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Order book, financial markets, and self-organized criticality

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ABSTRACT

We present a simple order book mechanism that regulates an artificial financial market with self-organized criticality dynamics and fat tails of returns distribution. The model shows the role played by individual imitation in determining trading decisions, while fruitfully replicates typical aggregate market behavior as the “self-fulfilling prophecy.” We also address the role of random traders as a possible decentralized solution to dampen market fluctuations.

1. Introduction

Financial markets are characterized by the interactions of many interconnected heterogeneous agents, who trade with each other and follow their own expectations with feedback mechanisms. The resulting aggregate behavior shows complex features, unpredictability and the occurrence of extreme events. Socio-economic systems can be studied as complex entities, by means of methods and concepts coming from statistical and theoretical physics [1–3]. Such an approach helps studying financial markets exploiting the idea of behavioral heterogeneity, entailing a specific role for the interaction among market participants, in terms of imitation and individual psychology [4–7].

The behavioral variability of agents operating in a complex network structure endowed with different informative sets justifies the evidence that empirical phenomena of socio-economic systems need new and alternative approaches. As an example, the beneficial role of random strategies has been shown in several recent papers for the efficiency of socio-economic systems [8–10], and in particular of financial markets [11–14]. Agent-based models may play a key role in understanding complex economic dynamics, needed for innovative policy design [15].

The adoption of agent-based approaches in financial markets models, surveyed in refs. [16] and [17], has revealed to be very useful to study the complex interactions of *different* individuals with *different* behaviors, as for example in [18–28]. Very often, in this stream of studies, two types of investors are taken into account: fundamentalists and chartists. The former are traders with an eye on the fundamental value of assets; thus they decide whether to buy a share or not, by looking at its current price level and by comparing it with its fundamental values (that is, roughly speaking, almost always the present discounted value of future expected dividends). The latter are technical analysts, who decide their strategies by following trends and graphic dynamics of past prices on charts.

In the existing literature, the imitative behavior of a trader has often been modeled by means of a switching oscillation from fundamentalists to chartists or vice versa. Recently, a more realistic kind of imitation has been proposed in [29], so that the imitation refers only to the trading decision, no matter which group the trader belongs to. Thus, the persuasive strength of information may induce, say, a chartist to imitate a fundamentalist without switching group. In the present paper, we go further along this direction and more realistically propose that the imitation will regard the trading status, i.e. the decision either to buy or to sell or even to wait without trading at all.

We will explicitly refer to herding phenomena deriving from information cascades between agents [30] as the underlying mechanism of financial avalanches. Differently from other attempts to describe herding in financial markets [31,32], our approach considers the pressure coming from the accumulation of information, by recalling some features of a Self-Organized Criticality (SOC) model for describing earthquakes dynamics [33]. Our present model builds up on [29], by adding an order book mechanism that determines the asset price by the matching of supply and demand, as in real markets. In such a way, heterogeneous traders of different kinds interact by means of personal strategies decided according to information, imitation and prospective utility.

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There exists a very well established branch of literature dealing with the characteristics and the dynamics of order books. As a matter of fact, the order book design is the mechanisms that lets financial markets everyday life to develop: the way orders are placed and influence the current price, the way the bid-ask spread is canceled trade after trade, the size and the timing of the execution of orders, and so on. Examples of these studies are in [34–38]. Different market mechanisms have been studied in the literature dealing with the market microstructure, such as in [39–44] among others. In the present paper we begin with a simple representation of the order book: limit order always executed at the best price, with the simplifying assumption that just one asset exists and that only one-share orders can be placed. Moreover, we do not consider any cancelation of orders, because we presume that at any time step every trader decides whether to buy or to sell and, consequentially, to submit the corresponding order.

In a previous study [29], a SOC model of financial markets has been presented with interacting agents and a contagion mechanism. There, the price formation was strongly based on an exogenous source of noise. The model here presented, instead, represents a first step toward a further advance, because it replaces the external noise with a more realistic microstructure of trading that induces the price formation. By combining together the influence of herding dynamics at the aggregate level and the orders matching, this model represents, as far of our knowledge, the first attempt to embed in a unique framework two fundamental aspects of real financial markets: aggregate contagion effects and individual orders placement.

The paper is organized as follows: in Section 2 the model is described; in Section 3 simulation results are discussed; in Section 4, conclusions and some policy suggestions are presented.

2. The OB-CFP model

This model builds on the CFP model presented in [29], and adds to it an order book mechanism to simulate the operation of a financial market. This is the reason why we named it *Order-Book-driven Contagion-Financial-Pricing* (OB-CFP henceforth). In the next subsections, all the elements of the model will be described, from the definition of traders to their character, to the type of their interaction and so on, till the aggregate dynamics. At each time step, the model proceeds following this evolution: as a first step, all market participants form their individual (heterogeneous) expectations for the future price; in a second step, according to individual expected values, traders select their trading status (hold, buy or sell); as a third phase, all orders are organized in the order book which operates the matching for the transactions to be done; finally, the new aggregate asset price is reported as function of both the last trading price and the possible market imbalances (either excess demand or excess supply), as it happens in true markets. It will be shown in Subsection 2.2, that the contagion mechanism comes into play when traders have to decide their status, in order to take into account the possibility that the infectivity of an euphoric or pessimistic perception of the market could generate information cascades of buying or selling behavior.

2.1. The order book dynamics

Let us consider an ideal financial market where only one asset exists and money has just an ancillary function for it to serve just for transactions regulation. The population consists of a given number N of market participants, i.e. traders A_i (with $i = 1, \ldots, N$). At the beginning of each simulation, they are endowed with an equally valued portfolio, composed by the same initial quantity of money $M_i = M$ $(\forall i)$ and the same initial quantity of the asset $Q_i = Q$ $(\forall i)$. The total wealth W_i of each trader will be therefore defined as: $W_i = M_i + Q_i \cdot p_t$, where p_t is the price of the asset at time t. Two groups of traders exist: (i) fundamentalists, (ii) chartists. However, a third category of traders, i.e. random traders, will be also considered to study their influence in the market dynamics. At each time step, traders will behave differently, according to their group. The difference among them is not new: fundamentalists presume the existence of a *fundamental value* and believe that the market price dynamics will tend to it. Therefore, they form their expectations by considering the actual difference between the fundamental price p_f (different for each trader and randomly chosen in the interval $[p_F - \theta, p_F + \theta]$, where p_F is a fixed global fundamental price) and the last market price p_t: they will expect a rise (fall) in the market price whether $p_f > p_t$ ($p_f < p_t$). Of course, a stationary dynamics is expected in case of equality. Thus, they form their expected price for the asset according to

$$E[p^f_{t+1}] = p_t + \phi(p_f - p_t) + \epsilon \quad (1)$$

The parameter ϕ is a sensitivity parameter that describes the expected speed of convergence to the fundamental price and ϵ is a stochastic noise term, randomly chosen in the interval $(-\sigma, \sigma)$, with σ fixed at the beginning of simulations and extracted with uniform probability. In order to limit the number of parameters, we let the value of ϕ be fixed but, in principle, it can be different for each trader of this group.

A chartist decides her behavior according to her inspection of past prices. Therefore, the expected price of each trader belonging to this group is a function of past prices: in particular we adopt the average of last T prices over a time window that is different for each chartist ($T \in [2, T_{max}]$). Thus, a chartist will form "her" expected price as a function of the difference between the last market price and the average of past T-prices, p_T. More precisely,

$$E[p^c_{t+1}] = p_t + \frac{\kappa}{T}(p_t - p_T) + \epsilon \quad (2)$$

Also in this case, we consider the sensitivity parameter κ as a constant, whereas ϵ is a stochastic noise term defined as in Eq. (1).

Finally, we consider also random-trading agents. Random traders are investors who do not care at all about either previous or fundamental values: these market participants decide randomly (with uniform probability) whether to buy, to sell or to hold, without forming any expectation for the value p_{t+1}.

After having calculated her own expected price, each trader decides her order type, i.e. either to buy, or to sell, or to hold, and assumes the corresponding status S_i (bidder, asker or holder). In case the expected price is greater than the actual one, it is profitable to buy the asset because the expected value of the owned portfolio is correspondingly higher. On the contrary, if a trader has a bearish expectation she will sell. It is worth to notice that in the model a sensitivity threshold τ has been introduced in such a way that if the expected price is equal or sufficiently close to the last price, the trader will decide to hold on without setting any orders. Of course, traders who decide to buy must have a positive amount of money ($M_i > 0$) and, similarly, those who decide to sell must have a positive amount of the asset ($Q_i > 0$).

Once the individual status has been decided, each trader sets her order in the book by choosing the preferred price for the transaction. Both in case of sales and purchases, the price chosen by each trader (personal bid price for bidders and personal ask price for askers) for the transcription in the order book is a function of the expectation that inspired the status of the same trader. More precisely, the personal bid price will be a real (positive) random number smaller than the minimum between the money amount of the bidder and her expected price, while the ask price will be a real (positive) random number between the expected asset price of the asker and the actual global asset price.