Information Technology and Time-Based Competition in Financial Markets

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This paper studies time-based competition in imperfect securities markets, linking IT investment decisions, information processing delays, and trading strategies. At the IT investment stage, traders trade off the cost of IT against their anticipated trading profits. At the trading stage, each trader devises a trading strategy based on his new information while taking into account the impact of both his own trades and those of other traders in the market. Our results illustrate how traders react to market imperfections due to trading costs and information processing delays, and how superior traders convert a timeliness advantage into higher trading profits. They also shed light on the relationship between the price adjustment process and traders' information processing delays. Timeliness imposes an interesting structure on trader competition: traders with longer information processing delays trade less frequently, submit smaller orders and enjoy lower profits per trade. Our analysis of traders' IT investment decisions demonstrates how factors such as IT costs, number of traders, and the frequency and nature of new information affect the level of IT investments. We further illustrate how improved IT infrastructure translates into competitive advantage.

(*Time-Based Competition; Trading; Financial Markets; Information Technology Investment; Information Technology Infrastructure*)

1. Introduction

Securities trading is one of the most information-intensive sectors of the U.S. economy, with the average firm spending some 20 percent of its total outlays on information systems (*Economist* 1991). Trading desks, in particular, channel as much as half of their revenues into information technology (IT). The importance of IT infrastructure is underscored by the proliferation of increasingly complex financial instruments and the globalization of financial markets. As one portfolio manager put it, "everything depends on information technology today, and the speed and accessibility of [that] information is paramount" (*Wall Street Computer Review* 1991).

A key impact of IT is to reduce the time required for information processing in all stages of the trading process.[1] A case in point is the shift in the early 1990s from video data feeds with page-based screens, where navigation across pages was time consuming, to digital feeds and software that places real-time data directly into the trader's spreadsheet (cf. *Wall Street Computer Review* 1990, Rohan 1993). Other technologies such as automated order routing systems that deliver orders electronically to preferenced or multiple dealers, touch and voice-activated screens, handwriting recognition tablets, ticketless order placement, and the like have fueled recent spending on modern trading rooms (*Wall Street Computer Review* 1991, *WST* 1995).

[1] For analyses of the relation between technology and timeliness in different contexts, see Dewan and Mendelson (1990), Dewan and Dewan (1995).

0025-1909/98/4405/0595$05.00

There is considerable research interest in the impact of IT on financial markets. In a pioneering study, Garbade and Silber (1978) examined how advances in communications technology (the domestic telegraph in the 1840s, the trans-Atlantic cable in 1866 and the consolidated ticker tape in 1975) improved market integration and performance. Since then, the rapid automation of financial markets was accompanied by a number of research articles that examined issues relating to the automation of market making and of stock exchanges (cf. Mendelson et al. 1979; Amihud and Mendelson 1985, 1988; Clemons and Weber 1990; Lucas and Schwartz 1989; Siegel 1990).

This paper focuses on the role of IT in securities trading and, in particular, it studies optimal trading strategies and IT investment decisions for traders competing to profit from new information. The arrival of new information about a security is followed by an increase in price volatility and trading volume due to the trading activity induced by the news. Informed traders try to sell (purchase, respectively) shares of the security if the information suggests that the current price is higher (lower, respectively) than the true value of the security. Such trading tends to close the gap between price and value (also called "price disparity"), bringing the market to a new equilibrium.

The gap between price and value closes neither completely nor instantaneously because of market imperfections, such as trading costs and information processing delays. Trading costs include commissions, taxes, spreads and, especially for large trades, the costs of market impact (i.e., the concession that a large sell order must offer, or the premium that a large buy order must pay, for immediate execution). Information processing delays include the time required to acquire, process and act on new information about the security. An information-motivated trader seeking immediacy can reduce his information processing delays through appropriate investments in information technologies that support data acquisition, portfolio analytics, order routing, and trade execution.

We model explicitly the process by which traders, characterized by their information processing delays, close the gap between value and price due to new information. Each trader maximizes his trading profits, taking into account transaction costs and the anticipated actions of the other traders. In equilibrium, each trader has a threshold of price disparity, and he submits trades only when the price disparity exceeds his threshold. Slower traders have higher thresholds, trade less frequently, submit smaller orders and obtain lower profits per trade. Each successive trader narrows the price disparity until it is no longer profitable to trade. The properties of the resulting price adjustment process are consistent with extant empirical evidence. Whereas earlier studies related the nature of the value discovery process to the structure of the market (cf. Amihud and Mendelson 1987, 1988, 1991b, 1992), in this paper we show how individual trading strategies—conditional on the technology available to traders—give rise to the process of price adjustment.

Our analysis of optimal trading strategies takes the trading technologies (and the associated information processing delays) as given. We then study optimal IT investments in the "IT investment game," where each trader chooses his IT investment to maximize his expected net-value. In equilibrium, both the average IT investment and the expected net-value per trader are increasing in the "market depth" as well as the frequency and "informativeness" of informational events, but both are decreasing in the number of traders and the level of transaction costs. Our results suggest that the underlying trends tend to make securities trading more technology-intensive over time, but they do not necessarily lead to higher industry trading profits. The real benefit from technological improvements lie in increased market efficiency.

Our analysis sheds light on the strategic role of IT infrastructure that enables the development of future IT applications. In the case at hand, the value of the IT infrastructure derives in part from the lower cost of developing and implementing IT applications that can improve trading timeliness. A firm with a superior IT infrastructure gains a timeliness edge over the competition because it can make its trading activities more technology-intensive at lower cost. This edge enhances the firm's profit opportunities, which gives it competitive advantage that is likely to endure because the IT infrastructure is a strategic resource, not easily duplicated by the rest of the market.

The rest of the paper is organized as follows. Section 2 presents our model of securities trading and analyzes optimal trading strategies and the resulting trading profits, taking IT investments and timeliness as given. In §3, we study the problem of IT choice as it affects timeliness and the strategic role of the IT infrastructure, and §4 offers our concluding remarks.

2. Trading Strategies

We consider competition among N traders indexed by $i = 1, 2, \ldots, N$, who seek to profit from new information about a security. As soon as a trader realizes that there is a difference between the new value of the security and its market price, she may attempt to take advantage of this difference by buying if the difference is positive and selling if it is negative. These transactions reduce the gap between price and value, affecting the opportunities available to other traders. The gap does not vanish instantaneously due to market imperfections—trading costs and information processing delays—which we describe in the following two subsections.

2.1. Trading Costs

Trading costs vary across securities and markets. In general, there are two types of trading cost: (1) *direct transaction costs* of buying or selling shares, consisting of commissions, spreads, taxes, etc; and (2) *market impact costs*, reflecting the discount that a seller, or the premium that a buyer, has to offer for immediate execution. We discuss each in turn below.[2]

The direct transaction costs for a trade can be represented as $A + b \cdot |q|$. Here, A is the fixed cost that largely reflects the fixed component of the brokerage commission. In most markets it varies between zero and about \$200 per trade. For example, retail customers typically pay a fixed minimum commission varying between \$10 and \$100 per trade for equity transactions and \$10 to \$50 per trade for bond market transactions. Thus, A is small but not totally negligible.[3]

The proportional component $b \cdot |q|$ is mostly due to the variable part of the brokerage commission and the bid-ask spread. For U.S. equities, institutional investors' commissions amount on average to about 3–6 cents per share for listed stocks (i.e., about 0.1 percent of the value of a \$50 stock). In the U.S. Treasury Securities market, commissions on notes and bonds are of the order of \$1/256 on \$100 face value (or about 0.004 percent). In addition, timely execution of transactions requires traders to incur the bid-ask spread, which is the difference between the posted quotes at which market-makers are willing to buy or sell a limited quantity of securities.[4] The spread on highly liquid stocks is typically \$1/8, which constitutes 0.25 percent of the price of a \$50 stock. The average spread on New York Stock Exchange (NYSE) stocks was \$0.20 per share in 1994. Adding up the variable brokerage commission and half of the bid-ask spread, b (for institutional investors) is on average about \$0.15 per share for NYSE-traded stocks (for retail customers, b is of the order of \$0.20 per share).[5] For U.S. Treasury bills, b is about 0.008 percent of par value.[6] In contrast, bid-ask spreads on illiquid stocks and bonds can reach 5 percent of their value.

Market impact costs are due to adverse price movements against the trader who executes the trade. We follow the common assumption that the price change is linear in quantity (cf. Kyle 1985): a sale ($q > 0$) decreases the market price by mq, whereas a purchase ($q < 0$) correspondingly increases the market price. The total market impact cost is thus mq^2. As Kyle (1985) has shown, the market-impact parameter m is a decreasing function of the amount of noise trading, which increases the market's capacity to absorb larger quantities with less price impact. In our model, which takes the market structure as given, the effect of noise trading is summarized by the exogenous market-impact parameter m.

In the U.S. equity markets, sufficiently small orders can be executed at the current market quotes. Following Kyle (1985) and related models, we do not incorporate this intricacy in our model, which focuses on large, informationally motivated trades. Given the quadratic structure of the cost function, mq^2 is a negligible part of

[2] See Amihud and Mendelson (1991a) for a more detailed discussion of trading costs in securities markets.

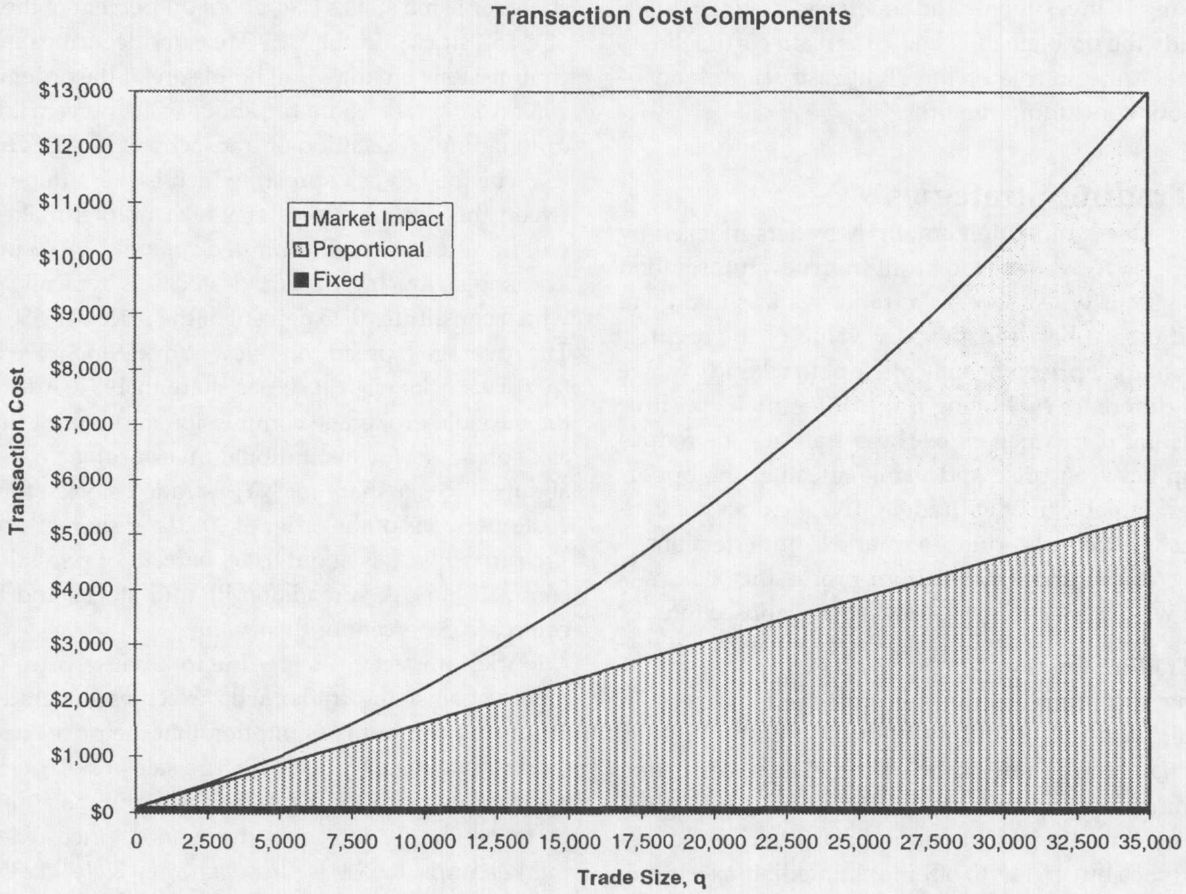
[3] As shown below, even small values of A have a noticeable impact on trading and price behavior. However, their effect on IT investments is small.

[4] On the determination of the spread, see Amihud and Mendelson (1980).

[5] The full spread is incurred on a round-trip transaction. Its contribution to b for a single transaction is thus half the total spread.

[6] Transaction costs in the Treasury Securities market were studied by Amihud and Mendelson (1991c).

Figure 1 Components of Trading Cost for an NYSE-Traded Stock



total trading costs for small q, as shown in the following example for a representative NYSE-listed stock.

EXAMPLE 1. Figure 1 shows the various components of trading cost for an NYSE traded stock with fixed cost A = \$100 per trade and proportional transaction cost b = \$0.15 per share. As for the market impact cost, we consider a stock where a 20,000-share block has a market impact of 1 tick (\$1/8), i.e., $m = 6.25 \times 10^{-6}$. As seen in Figure 1, the fixed transaction cost is small for large trades, whereas the market impact component is small for small trades. For example, for a trade size of 1,000 shares, the market impact cost is less than 1/40 of total trading cost. As trade size increases, both the proportional transaction cost and the market impact cost are significant, with the market impact cost becoming dominant for very large trades (in this example, for $q > 24{,}000$ shares, which is about the mean size of a block traded on the NYSE in 1994).[7]

2.2. Information Processing Delay

Another important source of market imperfection is information processing delay, which varies depending on the market and informational event. Information processing delays consist of (1) *observation delays*, representing the time required to acquire new data; and (2) *execution delays*, reflecting the time needed to process the data into useful information, determine the magnitude of the disparity between price and value, and implement a trade in the marketplace.

[7] Very large blocks are often syndicated to avoid excessive market impact (Burdett and O'Hara 1987). This, however, results in the loss of a timeliness advantage.

The magnitude of information processing delays can be estimated by studying how long it takes prices to adjust to new information. For example, Patell and Wolfson (1984) found that trading profits largely disappeared within 5–10 minutes following dividend and earnings releases in the stock market.[8] Ederington and Lee (1993) studied the effects of 19 U.S. macroeconomic announcements on the Treasury Bond and currency futures markets and found that futures prices adjust to these announcements in about one minute.[9] In these cases, the observation delay is minimal since the announcements are disseminated electronically. News that are not observed electronically give rise to slower price adjustment. Thus, for the Value Line Investment Survey's rank changes and for analysts' recommendations published in *Business Week*'s "Inside Wall Street" column, both of which were disseminated by mail to subscribers, price adjustment took from one to three days (Stickel 1985, Palmon et al. 1994). In the area of index arbitrage, Kawaller et al. (1987) find that the S&P 500 index futures lead the index itself, resulting in price disparities that get dissipated in about 20–45 minutes.

In our model, we denote by τ_n the *total* information processing delay of Trader n, i.e., the time from the point at which new data was generated all the way through the ultimate execution of a trade by Trader n. We have $\tau_n = \tau_n^o + \tau_n^e$, where the first term is Trader n's observation delay and the second is his execution delay.

Under some circumstances, a trader may be able to "follow the market" and infer the price disparity by observing other traders' market activities.[10] In our framework, this gives rise to a "follow the market" model where Traders 2, 3, ..., N observe the executions of Trader 1 and act on them. These observations are subject to a delay, which is determined by the communications facilities provided by the market and by its trading rules.[11] We call the delay between the execution of a transaction and the time it can be observed by traders the *market observation delay* and denote it by τ^m. The corresponding total observation delay is clearly $\tau_1 + \tau^m$. Since Trader n can also obtain the value of δ on his own with an observation delay of τ_n^0, his effective information processing delay is $\min\{\tau_n^o + \tau_n^e, \tau_1 + \tau^m + \tau_n^e\}$. Our results for the Trading Game thus apply to the "follow the market" model with the effective information processing delay playing the role of τ_n.

The relative magnitudes of τ_n determine the timeliness ranking and trading profits in the trading game, described next.

2.3. Trading Game

We consider a single informational event, at time $t = 0$, that shifts the market value of the security up or down by δ. While the information will ultimately become known to all traders, the market impact of each trade narrows the gap between value and price, thereby limiting the profit potential of later trades. Traders' information processing delays are common knowledge. We assume without loss of generality that traders are labeled so that $\tau_1 \le \tau_2 \le \cdots \le \tau_N$. We consider first the case where the information processing delays are all different; i.e., $\tau_1 < \tau_2 < \cdots < \tau_N$. Since the delays are common knowledge, we can assume without loss of generality that the observation delay is zero; that is, each Trader n observes δ, decides on his trade q_n, and submits it for execution.[12]

A trading strategy for Trader n, $q_n(\delta)$, specifies his trading quantity (possibly zero) as a function of the initial price disparity δ. Since Trader n incurs the cumulative market impact of all preceding trades, his profit depends on the total quantity of those trades. Let $\pi_n(q_n,$

[8] Similar orders of magnitude were found by numerous subsequent studies in the finance literature.

[9] Jain (1988) finds for an earlier sample period that the stock market adjusted to similar announcements in about one hour.

[10] Devising a profitable trading strategy based solely on market data is difficult. If the arrival of news is unpredictable, it is difficult to recognize whether or not an observed trade reflects new information. Further, the delay involved in tracking market activities may eliminate the profit opportunity for market followers. Nevertheless, traders sometimes engage in strategies that are driven by other traders' activities, with varying degrees of success. For example, using the Small Order Execution System on NASDAQ, "day traders" follow the market in an attempt to capitalize on temporary price disparities.

[11] For example, NASDAQ market makers can delay their trade reports by 90 seconds.

[12] Traders who require immediacy of execution use market orders, as opposed to limit orders that cannot guarantee timely execution. Accordingly, traders' strategic variable is quantity rather than price, as in Kyle (1985) and the ensuing literature. We also assume that traders do not collude, reflecting the legal prohibition against such practices.

$Q_{<n}|\delta)$ denote Trader n's profit when he submits the quantity q_n, the total quantity of preceding trades is equal to $Q_{<n}$, and the price disparity is equal to δ. Then, for $\delta > 0$, $\pi_n(q_n, Q_{<n}|\delta) = q_n(\delta - mQ_{<n} - mq_n) - K(q_n)$, where $K(q_n)$ is equal to $A + b|q_n|$ if $q_n \neq 0$, and equal to 0 otherwise. Define the optimal response function for Trader n by $r_n(Q_{<n}) = \text{argmax}_{-\infty<q_n<\infty}\, \pi_n(q_n, Q_{<n}|\delta)$. In a Nash equilibrium, each trader's quantity is an optimal response to the other traders' quantities, giving rise to the following *successive monopoly* equilibrium.[13]

THEOREM 1. *Assume $\tau_1 < \tau_2 < \cdots < \tau_N$, and define $d_n = b + 2^n\sqrt{Am}$. For $\delta > 0$, the trading strategies*

$$q_n^*(\delta) = \begin{cases} 0 & \text{if } \delta \le d_n, \\ \dfrac{1}{2^n}\cdot\dfrac{\delta - b}{m} & \text{if } \delta > d_n, \end{cases}$$

for $n = 1, 2, \ldots, N$, constitute the unique Nash equilibrium. The case of $\delta < 0$ is symmetric.

Trader 1's trades are not affected by the market impact of other traders' executions and he in effect operates as a monopoly. If $\delta \le d_1$, trading profits would not cover the fixed transaction cost A and Trader 1 refrains from trading. When $\delta > d_1$, Trader 1 starts to trade, but he does not consume the entire profit opportunity. The total market impact of this trade is $mq_1 = (\delta - b)/2$. Thus, after Trader 1 has completed his trading, the price disparity, net of proportional transaction cost, is reduced by *half* to $\delta - b - mq_1 = (\delta - b)/2$. If $\delta > d_2$, both Traders 1 and 2 will trade. However, because of Trader 1's time advantage, he still enjoys a monopoly, and Trader 2 incurs the full market impact of Trader 1's trades. Subsequently, Trader 2 has a monopoly in the range $d_2 < \delta \le d_3$, but with half the original net price disparity. This pattern continues with slower information traders, and each trader acts in turn as a monopoly facing half of the net price disparity available to the previous trader. If Trader n trades (i.e., $|\delta| > d_n$), his profits are given by

$$\pi_n = mq_n^2 - A = \frac{1}{4^n}\cdot\frac{(|\delta| - b)^2}{m} - A, \qquad (1)$$

[13] All proofs are in the working paper version of this paper, Dewan and Mendelson (1996).

which is the difference between Trader n's market impact cost and the fixed transaction cost. The longer a trader's trading delay, the higher his threshold, and the lower his profits. Traders with longer trading delays trade less frequently and, in addition, their profit *per trade* is lower.

EXAMPLE 1 (CONTINUED). For the parameters of Example 1, $\sqrt{Am} = 0.025$. Thus, $d_n = 0.15 + 2^n \times 0.025$. Absent the fixed transaction cost A, any price disparity $\delta > \$0.15$ would be successively corrected; with three traders, $\delta - b$ would be reduced to $\frac{1}{8}$ of its initial magnitude. For example, when $\delta = \$0.25$, all three traders will trade and the price will decrease by 8.75 cents. Even though the fixed transaction cost is small (see Figure 1), it has a noticeable impact on price behavior. The minimum price disparity triggering transactions (and a price correction) now increases to \$0.20. Further, when $\delta = \$0.25$ (or slightly below), the second trader already has no incentive to trade and as a result, the price correction will be 5 cents (compared to 8.75 cents when $A = 0$). With respect to trading profits, consider the average NYSE block trade of 24,000 shares. Since the expected market impact is $mq^2 = \$3{,}600$, by Equation (1) the expected trading profit for this trade is $\$3{,}600 - A = \$3{,}500$. Thus, the fixed transaction cost of \$100 constitutes only a small fraction of gross trading profits.

When the fixed transaction cost A is zero, all traders have the *same* price disparity threshold equal to the proportional transaction cost b. Whenever the initial price disparity δ is greater than b, all traders will submit trades, with successively smaller quantities and profits. As the number of traders N tends to infinity, trading will drive the price disparity down to b, where further trading cannot be profitable.

We turn now to the general case of possibly equal timeliness, i.e., $\tau_1 \le \tau_2 \le \cdots \le \tau_N$. Among the N traders, suppose there are M *distinct* levels of information processing delay, where $M \le N$. For $n = 1, 2, \ldots, M$, let S_n denote the set of traders with the nth shortest information processing delay, and denote by N_n the cardinality of set S_n. Let n_i index the ith trader in set S_n, for $n = 1, 2, \ldots, M$, where the index $i \in \{1, 2, \ldots, N_n\}$ is randomly assigned to the traders in the set. Thus, $\sum_{n=1}^{M} \sum_{i=1}^{N_n} n_i = N$. In this case, we have the following *successive oligopoly* equilibria.

THEOREM 2. *Assume $\tau_1 \le \tau_2 \le \cdots \le \tau_N$ and, for any n and k, define $d_n^k = b + \Pi_{j=1}^{n-1}(N_j + 1)(1 + k)\sqrt{Am}$, where the numbers N_j, $j = 1, \ldots, M$ are as defined above. There are a total of $N_1! \times N_2! \times \cdots \times N_M!$ pure strategy Nash equilibria, one for each unique permutation on $\{1, 2, \ldots, N\}$ that preserves the order of distinct trading delays. Consider one such random permutation and assume $\delta > 0$. Then, the trading strategies*

$$q_{n_i}^*(\delta) = \begin{cases} 0 & \text{if } \delta \le d_n^i, \\ \dfrac{1}{\Pi_{j=1}^{n-1}(N_j+1)(1+k)} \cdot \dfrac{\delta - b}{m} & \\ \quad \text{if } d_n^k < \delta \le d_n^{k+1}, \quad k = i, \ldots, N_n - 1, & \\ \dfrac{1}{\Pi_{j=1}^{n}(N_j+1)} \cdot \dfrac{\delta - b}{m} & \text{if } \delta > d_n^{N_n}, \end{cases}$$

for each Trader n_i, $i \in \{1, 2, \ldots, N_n\}$ and $n \in \{1, 2, \ldots, M\}$, constitute the unique Nash equilibrium. The case of $\delta < 0$ is symmetric. There is no Nash equilibrium in mixed strategies.

The *successive oligopoly* equilibria in the case of possibly equal timeliness above are characterized by an N_1-Oligopoly followed by an N_2-Oligopoly, and so on. Note that Theorem 1 corresponds to the case $N_n \equiv 1$; that is, each set S_n is a singleton. Theorem 2 is used in §3 to establish the existence of a mixed strategy equilibrium in the IT investment game.

3. IT Investment Decisions

In this section, we analyze the "IT investment game" where the traders simultaneously make their IT investments. The resulting information processing delays are specified by a function $\tau(c)$, satisfying $\tau' < 0$ and $\tau(0) = \theta$, which characterizes the delay for an IT investment of c dollars per unit of time. We thus assume that all traders face the same tradeoff between investment c and timeliness $\tau(c)$. In the IT investment game, traders balance the cost of their trading systems per unit time against the corresponding rate of trading profits. Our results from the previous section provide the expected trading profit per informational event, and we first convert them into expected average profit per unit time. The next subsection derives these profit rates and studies their characteristics.

3.1. Expected Average Trading Profits

Assume that the arrival of new informational events is governed by a renewal process whose interarrival times are the i.i.d. random variables $T_1, T_2, T_3, \ldots$, distributed as T. We assume that the time scale of price adjustment (i.e., trading) is much shorter than the time scale of informational events. In particular, we assume that $T > \tau_N$ with probability 1. T has a finite mean $1/\lambda$, where λ is the frequency of informational events. The price disparities $\delta_1, \delta_2, \delta_3, \ldots$, are i.i.d. random variables distributed as δ, possessing probability density function ϕ and having a finite variance. Under these assumptions, the results of §2.3 are applied to each period t.

Our model does not address market activities during the time interval between the last information trade and the subsequent informational event. Qualitatively, this period is characterized by idiosyncratic price changes, driven by so-called "noise" traders. Since the last informational event will ultimately be observed market-wide, subsequent transaction prices will tend to fluctuate around the new equilibrium value of the security, and any residual price disparity will be eliminated. Then, another event changes the value of the security and leads to another round of information trading and a new equilibrium.

To evaluate traders' long-run average profits, recall that for a renewal-reward process, the long-run average profit per unit time is equal to the expected profit per period, given by Equation (1), divided by the expected duration of a period, $1/\lambda$ (Ross 1983). By Theorem 1, Trader n's long-run average profit is given by[14]

$$v_n = \lambda \cdot \int_{-\infty}^{-d_n} \left[\frac{(\delta + b)^2}{4^n m} - A \right] \phi(\delta) d\delta + \lambda \cdot \int_{d_n}^{\infty} \left[\frac{(\delta - b)^2}{4^n m} - A \right] \phi(\delta) d\delta. \qquad (2)$$

It follows from the structure of the optimal trading

[14] Alternatively, the periodic cash flows can be discounted. The associated adjustments are straightforward.

strategies that $v_1 > v_2 > \cdots > v_N$. Some of the properties of the long-run average profits v_n are as follows: (1) v_n is a decreasing function of all three trading cost parameters, A, b and m, as expected; (2) v_n is proportional to the frequency λ of informational events; and (3) v_n increases as the variability of the distribution of δ increases, based on either the mean-preserving spread of (Rothschild and Stiglitz 1970) or the median-preserving spread of Mendelson (1987); i.e., the greater the "surprise" embedded in the new information, the larger the associated profit opportunity.

The case $A = 0$ is of particular interest since for large trades, A is small compared to other components of trading cost (see Figure 1). In this case, Equation (2) for the long-run average profit simplifies to $v_n = \nu/(4^n m)$, where $\nu = \lambda \cdot \int_{-\infty}^{-b} (\delta + b)^2 \phi(\delta) d\delta + \lambda \cdot \int_{b}^{\infty} (\delta - b)^2 \phi(\delta) d\delta$ is a measure of the *informational intensity* per unit time. Here, v_n is proportional to the informational intensity ν that incorporates both the arrival rate of new information and its "informativeness." The expected trading profit is also proportional to the market depth $1/m$: the more liquid the market, the greater the trading profits for a given level of informational intensity. Finally, information-based trading profits depend critically on the timeliness rank of the trader. Improving timeliness can translate into substantially higher trading profits: moving from rank $n + 1$ to n results in a 300-percent increase in trading profits.

3.2. Symmetric IT Investment Game

In choosing his level of IT investment, each trader seeks to maximize his expected net-value, which is equal to gross trading profit less IT investment (all measured per unit of time).[15] Let $U_n(c_n, c_{-n})$ denote Trader n's expected net-value per unit time when his IT investment is c_n while the other traders' investments are given by the vector c_{-n}. Trader n's payoff function $U_n(\cdot, \cdot)$ is discontinuous at points where one or more of the other traders have the same IT investment. These discontinuities of the payoff function imply the following result.

LEMMA 1. *There is no pure strategy Nash equilibrium in the IT investment game.*

This result differs from other games of timing, such as Reinganum (1981), where the payoff function is continuous (but not differentiable). Since the discontinuities satisfy the assumptions of Dasgupta and Maskin (1986a, Theorem 4), there exists a Nash equilibrium in continuous mixed strategies. One might question the meaning of such an equilibrium, but the issue has been thoroughly addressed in the game theory literature (see, e.g., Dasgupta 1988, Kreps 1990): The key point is that an agent is uncertain about *other agents'* choices (rather than his own). Indeed, many interesting games with discontinuous payoff functions have been solved using this concept (see the review in Dasgupta and Maskin 1986b).

Traders' IT investments determine their timeliness ranking and therefore their profits in the trading game. Recall that v_n is the gross trading profit for the trader ranked n in timeliness. Define $v_{i,j} = v_i - v_j$. Since the payoff series v_n, $n = 1, 2, \ldots, N$ assumes a simple geometric structure when the fixed transaction cost is zero, we assume in what follows that $A = 0$.[16] Clearly, a single trader ($N = 1$) has no incentive to improve timeliness relative to θ. The following theorem characterizes the equilibrium in the IT investment game for $N > 1$.

THEOREM 3. *In the IT investment game, each trader plays a symmetric, strictly increasing distribution function*

$$F(c) = \frac{1}{3}\left[\left(1 + \frac{c}{v_N}\right)^{1/(N-1)} - 1\right]$$

over the support $[0, v_{1N}]$, *and has an expected net-value of* v_N.

The difference $v_{1N} = v_1 - v_N$ bounds the gains that can be achieved from better technology. Hence, systems whose timeliness is better than $\boldsymbol{\tau} = \tau(v_{1N})$ are not economically viable and $\boldsymbol{\tau}$ represents the *best viable timeliness*. In equilibrium, however, traders are indifferent between choosing the best viable technology with an investment of v_{1N}, making no IT investment at all, or anything in between. Since the sum of trading profits

[15] Alternatively, the objective function can be taken to be the net present value; i.e., the periodic trading profits would be suitably discounted. The same applies to the IT investment c: whereas all system development costs are amortized here, an equivalent present-value formulation can be easily constructed.

[16] Recall that for a typical block trade, the fixed transaction cost is only a small fraction of gross trading profit; see Example 1.

for all traders is $\Sigma_{i=1}^{N} v_i$ and each trader's expected net-value is v_N, the expected IT investment per trader is $\Sigma_{i=1}^{N} v_i/N - v_N$. For the behavior of average IT investment levels, we have the following result.

COROLLARY 1. *The average IT investment is: (i) independent of the specific $\tau(c)$, (ii) increasing in market depth and informational intensity, (iii) decreasing in the transaction cost parameters A and b, and (iv) decreasing in the the number of traders for $N \geq 3$.*

In other words, the incentive to invest in IT is higher in markets that are more liquid, have fewer competing traders, have lower transaction costs and where informational events are more frequent such as the U.S. Treasury and foreign exchange markets. Indeed, both of these markets are characterized by high levels of investment in trading technology (Rohan 1993). Figure 2 shows the levels of IT investment (per trader and industry-wide) as a function of the number of traders N, assuming $v_1 = 1$. The IT investment per trader is highest when there are two or three traders. As the number of traders increases, a given trader's probability of being first to market declines, and so does his incentive to invest. Put differently, the return on IT investment is a decreasing function of N. In the aggregate, however, industry IT investment increases with the number of traders and levels off at the asymptotic level of $4v_1/3$. The average IT investment increases going from one to two traders because of the contention for trading profits. Going from two to three traders, the average IT investment per trader stays the same, reflecting the balance between the greater need for competitiveness and lower returns on IT investments due to the sharing of profits. The latter effect dominates as N increases beyond three, and the average IT investment steadily decreases.

Figure 3 shows the ex-post expected net-values of traders as a function of their (realized) timeliness ranks.

Figure 2 **IT Investment as a Function of the Number of Traders, *N*.**
(The solid line represents the investment *per trader*, and the dashed line gives the aggregate *industry* investment. In this example, v_1 = 1.)

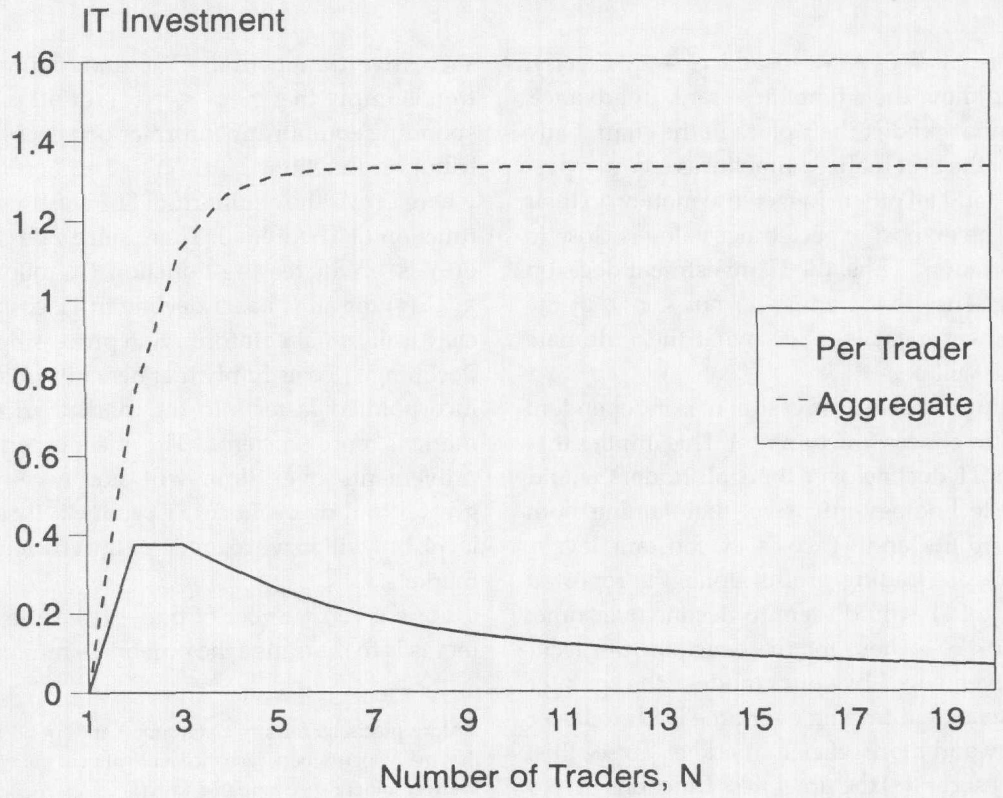
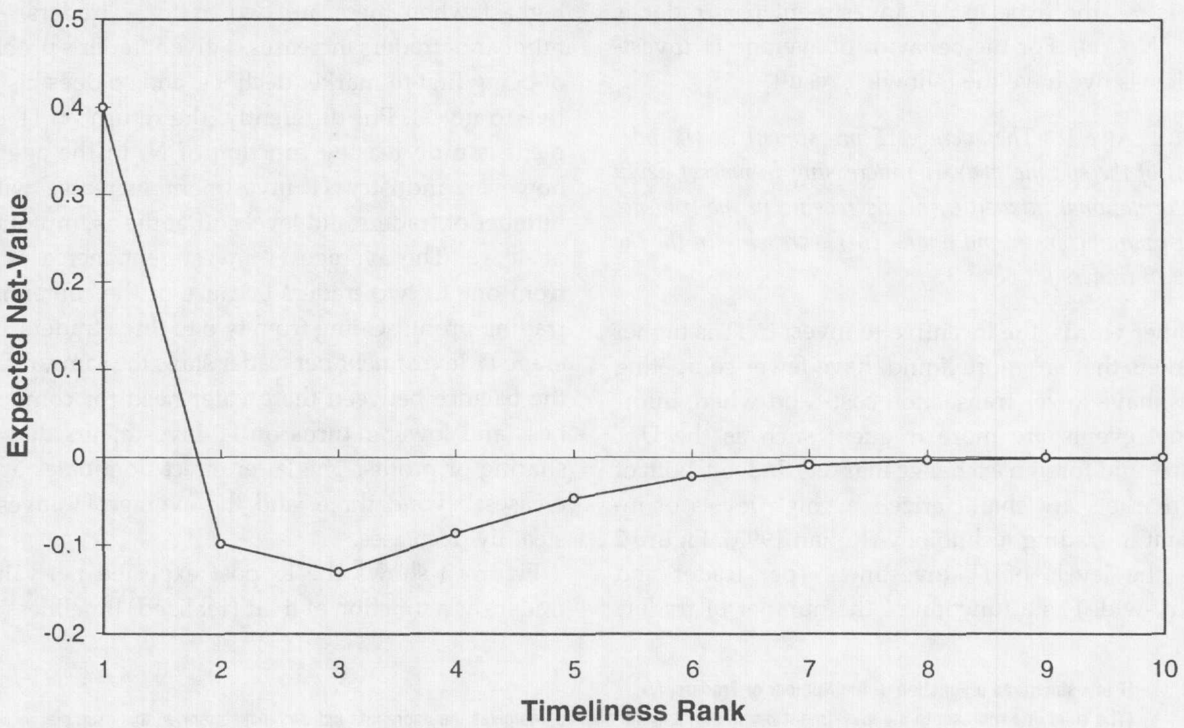


Figure 3 Ex-post Expected Net-Value as a Function of Realized Timeliness Rank for $A = 0$, $N = 10$, and $v_1 = 1$



In this example, $A = 0$, $N = 10$ and $v_1 = 1$. Clearly, traders do not know their timeliness rank in advance, hence they cannot predict their place in the chart. Only the trader with the best realized timeliness enjoys a positive net-value, and all others in fact lose money on their investments. The ex-post expected net-value is close to zero for most traders. Thus, the IT investment decision is risky in the sense that traders do not know, at the time their IT investment is made, what their ultimate timeliness rank will be.

The equilibrium level of IT investment is independent of the specific timeliness function $\tau(c)$. This implies that as unit costs of IT decline over time, all traders would become more technology-intensive, maintaining both their trading profits and IT costs at constant levels. Based on aggregate trading profits alone, the reported "productivity" of IT would seem to decline over time: we need to look elsewhere for the benefits from technology improvements. By our model, the greater technology-intensity in trading over time leads to faster value discovery and more efficient markets. To see this, denote by $\tau_1(\cdot)$ and $\tau_2(\cdot)$ the timeliness functions in two successive time periods. The underlying technological trends imply that $\tau_2(c) < \tau_1(c)$ for all c. Let the corresponding equilibrium information processing delay distribution functions be $G_i(t) = 1 - F(\tau_i^{-1}(t))$ $(i = 1, 2)$ where $F(\cdot)$ is the equilibrium IT investment distribution function of Theorem 3. Then, since $\tau_2^{-1}(t) < \tau_1^{-1}(t)$ and $F(\cdot)$ is an increasing function, it follows that $G_2(t) \geq G_1(t)$ for all t; i.e., a decline in IT costs leads to stochastically smaller information processing delays. Thus, declining IT costs imply that new information would be incorporated faster into the market price, making the markets more efficient.[17] The effect of technological improvements over time will not necessarily lead to greater trading profits or IT productivity at the industry level, but will serve to enhance the efficiency of financial markets.

For a given number of traders, the effect of IT investments is to rearrange the timeliness ranking and trading

[17] More precisely, for any given time t and for all x, the probability that the disparity between price and value at time t is greater than x is lower under $\tau_2(\cdot)$ compared to $\tau_1(\cdot)$.

profits without increasing total industry profits or IT productivity. This is consistent with Brynjolfsson's (1993) "redistribution" hypothesis regarding the IT "productivity paradox." With identical traders, the redistribution of IT costs and trading profits is random. When the results are observed ex post, the trader who ended up being first will appear to have "competitive advantage."[18] When all traders have identical IT costs, however, each trader is equally likely to be the one with positive net-value in Figure 3. To improve the odds of gaining real competitive advantage, traders need superior *IT infrastructure* relative to the rest of the market, as we demonstrate in the next subsection.

3.3. IT Infrastructure and Competitive Advantage

A firm's IT infrastructure consists of information systems, telecommunications, standards, databases, systems development tools, technical and managerial expertise, and the like, that enable business-related IT applications. Investments in IT infrastructure are typically long term and strategic in nature and, as reported by Weill (1993), constitute 35–40 percent of total IT investments for the average firm. A specific benefit that is attributed to IT infrastructure is the ability to develop future IT applications at lower incremental cost (Keen 1991, Weill 1993). For example, a firm that has already made such productivity-enhancing infrastructure investments as 4GLs, CASE tools, and client/server architectures might be able to add new systems and applications that further improve trading timeliness at lower cost relative to other firms that have not made similar investments. In what follows, we find the value of an improved infrastructure for the problem at hand, and study factors that affect this value.

Our analysis of IT investments has so far assumed that all traders are endowed with the same function $\tau(c)$. As discussed above, however, firms with different IT infrastructures will have different timeliness functions. The general problem with heterogeneous $\tau(c)$ functions is very complex. Fortunately, we can solve the case where one of the N traders, say Trader 0, has a different function $\tau_0(c)$ while the other $N-1$ traders have the same function $\tau(c)$. We say that Trader 0 is "IT-superior" when there is a function $\xi(\cdot)$ satisfying $\xi(c) < c$, such that $\tau_0(\xi(c)) = \tau(c)$ for all c; i.e., Trader 0 needs a lower IT investment relative to the other traders to achieve the same level of timeliness. Similarly, we say that Trader 0 is "IT-inferior" if $\tau(\xi(c)) = \tau_0(c)$. When Trader 0 is IT-inferior, we further distinguish between two cases: (1) if $\xi(v_{1N}) < v_{1,N-1}$, we call Trader 0 "grossly IT-inferior"; (2) if $v_{1,N-1} \le \xi(v_{1N}) \le v_{1N}$, we call Trader 0 "slightly IT-inferior." As shown below, when Trader 0 is grossly IT-inferior he will not make any IT investment, whereas if he is slightly IT-inferior he is indifferent between investing and not investing in IT. For the above function $\xi(\cdot)$, we assume that $0 < \xi'(c) \le 1$ and $\xi''(c) \ge 0$ for $c \in [0, v_{1N}]$. The restriction $\xi' \le 1$ is equivalent to assuming that, for a given level of timeliness, additional IT investment improves timeliness at a faster rate for the advantaged trader(s) relative to the others.

Our assumptions on $\xi(\cdot)$ are not highly restrictive, and they are satisfied by a number of function classes, including: (1) *linear*: $\tau(c) = \theta + \alpha c$ and $\tau_0(c) = \theta + \alpha_0 c$, (2) *reciprocal*: $\tau(c) = \theta/(1 + \alpha c)$ and $\tau_0(c) = \theta/(1 + \alpha_0 c)$, and (3) *exponential*: $\tau(c) = \theta e^{\alpha c}$ and $\tau_0(c) = \theta e^{\alpha_0 c}$. The theorem below characterizes the different equilibria that arise in this model.

THEOREM 4. (i) *If Trader 0 is grossly IT-inferior, there is a Nash equilibrium in which he selects $c = 0$ with certainty, and the other $N - 1$ traders each play the same strictly increasing distribution function F over the support $(0, v_{1,N-1}]$. The expected net-values are v_N for Trader 0 and v_{N-1} for the other traders.*

(ii) *If Trader 0 is slightly IT-inferior, there is a mixed strategy equilibrium in which he selects $c = 0$ with a positive probability p and plays a strictly increasing distribution function F_0 over the support $[\underline{c_0}, v_{1N}]$, where $\underline{c_0} > 0$. The other $N - 1$ traders play the same strictly increasing distribution function F over the support $(0, \xi(v_{1N})]$. Trader 0's information processing delay is stochastically larger than that of the other traders; i.e., $F(\xi(c)) \le F_0(c)$ for all c. The expected net-values are v_N for Trader 0 and $v_1 - \xi(v_{1N})$ for the other traders.*

(iii) *If Trader 0 is IT-superior, there is a mixed strategy equilibrium in which he plays a strictly increasing distribution function F_0 over the support $[\xi(\underline{c_0}), \xi(v_{1N})]$, where $\underline{c_0} > 0$. The other $N - 1$ traders play the same strictly increasing distribution function F over the support $[0, v_{1N}]$. Trader 0's*

[18] This is because this trader's expected net-value, $v_1 - c_1$, is larger than the industry average of v_N.

information processing delay is stochastically smaller than that of the other traders; i.e., $F_0(c) \le F(\xi(c))$ for all c. The expected net-values are $v_1 - \xi(v_{1N})$ for Trader 0 and v_N for the other traders.

For large N, an IT-inferior trader is essentially grossly IT-inferior and even with a small cost disadvantage he has no incentive to invest. The other $N - 1$ traders behave as if Trader 0 is absent from the market and enjoy a payoff that is *four* times as large as that of the grossly IT-inferior trader. As long as Trader 0's IT infrastructure is inferior, additional IT investments targeted towards improving timeliness are not productive. Regardless of whether he is grossly or slightly IT-inferior, Trader 0's expected net-value of v_N is lower than the expected net-value of the other traders, i.e., he suffers a *competitive disadvantage*.

When Trader 0 is IT-superior, the situation is markedly different. His information processing delay is stochastically smaller than that of the other traders, and he is able to translate this timeliness advantage into higher trading profits and net-value. The IT-superior derives a *competitive advantage* from his superior IT infrastructure, and his "excess" net-value is equal to $v_{1N} - \xi(v_{1N})$. This excess net-value is increasing in both v_{1N}, the difference in trading profits between the first and very last trader, and in Trader 0's marginal cost advantage characterized by the function $\xi(\cdot)$. Thus, having a superior IT infrastructure is more critical in more liquid markets, when the frequency or magnitude of events is higher, or when the number of traders N is larger.

Theorem 4 demonstrates the strategic role of IT infrastructure and associated *cost leadership* (cf. Porter 1985). As long as a firm's IT infrastructure is inferior relative to the market, investments directed toward improving timeliness are not productive and do not lead to higher expected net-value. The firm is better off channeling its new investments into IT infrastructure enhancements. After the firm has improved its IT infrastructure to the point where it is superior to the rest of the market, investments in timeliness-enhancing IT applications become productive and generate differential gains: the IT-superior firm is able to convert its cost advantage into competitive advantage.

In practice, trading firms typically build a proprietary infrastructure in support of trading by integrating their internal trading know-how with marketplace IT solutions such as turrets, data feeds, analytics, etc. The individual components are available in the marketplace, but their integration with the firm's inherent expertise is key. While all firms have access to IT components that can potentially improve performance, a firm with a better *IT infrastructure* can more productively exploit the available technologies. Thus, better IT infrastructure translates into substantial competitive advantage.

Our analysis and results in this section extend to the "follow the market" model as follows. We maintain the assumption that all traders have access to the same timeliness-improving technologies. The level of IT investment c determines the observation delay $\tau^o(c)$ and the execution delay $\tau^e(c)$, where both functions are monotone decreasing (recall that the market observation delay τ^m is determined by the securities market rather than by the traders). Clearly, the trader with the highest IT investment has the lowest information processing delay, denoted by τ_1. Then, the effective information processing delay for Trader n, whose IT investment is c_n, is given by $\min\{\tau^o(c_n) + \tau^e(c_n), \tau_1 + \tau^m + \tau^e(c_n)\}$. Thus, traders' effective information processing delays will be ranked in descending order of their IT investments. Since all payoffs depend only on traders' timeliness rankings, our results pertaining to equilibrium IT investments remain intact.

4. Discussion and Concluding Remarks

Timeliness is an important driver of IT investments by securities firms, as also reflected in a recent report by the Tower Group (1996). The report highlights various factors that stimulate IT investments, including the scope of market data, analytics and data visualization capabilities,[19] but it identifies timeliness, or "the need for speed," as the primary factor and calls it "hypercritical." This paper focuses on the timeliness dimension while abstracting from other factors (which are open for further research). We examined the role of IT

[19] Most broker-dealers engage in both proprietary trading and brokerage services, and the revenues from the two sources are comparable for NYSE member firms. Our focus is clearly on trading systems and the associated trading gains.

and timeliness in trader competition, modeling the interplay between trading strategies, IT investments and two sources of market imperfection: trading costs and information processing delays.

The equilibrium trading strategies are such that each trader has a certain threshold of price-value disparity, which depends on his timeliness rank. Slower traders trade less frequently, submit smaller orders and gain lower profits per trade. These trades translate the underlying *value* changes in the security into *price* changes observed in the marketplace (cf. Amihud and Mendelson 1987, 1991b, 1992). The observed returns during the adjustment period are positively autocorrelated, consistent with prior empirical evidence (cf. Amihud and Mendelson 1987, Ederington and Lee 1993).[20] Our results also imply that if timeliness is uniformly improved for all traders through changes in the underlying technology or in the exchange process, price adjustment will be accelerated, resulting in lower autocorrelations per unit of time but the same transaction-by-transaction autocorrelation. Overall improvements in trading technology would thus improve market efficiency without altering the gains from being first. Our analysis is readily adapted to arbitrage trading of a security between two markets, interpreting the price disparity as the price differential between the two markets.

In the IT investment game, the Nash equilibrium is characterized by mixed strategies. The average IT investment per trader and the trading profits are increasing in market depth and intensity of informational events, but decreasing in the level of transaction costs and the number of competing traders. Further, average trading profits increase sharply with improvements in a trader's timeliness rank. For example, in the case of zero fixed transaction cost, the fastest trader enjoys four times the trading profit of the second trader.

One may wonder what prevents the fastest trader from keeping all trading profits to herself. If the fastest trader could fully disguise her trades without losing her timeliness advantage, she would submit a sequence of trades that capture the entire profit opportunity. In many trading systems, however, it is difficult to "fool" the market-maker in this way. For example, NYSE specialists can identify frequently-used trading accounts and infer that multiple trades have come from the same source. They will thus adjust their quotes to avoid being "picked off," and the total market impact will accordingly increase. Similarly, market-maker trades in the NASDAQ market are not anonymous. Nevertheless, extending our model to the case of anonymous traders does not change the qualitative nature of our results in §3.

Our results show that IT capabilities arising from superior IT infrastructure can confer competitive advantage on a trading firm. It is therefore not surprising that securities firms periodically launch grandiose projects, costing hundreds of millions of dollars, to upgrade their IT platforms. Recent examples of such projects include Morgan Stanley's TAPS, First Boston's NTPA, Bankers Trust's DECtrade and Salomon Brothers' TP-21, not all of which lived up to their promise (*Institutional Investor* 1995). Once developed, the IT infrastructure is costly to change, and for competitors to duplicate. As a consequence, trading firms with a clear and purposeful technology plan, and perhaps some luck, that are successful in building a superior IT infrastructure relative to the rest of the market end up gaining a long-term competitive advantage.[21]

There are a number of directions for future research. One would be to incorporate the interaction between information and liquidity trading. Bagehot (1971) was the first to point out the distinction between information traders, who transact on new information, and liquidity-motivated noise traders who have no special information and merely want to convert securities into cash or vice versa. Much of the market-microstructure literature focuses on the effects of these two types of traders, coupled with the structure of the market, on the behavior of securities prices. As already discussed, in this paper we take the market structure and the effects of noise trading as exogenous factors, characterized by

[20] These results are consistent with $0 < \gamma < 1$ in the Amihud-Mendelson (1987) model. The finance literature has documented additional factors that may lead to either positive or negative autocorrelations.

[21] See Barney (1986) for the role of heterogeneous expectations and luck in the creation of resource-based competitive advantage.

the trading cost functions. An interesting avenue for future research is to integrate the two approaches and make *both* the liquidity of the market and the technology and trading choices of information traders, endogenous. Further, it would be interesting to consider dynamic trading strategies that incorporate the interaction of the different market participants over time. With respect to the IT investment game, it would be useful to try to generalize our model and results to cases where two or more firms have different IT capabilities. It also would be interesting to analyze the effects of trading system characteristics, such as anonymity and transparency on the incentives to invest in IT.

Another direction for future research is to empirically test our theoretical findings. It would be interesting to examine the empirical relationship between trading volume and price disparity based on the optimal trading strategies derived in §2. Also, our analysis suggests a specific pattern of price adjustment to new information, which can be subjected to empirical testing. Further, the results of §§3 and 4 regarding the relationship between the attributes of the market and the pattern of IT investments are amenable to empirical tests, subject to data availability issues. Alternatively, it would be interesting to conduct a detailed investigation of the technology strategies and performance of specific trading firms. In-depth case studies of this type will not only provide insights into actual behavior, but would also facilitate the development of richer analytical and empirical models for further understanding the role of IT in securities trading.[22]

[22] We thank the associate editor, two anonymous referees and seminar participants at Stanford University, WISE'95 at the London Business School, and the University of California, Irvine, for helpful comments. Partial financial support by the Stanford Computer Industry Project and by the IT Initiative of the Stanford Business School is also gratefully acknowledged.

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Accepted by Abraham Seidman; received August 22, 1995. This paper has been with the authors 4 months for 2 revisions.