirical studies often conclude that multi-regional business cycles exhibit intermittent transition between the synchronization and desynchronization of each regional fluctuation and we robustly observe this behavior (called chaotic itinerancy) in the model of this chapter, in which all the regions of a national economy are homogeneous and connected through producers' behavior based on the average level announced by the government. One of the main findings is that although a producer slowly adjusts his/her output toward the average level, regional business cycles begin to synchronize because of the entrainment effect. Moreover, when a producer emphasizes profit maximization more and places more weight on the average level in his/her decision-making, the economy is more likely to exhibit such intermittent transition. Further, it is clarified that behind intermittent transition exist cycles among periodic orbits with a different number of unstable directions.

In Chapter 6 and 7, we investigate the time evolution of the market structure in terms of market share dynamics, by employing agent-based models with boundedly rational firms and consumers interacting with each other. The common basic feature of boundedly rational firms is that since they do not know the shape of their demand functions they face, they adaptively revise production levels and prices so as to raise their profits based on the reaction by consumers. The main difference lies in consumers' behavior.

The model presented in Chapter 6 considers product differentiation and boundedly rational consumers in the sense that each consumer has a preference for the

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product of a particular firm and exhibits habitual purchasing behavior unless the relative price differences exceed a certain critical level. Each firm revises its production decisions and prices to raise its profit based on the reaction by consumers. We do not take into consideration mergers and acquisitions or the game-theoretic settings among firms. Hence, this kind of consumer brand loyalty is the only source of the emergence of monopoly and oligopoly. The simulation results show that as the control parameter of a consumer's brand loyalty increases, monopoly and oligopoly emerge led by the invisible hand. In addition, oligopoly rather than monopoly is the final state of a market economy.

In Chapter 7, we continue to investigate a competitive market as a complex adaptive system consisting of mutually interacting, boundedly rational firms and consumers. In the model presented in Chapter 6, product differentiation was considered, showing that a consumer's brand loyalty plays an important role in the emergence of oligopoly. By contrast, in this chapter, we consider a market of homogeneous goods. In this market, boundedly rational consumers decide from which firm to purchase goods to increase their utility, and we employ, as a first step, a statistical description to represent firms' distribution of consumer share because the number of consumers is very large. Firms' distribution is characterized by a single parameter representing how "rationally" the mass of consumers pursue higher utility. Aggregate consumer behavior is described by the Boltzmann distribution, which indicates how rationally the consumer seeks to increase his/her utility. Since the boundedly rational firms do not know the shape of the demand function they face, they adaptively revise their production levels and prices to raise their profits with the aid of a simple reinforcement learning algorithm (i.e., by learning through experience). The simulation results show that the three market structure phases, namely the uniform share phase, oligopolistic phase, and monopolistic phase, arise depending upon how rational consumers. In the oligopolistic phase, the market share distribution of firms follows Zipf's law and the growth rate distribution of firms follows Gibrat's law. This phase is the best state in the sense that it maximizes consumers' utility. However, it minimizes firms' profits because the moderate rationality of consumers generate severe competition.