

Chapter 2

Microstructure Foundations

This chapter gives an overview of institutional and theoretical market microstructure foundations. Section 2.1 introduces to the institutional framework of trading on modern financial markets. We discuss different forms of trading, types of traders as well as types of orders. Moreover, we present fundamental types of market structures, most importantly quote-driven markets vs. order-driven markets, and provide insights into common order precedence and pricing rules. In the last section, market structures and trading rules on some selected international exchanges are discussed. This section is understood as an overview of the most important institutional aspects of financial market microstructures and mainly follows [Harris \(2003\)](#).

Section 2.2 provides a compact overview on the fundamental strings of theoretical market microstructure literature. We review classical approaches of asymmetric information based market microstructure theory, such as sequential trade models and strategic trade models, as well as inventory-based approaches and models for limit order markets. The purpose of this section is not to provide an in-depth derivation and discussion of the individual models. Rather we compactly illustrate the basic principles underlying the different approaches and review their major predictions for market microstructure relationships and trading dynamics. Readers interested in more details are referred, e.g., to [Hasbrouck \(2007\)](#).

2.1 The Institutional Framework of Trading

2.1.1 Types of Traders and Forms of Trading

Traders either trade on their own account, arrange trades for others or have others arranging trades for them. Accordingly we distinguish between *proprietary traders* trading on their own accounts and *brokers* arranging trades as agents for their clients. This results either in *proprietary trading* or *agency or brokerage trading*. *Dealers*

are traders who stand ready to trade with other traders (or clients) when they want to trade. Correspondingly, they serve as liquidity suppliers taking the opposite side of the market if required. They operate as market makers, specialists or floor traders. Often traders simultaneously serve as brokers and dealers and are known as *broker-dealers*.

The buy side of a market is typically driven by investors (e.g., individuals, funds, money managers, endowments), borrowers (e.g., individuals or companies), hedgers (e.g., banks) or speculators. The market's sell side consists of dealers serving, (e.g., as market makers or floor traders), brokers (e.g., retail brokers or institutional brokers), or broker-dealers representing well-known companies, like Goldman Sachs or Merrill Lynch.

Exchanges are the platform where traders arrange their trades. On most exchanges only member brokers are allowed to trade. Non-members can only trade by instructing a member to trade for them. We distinguish between *floor trading*, where traders meet on exchange floors to arrange trades and *electronic trading* where traders trade via electronic systems. *Order-driven systems* are, most generally, platforms where matches between buy and sell orders are arranged according to certain trading rules. Here, trades can be processed via computers, clerks or member brokers. For instance, classical floor-based oral auctions are also order-driven systems where trades are arranged by personally exchanging information. Conversely, in an order-driven computerized system, the order matching is performed by a computer. Often, brokerages have their own (typically order-driven) trading platforms to arrange trades for their clients. Important examples are the *electronic communication networks* (ECNs), such as Island ECN or Archipelago, which are electronic order-driven systems that are not regulated as exchanges and are owned by brokerages and dealers. These trading platforms are best-known as *alternative trading systems* and are competitors to regulated exchanges. Finally, trades can be also arranged *over the counter* without involving an exchange. An example is the corporate bond market, where most trading is arranged over the counter.

2.1.2 Types of Orders

An order represents an instruction of a trader who cannot personally negotiate his trades and therefore determines what to trade, when to trade and how much to trade. A *bid (offer)* reflects a trader's willingness to buy (sell) and contains the respective price and quantity the trader will accept. Correspondingly, bid and ask (offer) prices are the prices at which the trader is willing to trade. The highest (lowest) bid (ask) price available is called *best ask (bid) price* or *ask (bid) quote*. A *market quotation* gives the best bid and offer in a market and is called *Best Bid and Offer* (BBO). The best bid and offer across consolidated markets for National Market System (NMS) stocks is called the *National Best Bid and Offer* (NBBO). The difference between the best ask and best bid is called the *bid-ask spread*.

A *market order* is an order that trades immediately at the best price currently available in the market. The corresponding price at which an order is executed is called *transaction price*. Market order traders “pay” the bid-ask spread as long as the order is filled with the offered quantity at the best ask or bid price. If the size of the market order is larger than the quantity offered at the best ask or bid, the trader must move prices and thus has to pay an extra premium (“*price concession*”). Then, buyers (sellers) have to bid prices up (down) in order to find a counter-party who is willing to take the other side a large trade. The resulting price movements are called (instantaneous) *market impact* or *price impact* and naturally increase with the order size and are the dominant part of the trading costs (on top of the bid-ask spread). These trading costs induced by a potential market impact and the execution price uncertainty are often referred to as the price traders have to pay to obtain priority in the market, i.e., the “price of immediacy”. In some markets traders can negotiate prices and receive prices which are better than the currently available best ask and bid. In this case, the trader receives price improvement due to a counter-party who is willing to step in front of the currently best quote.

A *limit order* is a trade instruction to trade at a price which is no worse than the so-called *limit price* specified by the trader. As the corresponding limit price is not necessarily offered on the other side of the market, a limit order faces execution risk. If no one is willing to take the opposite side at the required limit price, the order is not executed and is placed in the *limit order book* where all non-executed limit orders are queued according to price and time priority. Correspondingly, the larger the distance between the limit order and the best quote, the worse is the order’s position in the queue and the lower is its execution probability in given time. Hence, in order to increase the execution probability and to reduce the time until execution, the limit order trader has to bid more aggressively with a limit price closer to the market. Limit orders at the best bid or offer are called *at the market*. Accordingly, limit orders with prices worse (better) than the current best quotes are called *behind (in) the market*. A limit order with a limit price at or above (below) the best ask (bid) price in case of a buy (sell) order is executed immediately and, if necessary, filled until the limit price level is reached. Such an order is called a *marketable limit order* corresponding to a market order where the trader limits the potential price impact (by correspondingly setting the limit price). If the limit price is worse than the current best price, the order has to “walk up (down)” the book in case of a buy (sell) order. Finally, a *market-to-limit order* is a market order, which is executed at the best ask/bid quote in the order book. Any unfilled part of a market-to-limit order automatically enters the order book.

Besides the risk of execution uncertainty, limit order traders face *adverse selection risk* corresponding to the risk that the order is executed (“picked up”) and then the markets moves against their new position causing a loss. This happens, for instance, if the market moves downwards, picks up a standing buy (bid) limit order and continues declining. Adverse selection risk can only be reduced by posting far away from the market which, however, increases the execution uncertainty.

A *stop order* is an order which automatically buys (sells) a given quantity after the price rises (falls) to the “stop price”. In case of a sell, the stop order prevents further losses in case of further falling prices and thus is called *stop loss order*. Hence, in contrast to a limit order, a stop order is activated as soon as the price passes the specified stop price. In contrast, a limit order is only executed as long as the price is *better* than the corresponding limit price. Combinations of both trade instructions result in a *stop limit order* with the stop price determining when the limit order becomes active and the limit price indicating the limit until which the order is executed.

A so-called *market-if-touched order* is a market order which becomes only valid if the price reaches a certain *touch price*. While stop orders buy (sell) after the price rises (falls) to the stop price, a corresponding market-if-touched order sells (buys) after the price falls (rises) to the touch price. While loss orders enforce price movements by trading in line with the market trend and thus generate momentum, market-if-touched orders do exactly the opposite. They buy when prices drop and sell when prices rise and thus generate contrarian trading patterns.

Limit orders are typically combined with specific attributes specifying for instance, for how long an order is valid and under which conditions it might be canceled. Examples are *fill-or-kill order* whose portions that cannot be filled immediately are canceled or *all-or-none* orders which are only executed if they can be filled at once. For other types of orders, see, e.g., [Harris \(2003\)](#).

Finally, on a growing number of markets, orders can be partly or even completely hidden. A common type of order is the so-called *iceberg order* (or *reserve order*) where a certain proportion of the order can be non-displayed and thus is non-visible for other market participants. Such orders are used to hide trading strategies and to reduce adverse selection risk. The minimum display size is fixed by trading rules and differs across exchanges. Some markets, such as the NASDAQ allow to post *hidden orders*, where the order is entirely hidden. As shown by [Hautsch and Huang \(2011\)](#) based on NASDAQ data, the possibility to post completely hidden orders in the spread, might create substantial market activity as traders “search” for hidden volume by submitting “fleeting limit orders” to test for potential execution.

2.1.3 Market Structures

The market structure determines who can trade, what can be traded, when can be traded, and how it can be traded. We generally distinguish between *continuous trading*, where traders can trade whenever the market is open and *call markets* where all traders trade simultaneously in a call auction when the market is called. Call markets are often used to open a trading session and to settle the price before the market switches to continuous trading. Likewise they are also used to end a trading session, to have a mid-day call auction interrupting continuous trading or to re-start it after a trading halt. In some markets, call markets are also used to trade less liquid assets.

The most important characteristic of a market is the form of its execution system. We distinguish between the three major types of execution systems leading to *quote-driven dealer markets*, *order-driven markets* and *brokered markets*.

2.1.3.1 Quote-Driven Dealer Markets

In a quote-driven market (dealer market), trades are only executed by dealers. The dealers quote the ask and bid prices and supply liquidity by standing ready on the opposite side of the market. They often trade among themselves. In a *pure* quote-driven market, traders (or brokers acting on behalf of traders) cannot trade themselves (even if they have matching positions) but must execute their trades by dealers which earn the bid-ask spread. In some (though not pure) dealer markets, however, traders can trade directly without interacting with a dealer. A prominent example is the NASDAQ Stock Market as described in Sect. 2.1.5.2.

Dealers are often specialized in serving specific clients which are trustworthy and creditworthy and tend to refuse trading with counter-parties outside their clientele or which might be better informed. Traders who do not have credit relationships with dealers have to trade via brokers stepping in and guaranteeing credit worthiness. *Interdealer brokers* are brokers arranging trades among dealers if dealers prefer keeping anonymity and not informing their rivals about their quotes.

Quote-driven dealer markets are popular forms of trading for bonds, currencies and stocks. Examples are the NASDAQ Stock Market or the London Stock Exchange.

2.1.3.2 Order-Driven Markets

In an order-driven market, traders trade directly with each other. As there are no dealers serving as intermediaries, trading occurs according to specific trading rules. *Order precedence rules* determine which buyers trade with which sellers and *trade pricing rules* determine the resulting transaction prices. Liquidity provision in an order-driven market is ensured by traders taking the opposite side of the market or by dealers serving as traders. In some order-driven markets, most of the liquidity is still provided by dealers. However, a main characteristic of an order-driven market is that dealers cannot choose their clients but have to trade with anyone accepting the offer.

Order-driven markets are mostly *auction markets*. An auction is a formalized process, the so-called *price discovery process* by which buyers seek the lowest available prices and sellers seek the highest available prices. In a *single-price auction* all trades at the same price following a call are simultaneously arranged. Conversely, in *continuous two-sided auctions*, traders continuously arrange their trades on both sides of the market based on prices varying over time. In markets with *oral auctions* traders trade face-to-face on a trading floor. As they negotiate their trades by crying out their bids and offers these markets are called *open outcry*.

markets. Order-driven markets which use an electronic execution system employ *rule-based order matching*.

Only order-driven markets which are not organized as auctions are *crossing networks* where trading takes place at prices which are determined on other markets. These prices are called *crossing prices*. Crossing networks are call markets where submitted orders are matched according to order precedence rules. Such market structures are sometimes used to organize after-hours trading based on closing prices from continuous trading (e.g., at the New York Stock Exchange). Alternatively, they are used to organize intraday calls where the crossing prices correspond to a price in a continuous market at a random time within a certain time interval following the call.

As in an order-driven market, in contrast to quote-driven dealer markets, trades are arranged according to precedence rules and traders cannot choose with whom they trade, traders typically trade with counter-parties with whom they do not have credit relationships. To ensure proper order settlement, these markets require elaborate clearing mechanisms.

2.1.3.3 Brokered Markets

In *brokered markets*, brokers initiate the matches between buyers and sellers. The broker's role is to find liquidity provided by a counter-party. We distinguish between *concealed traders* and *latent traders*. Concealed traders are traders who intend to trade but do not make public offers to hide their strategies. However, they trade if brokers offer them suitable matches. A latent trader has no concrete trade intention but only trades if she is confronted with an attractive trading opportunity. Successful brokers in a brokered market have to find both concealed traders and latent traders.

2.1.4 Order Precedence and Pricing Rules

The order precedence rules in an oral auction are *price priority* and *time precedence*. According to the price priority rule, traders who offer the most competitive prices have priority. Traders are not allowed to accept bids and offers at inferior prices. The time precedence rule gives priority to traders whose quotes *first* improve the prevailing best ask and bid prices. Time precedence is retained as long as the quotes are maintained or accepted by the counter-party. In oral auctions, according to traders "a quote is good only as long as the breath is warm" requiring to repeating offers to maintain precedence. However, time precedence is only helpful as long as the minimum price increment, the so-called *minimum tick size*, is not too small. Otherwise, time precedence gives only little privilege as competitors can easily improve the best quotes. In oral auctions, price priority is self-fulfilling as traders try to trade to best possible prices which encourages seeking for the best offer. This,

however, is not guaranteed for time precedence as for traders it makes no difference with whom to trade as long as quotes are equal.

Most exchanges and electronic trading platforms use *rule-based order-matching systems*. Here, trading is typically anonymous, decentralized and traders trade by electronically submitting, canceling or amending (already existing) orders. Order matching is arranged by a typically automatized system using a sequence of procedures. All systems use price priority as primary order precedence rule. As second order precedence rule, mostly time precedence is used. Some markets use *display precedence* giving priority to displayed orders over undisclosed orders or *size precedence* where orders with either large or small sizes are privileged. *Pro rata matching* yields an allocation where each order is filled in proportion to its size.

In *single-price auctions*, the market ranks the orders and starts by matching the highest-ranking buy and sell orders to each other. This match results in a trade as long as the buyer pays at least as much as the seller demands. If the two orders have the same size, both will execute completely. Otherwise, the unfilled part of an order will be matched with the next highest-ranking orders. This process continues until all possible trades are matched. The price of the last possible match is the *market-clearing price*. In a single price auction, all trades take place at the market clearing price.

The market-clearing price of a single price auction corresponds to the price where the supply schedule equals the demand schedule. The supply schedule lists the total offered volume according to price priority and thus is a non-decreasing curve. Likewise, the demand schedule lists the total sell volume and is a non-increasing curve. Correspondingly, at prices below the clearing price there is excess demand in the market while there is excess supply for prices above the clearing price. By choosing the market-clearing price to match all orders, a maximum amount of possible volume is traded. Moreover, it is easily shown that traders' overall benefits from participating in this auction are maximized.

If the buy order in the last feasible trade bids at a higher price than the sell order, the resulting market-clearing price can be either of these two prices or can be between them. In this case, the market-clearing price does not provide an exact match and some excess demand or supply might be left. In case of excess supply (demand), all buyers (sellers) at the market-clearing price fill their orders, while the secondary precedence rules determines which sell (buy) orders to be filled.

The pricing rule in an oral auction and in a continuous rule-based order matching system is called *discriminatory pricing rule*. According to this rule, every trade takes place at the price proposed by the trader whose ask or bid is accepted. Consequently, the entire offer or bid side of the market is matched in a discriminatory fashion with progressively inferior prices. This is similar to the way how a large order is simultaneously matched with all trades pending on the opposite side yielding best prices for the first piece and progressively inferior prices for the other pieces as the order walks up or down the ask or bid schedule and exhausts liquidity.

In continuous auction markets, this process is maintained by an order book which is automatically updated whenever a new order arrives. New orders enter the

book according to order precedence rules. If they are marketable, they are matched against the standing orders. Then, under discriminatory pricing, the limit price of any standing order determines the price for each match. Accordingly, large orders trade their individually matched parts at different prices as they walk up or down the book. In contrast, under uniform pricing, the individual orders trade at the same price corresponding to the worst price under discriminatory pricing. Hence, large impatient traders prefer discriminatory pricing while liquidity suppliers prefer uniform pricing.

Finally, refined and modified rules are applied to special type of orders. For instance, in order-driven markets allowing for hidden orders, special rules regulate order precedence for displayed and non-displayed parts of an order. A common rule is that, for a given limit price, visible order volume has priority over non-visible volume (even if the non-displayed volume has been posted before). For more specific details, see the trading rules, e.g., on NASDAQ.

2.1.5 Trading Forms at Selected International Exchanges

In this section, we illustrate the current trading forms at some selected international exchanges. We concentrate on those exchanges where most of the data used in the remainder of the book come from. These are the two most important exchanges in the U.S., the New York Stock Exchange (NYSE) and NASDAQ as well as the electronic trading systems of the Frankfurt stock exchange (XETRA) and the Australian Stock Exchange (ASX) as representatives of typical electronic limit order book markets commonly used for equities.

2.1.5.1 The New York Stock Exchange (NYSE)

Trading at the NYSE is based on a hybrid system, i.e., the trading mechanism combines elements from quote-driven, order-driven and brokered markets. Essentially, it is an order-driven market, however, there are still specialists who have to provide liquidity. In fact, NYSE trading combines an open outcry system, a dealer market and an electronic limit order book.

The NYSE started in 1792 as an order-driven open outcry floor market and was historically the dominant trading platform for U.S. equities. Later, components of a dealer market have been integrated in the open outcry system. As a result, for each stock, one market maker (specialist) has to manage the trading and quote process and has to guarantee the provision of liquidity, when necessary, by taking the other side of the market. The specialist also has to maintain the underlying limit order book. Besides from orders posted by the specialist, the limit order book also receives orders directly from the exchange's routing system. These are orders which do not require to be handled by a broker and are sent directly to the specialists's workstation. The specialist sets bid and ask quotes representing his own interest,

those of a floor broker or the best ask and bid implied by the limit order book. In his function to serve as an agent for the book, she is considered as a single floor trader. According to present rules, the specialist must display limit orders (from the book) that are better than the prevailing ones within 30 s. Hence, during short time spans, orders from the book might not have price priority over prices offered by floor brokers. Moreover, the book might not have time priority over floor traders. The dealer market starts with a single-price call auction as opening procedure.

Regular trading at the NYSE starts at 9:30 and ends at 16:00. The closing procedure has some similarities to an auction and requires the specialist to balance supply and demand and to establish a (preferably smooth) transition path to the closing prices. Accordingly, trading “at the close” is governed by relatively complex rules.

While in the (open outcry) dealer market trades are only executed by the specialists, NYSE offers also automatic (electronic) execution. The NYSE Direct+ system, which was introduced in 2000, is an electronic trading system which runs parallel to the dealer market. Induced by the rising competition with ECNs, the NYSE established several mergers. One important merger was the merger between the NYSE and the ECN “Archipelago” yielding “NYSE Arca”.

2.1.5.2 NASDAQ

The name NASDAQ is an acronym for “National Association of Securities Dealers Automated Quotations” and was founded in 1971 by the National Association of Securities Dealers (NASD). Historically, it was primarily organized as a dealer market linking geographically non-centralized dealers via an electronic system. In the early 1990s NASDAQ gave little protection to customer limit orders. For instance, competitive customer quotes were not necessarily immediately displayed but were used by the dealers to trade on their own account. Such a proceeding was prohibited by the so-called “Manning Rules” adopted in 1994/1995. In 1994, the SEC started investigations on coordinated quote setting behavior of NASDAQ dealers resulting in unnecessarily discrete price grids and large spreads. These investigations resulted in civil lawsuits against NASDAQ dealers and more explicit order execution rules set by the SEC (which were not only limited to NASDAQ). The two most important components of these rules are the “display rule” requiring the display of customer orders with prices better than the currently prevailing quotes and the “quote rule” requiring a market maker to make publicly available any (potentially superior) prices that she quotes in inter-dealer markets. As a result of these reforms, NASDAQ spreads declined significantly.

Subsequently, NASDAQ established an electronic system (“SuperMontage”) which organizes trade execution, reporting, confirmation, and interdealer communication. The underlying principles resemble mostly those of an electronic limit order book, which, however, is maintained only by the dealers and not by the customers. NASDAQ’s position further increased by numerous alliances and take-overs. For instance, NASDAQ purchased the American Stock Exchange (AMEX) in 2003, the

ECN's INET (formerly Island/Instinet) and Brut in 2004/2005 and the Philadelphia Stock Exchange in 2007. As a result, NASDQA is currently the biggest electronic stock market in the U.S.

2.1.5.3 XETRA

The German Exchange Electronic Trading (XETRA) is the electronic trading system of the Deutsche Börse AG for cash market trading in equities and a variety of other instruments including Exchange Traded Funds, mutual funds, bonds, warrants, certificates, among others. It has been introduced in November 1997 as an electronic supplement of the classical floor trading at the Frankfurter Wertpapierbrse. XETRA is a double continuous auction system with an opening and closing call auction at the beginning and at the end of the trading day, respectively, and a mid-day call auction. During the normal trading period, trading is based on an automatic order matching procedure. Limit orders enter the queues of the order book according to strict price-time priority. Auctions consider all order sizes for price determination, whereas continuous trading is based upon round lots only. XETRA trading is completely anonymous and does not reveal the identity of the traders. A trader can act as agent trader or as proprietary trader. Some traders might act as market makers on behalf of XETRA and are obliged to guarantee liquidity on both sides of the market as well as to adjust supply and demand imbalances. Normal trading currently takes place from 09:00 to 17:00.

2.1.5.4 Australian Stock Exchange

The Australian Stock Exchange (ASX) is a continuous double auction electronic market and as such is an example for an electronic limit order book trading system similar to those operating, for instance, in Paris, Hong Kong and Sao Paulo. The continuous auction trading period is preceded and followed by an opening call auction. Normal trading takes place continuously between 10:09 and 16:00 Sydney time on Monday to Friday. Limit orders are placed in the buy and sell queues according to a strict time-price priority order. Any buy (sell) order entered that has a price that is greater (less) than existing queued sell (buy) orders, will be executed immediately. The order will be automatically matched to the extent of the volume that is available at the specified limit price. All orders and trades are always visible to the public. Order prices are always visible, however orders may be entered with an undisclosed (hidden) volume if the total value of the order exceeds AUD 200,000. The identity of the broker who entered an order is not public information, but is available to all other brokers. A comprehensive description of the trading rules of the Stock Exchange Automated Trading System (SEATS) on the ASX can be found in the SEATS Reference Manual available at www.asxonline.com.

2.2 A Review of Market Microstructure Theory

In this section, we give a compact overview of the fundamental approaches and directions in theoretical market microstructure literature. More in-depth treatments of this material are given, for example, by O'Hara (1995), the surveys by Madhavan (2000) and Biais et al. (2005) or the monograph by Hasbrouck (2007).

As stated by Madhavan (2000), market microstructure theory is concerned with “the process by which investors’ latent demands are ultimately translated into prices and volumes.” Consequently, central topics in market microstructure theory deal with price formation, price discovery, inventory, liquidity, transaction costs as well as information diffusion and dissemination in markets. Traditional microstructure theory provides two major directions to explain price setting behavior: asymmetric information based models and inventory models. The former branch models market dynamics and adjustment processes of prices using insights from the theory of asymmetric information and adverse selection. As discussed in Sect. 2.2.1, two main approaches are *sequential trade models* and *strategic trade models*. The branch of inventory models, as discussed in Sect. 2.2.2, investigates the uncertainty in order flow and the inventory risk and optimization problem of liquidity suppliers under possible risk aversion. We summarize the major theoretical implications of the individual approaches in Sect. 2.2.3. Finally, more recent work addresses trading behavior and equilibria on limit order book markets. We briefly review this literature in Sect. 2.2.4.

2.2.1 Asymmetric Information Based Models

2.2.1.1 Sequential Trade Models

In *sequential trade models*, randomly selected traders sequentially arrive at the market. The framework is based on the assumption of the existence of differently informed traders. Accordingly, there are so-called “informed traders”, who trade due to private information on the fundamental value of the asset and “liquidity traders”, who trade due to exogenous reasons, like portfolio adjustments or liquidity aspects. The assumption of heterogeneous groups of traders provides the basis for a plethora of asymmetric information based models. Seminal papers in this direction are Copeland and Galai (1983) and Glosten and Milgrom (1985).

In the Glosten and Milgrom (1985) model, securities have a payoff which is either high or low with given probability and is revealed after market closure. The population of traders consist of informed traders knowing the true asset payoff and uninformed traders who buy or sell randomly with equal probability. Informed traders buy (sell) if the true asset value is high (low). The proportion of informed traders in the market is given. Dealers are uninformed and infer on the asset’s true value based on the trade history. In particular, observing a buy (sell) request of a

trader, the dealer computes the conditionally expected value of the asset given a trade is a buy or sell. Then, she sets the ask (bid) quote such that the expected gain from an uninformed buyer (seller) are balanced by the loss to an informed buyer (seller). After the next trade, the dealer updates her beliefs on the asset's true value using her initial beliefs as priors. This results into updating recursions on the probabilities for the asset's true values. The resulting bid-ask spread is a function of the asset's potential values (high vs. low), their corresponding probabilities, and the relative proportion of informed traders. Fundamental implications of this sequential trade model is that trade prices follow a martingale, order flow is correlated (buys tend to follow buys, sells tend to follow sells), bid-ask spreads decline over time as the dealer's uncertainty is reduced and individual trades have price impact.

The [Glosten and Milgrom \(1985\)](#) model has been extended and modified in various directions. [Easley and O'Hara \(1992\)](#) allow for event uncertainty by assuming the random occurrence of a trade event at the beginning of each day. In case of no information event, informed traders refrain from trading and only uninformed traders (randomly) trade in the market. [Easley and O'Hara \(1992\)](#) assume that uninformed traders do not necessarily always buy or sell but can also refrain from trading. Consequently, also the occurrence of no trade (i.e., a slow-down of the trading process) carries information. Therefore, besides bid-ask spreads also the time between trades is informative. Variations of this framework are [Easley and O'Hara \(1987\)](#) where different order sizes are possible and [Easley and O'Hara \(1991\)](#) allowing for different types of orders.

[Easley et al. \(1997\)](#) and [Easley et al. \(2002\)](#) extend the framework of [Easley and O'Hara \(1992\)](#) to allow for Poisson arrival of the events determining the asset's true value. Then, traders do not sequentially arrive in discrete time but arrive randomly in continuous time. This arrival process is governed by further Poisson processes with different intensities for informed and uninformed traders. As a result, the numbers of daily buys and sells are jointly distributed based on a mixture of Poisson distributions. Then, based on the information arrival intensity as well as the arrival intensities for informed and uninformed traders, the probability of informed trading (PIN), i.e., the probability that a randomly chosen trader is informed, can be computed. [Easley et al. \(2008\)](#) extend this approach to a dynamic framework and estimate time-varying PINs.

2.2.1.2 Strategic Trade Models

In a sequential trade model, a trader participates in a market only once. Therefore, she does not take into account the impact of her trade decision on the subsequent behavior of others. As a consequence, informed traders trade largest possible quantities as they do not have to account for possible adverse price effects in future trades. This situation is completely different in a *strategic trade model*, where a trader repeatedly participates in the market and therefore has to behave strategically. A seminal paper in this area is [Kyle \(1985\)](#). In the Kyle model, the security's value is stochastic but is known by an informed trader. Uninformed traders ("noise traders")

trade independently of the asset's true value and submit a stochastic order flow. The market maker receives the demand of both the uninformed and informed traders and has to set a price such that all trades are cleared. However, as the informed trader might trade aggressively, the market maker has to protect herself against being on the wrong side of the market by setting the price as a linearly increasing function of the net order flow (i.e., the total net volume requested by informed and uninformed traders). This, however is anticipated by the informed trader who computes her profits given her conjecture on the market maker's price setting rule and her demand. Note that in contrast to a sequential trade model, the informed trader's profit is not necessarily positive as a high demand from liquidity traders might drive up the price set by the market maker. The informed trader's optimization problem is to choose her demand such that her expected profit is maximized. This yields a linear demand function in the asset's true value.

When the market maker conjectures the informed trader's underlying optimization problem, she can compute the trader's linear demand function in dependence of the parameters of her own price setting rule. This yields an inverse relationship between the slopes of the trader's demand and the market maker's price setting rule. The slope of the market maker's price setting rule determines the price impact of net order flow and is commonly referred to as "Kyle's lambda".

Kyle (1985) makes this quantity operational by exploiting properties of bivariate normal random variables. In such a framework, it can be computed as a function of the covariance between the total asset demand and the true value of the asset as well as the variance of noise trading. An implication of the Kyle model is that the informed trader's expected profit is increasing in the divergence between the asset's true value and the market maker's unconditional price (irrespective of the order flow) and in the variance of noise trading. The latter effect is interesting as it implies that the informed trader's profit is higher when there is more liquidity in the market.

Kyle's model has been extended in various directions. For instance, Admati and Pfleiderer (1988) and Foster and Viswanathan (1990) allow for uninformed traders who behave strategically themselves. Foster and Viswanathan (1996), among others, allow for multi-period models.

2.2.2 Inventory Models

Inventory models consider the inventory problem of a dealer who is facing buyers and sellers arriving asynchronously. This string of the literature originates from Garman (1976) who models the arrival processes of buyers and sellers as Poisson processes. The arrival intensities depend on the price they pay or receive, respectively. Hence, as long as the intensities are equal, the dealer is on average buying and selling at the same rate. The dealer makes profits by setting a spread. Then, the larger is the bid-ask spread, the higher are the profits per trade but the lower is the trade arrival rate. Garman (1976) characterizes the inventory problem of the market

maker who has to ensure that her holdings of the security and cash do not drop below a given level. If ask and bid quotes are set such that the resulting arrival intensities of buyers and sellers are equal, holding of stock follow a zero-drift random walk while cash holding follow a positive-drift random walk (as long as the spread is strictly positive). This causes the market maker to go bankrupt with probability one as a zero-drift random walk hits any finite level with probability one. Hence, as long as the market maker keeps ask and bid quotes constant, she must expect to be ruined within short time. [Amihud and Mendelson \(1980\)](#) present a similar framework where the market maker's inventory is constrained to lie between upper and lower bounds. They show that the market maker updates her quotes whenever the inventory approaches these boundaries to drive up or down, respectively, the arrival rates of buyers and sellers. As a result, bid and ask quotes are monotonically decreasing in the inventory levels and quotes are not necessarily set symmetrically around the asset's true value.

Dealer's price setting can be also analyzed in a framework where the dealer is risk averse and sets ask and bid quotes to appropriately balance her portfolio. This is, e.g., studied by [Stoll \(1978\)](#), [Ho and Stoll \(1981\)](#), [Stoll \(1989\)](#) and [Huang and Stoll \(1997\)](#), among others.

2.2.3 Major Implications for Trading Variables

The main theoretical findings on the properties and determinants of key microstructure variables and relationships thereof are summarized as follows:

1. *Transaction volumes:* In the [Easley and O'Hara \(1987\)](#) model, traders are allowed to trade either small or large quantities, but are not allowed to refrain from trading. Thus, large quantities indicate the existence of information. [Blume et al. \(1994\)](#) investigate the informational role of volume when traders receive information signals of different quality in each period. The authors analyze how the statistical properties of volume relate to the behavior of market prices and show that traders can infer from the volume about the quality and quantity of information in the market. An important result is that the volume provides additional information that cannot be deduced from price statistics. As a consequence, volume and volatility are correlated.

2. *Bid-ask spreads:* In the [Glosten and Milgrom \(1985\)](#) model, the market maker determines the spread in a way that it compensates for the risk due to adverse selection. The higher the probability that she transacts at a loss due to trading with market participants with superior information, the higher the bid-ask spread. Moreover, bid-ask spreads are positively correlated with market maker's inventory risks and risk aversion. In the [Easley and O'Hara \(1992\)](#) approach, the market maker uses no-trade-intervals to infer the existence of new information. Consequently, lagged durations and the size of spreads are negatively correlated.

3. *Trade durations:* [Diamond and Verrecchia \(1987\)](#) propose a rational expectation model with short selling constraints. They assert that the absence of a trade

is associated with the occurrence of “bad” news. Then, the absence of a trade is informative and is correlated with price volatility. In this framework, time matters only because of the imposed short selling restrictions. In [Easley and O’Hara \(1992\)](#), however, informed traders enter the market whenever there are information signals while non-informed traders might also refrain from trading. As a consequence, short trade-to-trade durations indicate the existence of information. [Admati and Pfleiderer \(1988\)](#) provide an explanation for temporal clustering of durations. In their setting, liquidity traders prefer to minimize their transaction costs and to trade if other traders are in the market. In equilibrium, it is optimal for informed traders to behave similarly. As a consequence, trading is clustered, and trade durations are positively autocorrelated.

2.2.4 Models for Limit Order Book Markets

A seminal paper to model limit order markets is [Glosten \(1994\)](#). In this model, all market participants have access to an electronic screen. Posting limit orders is done costlessly and the execution of a trade against the book occurs in a “discriminatory” fashion. That is, each limit order transacts at its limit price. Investors are rational and risk averse and maximize a quasi-concave utility function of their cash and share position as well as personal preferences. The trading behavior of market order traders depends on their marginal valuation functions and the prevailing terms of trade, i.e., the list of bid and ask quotes available, which influence the changes in investors’ cash and share positions. It is assumed that an investor chooses the trade quantity such that her marginal valuation equals the marginal price corresponding to the price paid for the last share in a transaction. There is informed trading if an investor’s marginal valuation is associated with the future payoff. Then, incoming market orders reveal information about the unknown “full information value” of the traded security. Due to the anonymity of the electronic market, the underlying marginal valuation implied by an arriving market order can be assessed by the liquidity suppliers only through the observed limit price and the traded quantity given the terms of trades offered by the book.

Glosten assumes that there is a large number of uninformed, risk-neutral and profit-maximizing limit order submitters who set limit prices and quantities on the basis of their “upper tail expectation”. The latter corresponds to the conditional expectation of the asset’s full information liquidation value given that the next arrival’s marginal valuation is greater than or equal to the traded quantity. In the presence of private information, liquidity suppliers protect themselves against adverse selection by setting the limit price at least equal to the upper tail expectation given a market order trading at the corresponding price. It is shown that such a strategy leads to a Nash equilibrium which is characterized by a zero-profit condition for prices at which positive quantities are offered.

Glosten’s model is extended in several directions by [Chakravarty and Holden \(1995\)](#), [Handa and Schwartz \(1996\)](#), [Seppi \(1997\)](#), [Kavajecz \(1999\)](#), [Viswanathan](#)

and Wang (2002) and Parlour and Seppi (2003). However, while static equilibrium models provide insights into the structure of the limit order book, they do not allow to analyze (dynamic) interactions between the order flow and the state of the limit order book. For this reason, Parlour (1998) proposes a dynamic game theoretical equilibrium model where traders have different valuations for the asset and choose between submitting a market order, a limit order or refraining from trading. Since the expected future order flow is affected by their own order submission strategies, the execution probabilities of limit orders are endogenous. This leads to systematic patterns in traders' order submission strategies even when there is no asymmetric information in the market. The basic underlying mechanism is a "crowding out" effect whereby market orders and limit orders on the individual market sides crowd out one another when the ask or bid queue is changed. In particular, the probability of the arrival of a buy (sell) trade after observing a buy (sell) trade is higher than after observing a sell (buy) trade. This results from a buy transaction reducing the depth on the ask side which in turn increases the execution probability for limit sell orders. Hence, for a potential seller, the attractiveness of limit orders relative to market orders rises inducing a crowding out of market sell orders in favor of limit sell orders. Handa et al. 2003 extend this approach by introducing an adverse selection component due to the presence of privately informed traders.

An alternative dynamic game theoretical equilibrium model has been proposed by Foucault (1999) in order to study the cross-sectional behavior of the mix between market orders and limit orders and the implied trading costs. He analyzes the influence of the risks of being picked off and of non-execution on traders' order submission strategy and derives testable implications regarding the relationship between the proportion of limit orders and market orders in the order flow, the fill rate (i.e., the percentage of executed limit orders), the trading costs and the volatility of the asset price. Handa et al. (2003) extend the approach by Foucault (1999) by introducing private information in his model. While in Foucault's model trading occurs because of differences in traders' valuation for the security, Handa et al. introduce an adverse selection component due to the presence of privately informed traders. As a result, the size of the spread is a function of the differences in valuation among investors and of adverse selection. Further extensions of these frameworks are, among others, Foucault et al. (2005) and Goettler et al. (2005, 2009). Recent literature focuses on the theoretical analysis on automated trading and smart order routing in electronic trading platforms. See, e.g., Foucault and Menkveld (2008), Hendershott et al. (2011) or Biais et al. (2010), among others.

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