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Human behavioral regularity, fractional Brownian motion, and exotic phase transition

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ABSTRACT

The mix of competition and cooperation (C&C) is ubiquitous in human society, which, however, remains poorly explored due to the lack of a fundamental method. Here, by developing a Janus game for treating C&C between two sides (suppliers and consumers), we show, for the first time, experimental and simulation evidences for human behavioral regularity. This property is proved to be characterized by fractional Brownian motion associated with an exotic transition between periodic and nonperiodic phases. Furthermore, the periodic phase echoes with business cycles, which are well-known in reality but still far from being well understood. Our results imply that the Janus game could be a fundamental method for studying C&C among humans in society, and it provides guidance for predicting human behavioral activity from the perspective of fractional Brownian motion.

1. Introduction

Competition and cooperation (C&C) [1–3] are two opposite activities, which, however, widely coexist in human society [4,6,7,5,8–10]. They are even found and studied in the microbial systems [11,12]. In spite of extensive researches, C&C still remains poorly explored due to the lack of fundamental and reliable methods. Nevertheless, the comprehension of C&C is particularly important because of the exigent need to understand and predict behavioral activity of human individuals or crowds [13]. For this purpose, minority game models based on multi-agents [3,5,8–10,14,15] are believed to be a fruitful and fundamental method.

In this work, we propose a free-competition artificial market with two substitute products. Participants in the market are divided into two groups, namely, suppliers and consumers. Every supplier tries to choose which type of products to produce, while every consumer has to decide which to buy, for the purpose of maximizing their own utilities. Hereafter we use “Janus game” to denote the market proposed in this work. As is known, the word “Janus” refers to one kind of God with two faces in the ancient Roman myth. There are two main reasons for naming “Janus game”: two opposite kinds of roles, producers and consumers, are involved in the market-based economy; there exist two opposite goals of the game, competition and cooperation. As an application, we shall show that the Janus game may help to realize human behavioral regularity, which is characterized by fractional Brownian motion associated with an exotic transition between periodic and nonperiodic phases. Specifically, the periodic phase herein reflects the occurrence of business cycles, which are well-known in economic activities but still far from being satisfactorily understood [16–19].

Business cycles bring economic recovery and prosperity, as well as the burst of bubbles and depression. Most of the literatures on business cycles focus on either the empirical factors affecting the properties of business cycles [20–22] or the technical methods of analyzing business cycles time series [23–25]. They seldom relate to microscopic understandings regarding individual agents. This work presents a bottom-up model called Janus game in the light of minority game [8–10,26], and we shall show that the Janus game would be appropriate to construct behaviors of suppliers and consumers, thus yielding a possible microscopic understanding of the dynamics of business cycles.

2. The Janus game

Fig. 1 shows a sketch of the Janus game, the details of which are described as follows.

1. The market is isolated without any external interference. The individuals in the market, who are supposed to be rational, take aim at earning payoffs as much as possible.

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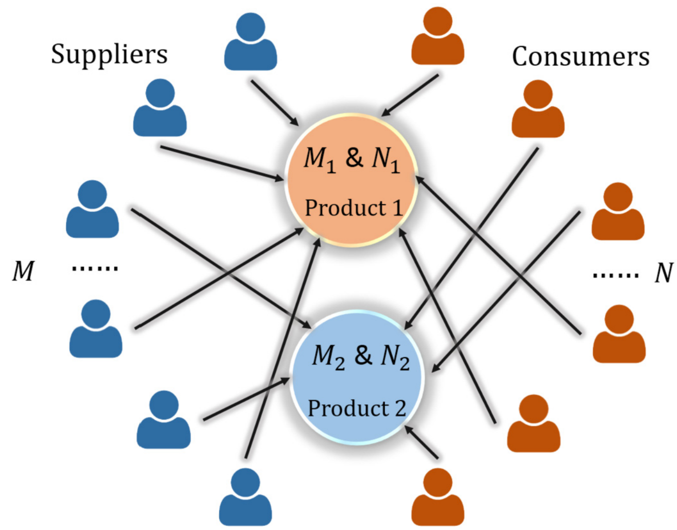

Fig. 1. Sketch of the Janus game with two basic groups of participants, M suppliers and N consumers, for two types of products, Product 1 and Product 2: $M = M_1 + M_2$ and $N = N_1 + N_2$.

2. Two products, labeled as Product 1 (P_1) and Product 2 (P_2), are freely traded in the market. The two products are alternative for each other, which means that their price elastic coefficients are nearly the same.
3. The market participants are randomly assigned to two roles, namely, suppliers and consumers. M and N denote the total numbers of the individuals in the two groups respectively.
4. Suppliers are supposed to choose products to produce, whereas consumers should choose which product to buy. According to their strategies, which should be also subject to the competition and cooperation situations, each individual can choose any one of the two products.
5. Every one of suppliers (or consumers) is assumed to produce (or purchase) only one unit of the product he chooses. So, the amount of supply and demand for P_1 and P_2 can be denoted as the actual numbers of suppliers and consumers for each product, i.e. M_1, M_2 and N_1, N_2 respectively, where $M = M_1 + M_2$ and $N = N_1 + N_2$.
6. The market operates in discrete time steps, which means that it is a repeated game like minority game [8–10]. However, because of poor liquidity of resources, suppliers wouldn't change their choices much too frequently, until the arbitrage chance in the market gradually fades away.

Since the model is built based on minority game, it can be basically interpreted as one kind of two-sided minority game, where the minority of consumers and the minority of suppliers could win at the same time. We can see that the market equilibrium occurs at the point when $M_1/N_1 = M_2/N_2$. If $M_1/N_1 > M_2/N_2$, it indicates that consumers, on average, are able to buy more P_1 than P_2 produced by suppliers. It also means that the average "cost" for consumers buying P_2 is relatively higher than that for consumers buying the other product. So, consumers who choose to buy P_1 obtain relatively more payoffs than the other consumers. At the same time, suppliers who choose to produce P_2 actually obtain relatively more payoffs than the other suppliers. Hence, we can say that suppliers of producing P_2 and consumers of buying P_1 win at this time due to right choices. In contrast, in the case of $M_1/N_1 < M_2/N_2$, suppliers who produce P_1 and consumers who buy P_2 are the winners. It's worth noting that in the game, prices of products are not necessary information since what the individuals really concern is only the win–lose outcome. Regarding the assumption of "rational man", actually no matter which roles the individuals are, all should make their best choices with the intent to obtain benefits.

3. Agent-based simulation

3.1. Decision-making process

Inspired from the market-directed resources allocation game (MDRAG) [9,10], the similar decision-making processes for agents are adopted in the Janus game. The MDRAG, where agents' heterogeneous preferences are introduced, is actually an extended model derived from the minority game [8]. According to the minority game [8], if m denotes the memory length of an agent, then the number of all situations he may be confronted with should be 2^m. However, Cavagna proved that the memory of minority game is irrelevant to decision-making processes [27], thus suggesting that the m-bit detailed situation set could be encoded by integers. We assume that the number of possible situations that an agent may encounter is P, which is generally in the range of 1 to 2^m. Each value of P corresponds to a choice, 1 or 0 (1 refers to P_1 while 0 refers to P_2). Since the length of situations is P, the full strategy pool should be 2^P. Every agent's initial S pieces of strategies are randomly selected from this pool. So the strategy table of each agent is a $P \times S$ matrix containing the bits of 1 or 0. When P is large enough, the probabilities of 0 or 1 in every strategy are nearly the same, 50% [8,9]. This leads to the homogeneous preference for 0 or 1, no matter which strategy the agent uses. However, this kind of homogeneous preference cannot easily bring the market into equilibrium, especially when the population bias between the two products is too big. Thus, following the MDRAG, in this work we adopt the parameter P to take into account the heterogeneous preferences of agents. Whatever the present situation is, all of the agents ought to make choices according to their highest-scored strategies. At each time step, after their choices have been made and the win–lose result has come out, all the strategies, which may lead the agent to win under the present situation, should be scored.

In the mean time, consumers in the Janus game are able to make new choices for buying products. Moreover, in spite of inevitable transfer costs and poor liquidity of resources, suppliers are given the abilities to determine the time when they should make new choices for producing products. The length of the time intervals for changing is denoted as ΔT. In fact, if $M_1/N_1 = M_2/N_2$, the market will be in the balanced state (equilibrium). As long as the system reaches the equilibrium, the population ratio of choosing the two products will keep stable. At this time, everyone who wants to break the equilibrium will make himself at a disadvantaged situation where the number of players of his type (maybe producers or consumers) has already been saturated. Moreover, in the perspective of entropy, a well-balanced system corresponds to a maximal entropy. Therefore, it becomes hard for suppliers or consumers to break the stable equilibrium. To find how far the system is deviated from the equilibrium, an arbitrage index (a_I), which is derived from the Shannon entropy, has been defined as

$$a_I = 1 + \sum_{i=1}^{2} p_i \log_2 p_i .$$

Here p_i is understood as the non-balanced degree of market supply and demand, defined as

$$p_i = \frac{M_i / \langle N_i \rangle}{M_1 / \langle N_1 \rangle + M_2 / \langle N_2 \rangle} .$$

$\langle \cdots \rangle$ in p_i represents for the average of $\cdots$ from the last time step when suppliers make their choices to the current time step. a_I has a value in $[0, 1)$. It is evident that a lower value of a_I means