Understanding the complex dynamics of financial markets through microsimulation

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Chapter 1

Introduction

1.1 Complexity of financial markets

In today's financial markets huge volumes of interdependent assets are traded by a large number of interacting market participants in different locations and time zones. Their behavior is of unprecedented complexity and is exhibited in for example the unpredictable dynamics of asset prices characterized by strong cross-asset and intercontinental dependence. To introduce our work and in particular this thesis, here we briefly describe the components and the behavior of financial markets.

1.1.1 Financial markets as complex systems

Financial markets are (physical or virtual) places at which financial assets are traded. Connecting potential buyers and sellers and facilitating allocation of resources, they are crucial to the efficient operation of a market economy.

According to their functions, financial markets can be categorized into different types. Capital markets enable the raising of capital through stock (equity) or bond (debt) issuance and organize the trading of these assets. Money markets specializes in short-term cash borrowing and lending. Derivatives markets produce instruments for controlling financial risk and coordinate the trading of these products. Insurance markets provide financial protection against contingent losses. Foreign exchange markets facilitate the conversions between currencies. A

detailed introduction to financial markets was presented in Melicher and Norton (2008).

The first stock market, the Amsterdam Stock Exchange, was invented by the Dutch East India Company (*'Verenigde Oostindische Compagnie'*) in 1602 for dealings in stocks and bonds (Melicher and Norton (2008)). Futures markets can be traced back to the Middle Ages and the first trading in options began as early as the eighteenth century (Hull (2004)). Financial markets have evolved significantly over several hundred years and there are now many financial exchanges in the world. With the vast increase in worldwide trading volumes in the last decades, financial markets are indispensable to the modern economy.

Usually, a financial market is composed of a large number of traders with different functions, motivations, and strategies. In order to achieve their respective objectives, they interact with each other in many distinct manners. The composition and mechanisms of financial markets will be briefly described below.

Types of assets and their interdependence

A financial asset is an intangible representation of, and a contractual claim to, the future cash flow arising from a physical item. We can classify financial assets in different ways, among which one is presented in Johnson et al. (2003). It categorizes financial assets into three groups corresponding to (1) whether the asset is a debt, equity, or foreign exchange, (2) whether the settlement should be made at the time the contract is agreed between the two parties of the contract, or settled at some time in the future from the time it was agreed, and (3) whether the contract has an associated obligation, or only the right but not the obligation to deliver another product. For simplicity, we divide financial assets into two groups: Those that are directly associated with some real assets, and those that whose values are dependent on or derives from the values of some other more basic financial assets known as underlying assets.

The first group of financial assets includes stocks, bonds, currencies, etc. Briefly, a stock is an equity claim, i.e., it represents the ownership of a portion of a corporation and a claim on its proportional share in the earnings and

assets of the corporation. A bond is an interest-bearing or discounted debt instrument whose issuer has the obligation to repay the bondholders the principal along with interest (coupons) at maturity. A currency is a form of money that is legally designated as such by a governing body and is in public circulation. Detailed descriptions of these assets can be found in Melicher and Norton (2008). These assets have different return-risk profiles that require distinct modeling approaches. This is a nontrivial task because the payoff of each asset is determined by a few or many factors, such as interest rate, dividend rate, default rate, etc. To further complicate matters, these factors may fluctuate over time and are correlated with one another.

The most commonly used financial instruments of the second group are futures contracts and options. A futures contract is a standardized agreement to buy or sell a specified standardized commodity at a certain future date, for a certain price. An option is a contract between a buyer and a seller that conveys the buyer the right, but not the obligation, to buy (in case of a call option) or sell (in case of a put option) a particular asset termed the underlying asset (or simply the underlying), at a certain date known as the expiration date or maturity, and at a prescribed price termed the strike price. Detailed descriptions of futures, options, and other derivatives can be found in Melicher and Norton (2008) and Hull (2003). Derivatives can be used to hedge or mitigate risk in the underlying. In addition, they are ideal instruments of speculation because they are often leveraged, i.e. a small movement in the underlying value can cause a large difference in their values. Indeed, developing new derivatives is the focal point of modern financial innovations. New types of derivative have been created which are dependent on the payoffs of different underlying variables greatly beyond the traditional scope of underlying variables such as stock prices, exchange rates, commodities prices, etc. However, due to the complexity of the payoffs of underlying assets and the complicated dependence of derivatives on their underlying assets, the estimation of the values and inherent risk of investment portfolios becomes increasingly sophisticated.

Types of traders and their interactions

Financial traders are different in trading strategy, level of risk aversion, financial knowledge and information, etc. According to Hull (2003) and Johnson et al. (2003), three broad categories of traders can be identified: Hedgers, speculators, and arbitrageurs.

A hedger is a market participant who performs a security transaction with the goal of minimizing the exposure to the risk of an unfavorable price change of an asset. For example, a hedger who owns a bond and is concerned that its price might decline can sells a futures contract on the bond. If the price of the bond does fall, the profit on the transaction of the futures contract will cover the loss on the bond. There are many financial vehicles to accomplish a hedge, including insurance policies, forward and futures contracts, options, etc. A common aspect of all these vehicles is that, although reducing potential losses, they also tend to reduce potential profits. Continuing the example, if the price of the bond rise, the hedger gives up the potential profit.

A speculator is a trader who aims to make capital gains from risky transactions in anticipation of future price movements. For instance, a speculator who expects that the price of an equity will rise (fall) will buy (sell) the equity in order to make a profit if the price indeed moves in line with the expectation. By doing so, the trader bears the risk of a loss arising from a opposite price movement. Speculators can employ many different strategies by making use of different types of financial instrument. However, it has been realized in financial markets that speculations with high potential profits are usually associated with high potential risks. In general, speculators can in turn be categorized into the following few types. Fundamentalists are those traders who are informed of the nature of the asset being traded and act according to its fundamental value. They believe that the price of the asset may temporarily deviate from, but will eventually return to, the fundamental value. Imitators do not know or do not care about fundamental values. Instead, they follow their acquaintances and adopt the trading opinions of the majority. Chartists, also called technical analysts, forecast the future direction of some financial variables, primarily price and volume, through recognition of chart patterns in market data.

An arbitrageur is a market agent who attempts to profit from price disparities by simultaneously taking offsetting positions and capturing risk-free profits. For example, an arbitrageur would buy a currency which is cheaper in a market and then immediately sell it in another market, in which the price of the very same currency is higher, to lock-in a profit. Arbitrage opportunities can occur in various types of financial asset but cannot last for long. They will quickly be exploited by arbitrageurs. Therefore, the presence of arbitrageurs ensure that financial markets are generally arbitrage-free markets.

Traders of different types may interact with each other in different direct or indirect ways. The most typical direct interactions in financial markets involve imitative speculators who may copy the behavior of some other traders or do so by indirectly following the price trend that reflects the aggregate effect of the behavior of other traders in the whole market. Indirect interactions are, however, ubiquitous in financial markets. In fact, when estimating payoffs of financial investments, many traders refer to the market prices of the assets of interest, which is in turn determined by the supply and demand for the assets generated by the traders in the overall market. This behavior-price feedback, which embodies the indirect interactions of different traders, are realized through *market makers* — intermediations who always stand ready to facilitate trading in financial assets by offering competitive prices and act to ensure market liquidity.

Interactions in financial markets are highly nonlinear and can considerably impair our ability to identify cause-effect relations of market movements and predict consequence of investment transactions and market regulations.

1.1.2 The complex dynamics of financial markets

In literature, the study of the complexity or the complex dynamics of financial markets deals with a wide range of subjects and dates back to at least the sixties of the last century. For example, Simon (1962) reported the development of the concept of bounded rationality; Zeeman (1974) showed that stock market crashes can happen when there are too many chartists relative to fundamental traders; Grandmont (1985) suggested that unpredictability undermines the possibility of

rational expectations in economics; and Brock and Hommes (1997) claimed that high rationality in an unstable market with information cost implies chaos.

In this thesis, we focus on those aspects of market dynamics that are characterized by some persistent patterns empirically observed in financial time series which can hardly be explained by the traditional economic theories. Specifically, we focus on stock and options markets, which are two of the most active types of financial market. We believe that these two types of market share many features with other types of financial market, and the understanding of their complex dynamics will be beneficial to, or even directly applicable to, the understanding of the complexity of any other types of financial market.

Stock markets

The complex dynamics of stock markets can be characterized by some 'stylized facts', which are common across many stocks, markets, and time horizons. Most of them are counterintuitive and contrary to the expectations of traditional financial theories.

On long time scales (typically a week or longer), empirical distributions of financial return (defined in Chapter 2) generally fit the Gaussian distribution. However, most financial returns over short time scales are described well by a non-Gaussian heavy-tailed or fat-tailed distribution, implying a greater frequency of extreme events than would be expected if they followed a normal distribution.

In addition, the autocorrelation function (ACF) (defined in Chapter 2) of the daily price changes quickly converges to the noise range, whereas the corresponding ACF of absolute price changes decays slowly. The long-term autocorrelation of volatility is the reflection of the phenomenon termed 'volatility clustering' — high positive or negative returns tend to group together. These stylized facts are discussed in detail in Chapter 2.

Option markets

The most widely used mathematical model for pricing options is the Black-Scholes (BS) model (Black and Scholes (1973); Merton (1973)). All parameters in the BS model other than the volatility (defined in Chapter 2) are observables, and

according to the model the theoretical value of an option is a monotonic increasing function of the volatility. A unique volatility is therefore implied by the market price of an option, the so-called implied volatility (IV).

According to the BS model, IV should be independent of strike for a fixed time to maturity. Hence, plots of IV against strike should be flat. In reality, however, it is well known that IVs exhibit a remarkable curvature, which is commonly referred to as a volatility smile. Another important fact is that the volatility smile changes over time. This phenomenon obviously conflicts with the BS framework and understanding its origin has eluded the financial world for more than two decades. The volatility smile phenomenon is described in detail in Chapter 2.

1.2 Motivation and methodology

As discussed above, financial markets are among the most complex systems in reality and many phenomena observed in the dynamics of asset prices are still poorly understood. Specifically, markets often exhibit extraordinary or unexpected changes seemingly not induced by external causes, instead arising endogenously. This seriously challenges the neoclassical economics, which depicts markets as efficient machines that automatically seek out an equilibrium state and price changes are only caused by the arrival of news.

We aim to discover the mechanisms through which the complex market dynamics is generated. Specifically, we want to understand how the behavior of financial agents and their interactions, when trading different financial assets, give rise to the complex dynamics of financial markets characterized by some unexpected phenomena, i.e. how the complex macro-dynamics emerges from the ordinary and typical micro-behavior.

During the last few decades, behavioral approaches and agent-based methods have been widely applied to the study of market dynamics. They can explain many phenomena in a more plausible way than traditional financial theories. However, most of these theories or models either do not systematically examine the mechanisms underlying the unexpected phenomena or are too complicated to be helpful for clearly identifying the causal relations of the mechanisms. In

addition, the majority of the agent-based models focus on stock markets, while very few center on derivatives markets.

In view of these facts, our general motivation is to apply a bottom-up approach for studying the mechanisms through which the complex market dynamics is generated. We study a financial market by realistically modeling its individual elements and their interactions. The macro-dynamics of the system will eventually emerge from the micro-behavior. In particular, we wish to develop microsimulation (MS) models with simple structures[1] that can reproduce the extraordinary patterns observed in the financial time series recorded in stock and options markets. Importantly, we present our models in the order of successive complexification so as to offer important insights into the origins of some puzzling phenomena observed in financial markets.

We focus on two of the most active markets and address the following research questions:

a. What are the principal mechanisms underlying stylized facts observed in stock markets? Are these mechanisms common across explanations provided by the well-established microsimulation models proposed in the literature?

b. What is the origin of the poorly understood volatility smile phenomenon observed in option markets and what are the driving factors determining the shape and the dynamic properties of the smile?

The outline of this thesis follows. In Chapter 2, we present the stylized facts observed in stock and options markets and discuss pitfalls and limitations of mainstream financial theories. These have stimulated the development of alternative theories, some of which are introduced in Chapter 3. Chapter 4 focuses on the first research question raised above, while Chapter 5 and Chapter 6 address the second question. In Chapter 7, the conclusions of this research and some directions for future research are presented.

[1] "Everything should be made as simple as possible, but no simpler"— Albert Einstein.