# Price Discovery in the U.S. Stock Options Market

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*In the U.S., several exchanges with different market microstructure designs compete to provide quotes and attract order flow on a common set of stock options. In this article, we analyze how the different microstructure designs affect the price discovery of options quotes and how they alter the flow of options trading activities over time. We find that the fully electronic exchange system at the International Securities Exchange (ISE), where several market makers provide quotes independently and anonymously to compete for order flow within the exchange, generates options quotes that are the most informative and the most executable, with the narrowest bid–ask spreads. Over time, the ISE's leading quote quality has attracted order flow to the exchange, and has compelled other exchanges to pursue technology innovations and structural reforms through either expansion or consolidation.*

The financial industry has come to recognize the importance of derivative securities in providing unique investment opportunities and risk-management vehicles. Trading volume on derivatives has increased tremendously during the past few years. Accompanying this expansion in derivatives have been rapid expansions and transformations in the stock options market. In the United States, in an effort to reduce trade-throughs and other market segmentations, a series of regulatory changes have taken place since the late 1990s. In July 2000, the Securities and Exchange Commission (SEC) approved a plan to electronically link the various market centers (the "Linkage Plan"). The SEC has also adopted more stringent quoting and disclosure rules on the options market. The "firm quote" rule was applied to the options markets on April 1, 2001.

At the time of our study, five options exchanges compete to provide quotes and attract order flows on a common set of stock options: the American Stock Exchange (AMEX), the Chicago Board of Options Exchange (CBOE), the International Securities Exchange (ISE), the Pacific Stock Exchange (PCX), and the Philadelphia Stock Exchange (PHLX). The five exchanges differ in both histories and market microstructure designs. AMEX, CBOE, PCX, and PHLX are all floor-based exchanges that have been in existence since the 1970s. The AMEX and the PHLX apply a specialist structure resembling that used in the stock market. The CBOE and the PCX trade options under a modification of the open outcry structure used in the futures pit, where one primary or lead market maker works with several market makers on the floor to make the market. The roles of the primary market maker are similar to those of a specialist, except that options traded under the primary market maker can also be traded by other market makers. By contrast, the ISE is a relatively new entity, which started its first day of options trading on May 26, 2000. It is a fully electronic exchange without a physical floor. For each option series, one primary maker and several competitive market makers send in quotes independently and anonymously via their respective quoting engines. These quotes are consolidated via a centralized consolidating system and compete internally for order flows directed to the exchange.

In this article, we analyze how the different microstructure designs affect the price discovery of the options quotes from different exchanges and how they alter the flow of options trading activities over time. Based on the real-time feeds from the Options Price Reporting Authority (OPRA) during January of 2002, we choose 39 stocks that have the highest options trading volume during that month. At each of the 20 business days in that month, we extract both the quotes and trades on the most actively traded option series on each of the 39 stocks. We measure the Hasbrouck [1995] information share by using the second-by-second quote book, and we analyze the relation between price discovery and other market conditions. We also investigate the general statistical properties of the bids and asks from each exchange and analyze how they match with the transactions.

Our analysis shows that among the five options exchanges, quotes from the ISE have the highest information share estimates on average. The difference becomes more pronounced when the options series have higher aggregate trading activities. Among the four floor-based exchanges, the modified outcry systems at the CBOE and the PCX provide more informative quotes than the specialist systems at the AMEX and the PHLX. These findings suggest that intra-exchange competition from multiple market makers enhances the informativeness of the options quotes, and quote source anonymity enhances the intra-exchange competition.

We also find that quotes from the ISE have the narrowest mean bid-ask spreads. Among the four floor-based exchanges, the two larger exchanges, the AMEX and the CBOE, deliver quotes with narrower bid-ask spreads than do the two smaller exchanges, the PHLX and the PCX. Finally, quotes from the ISE are also the most executable: Transactions at the ISE occur exactly at the bid or offer for 84% of time, the highest among all five options exchanges. The percentage drops to 57% for AMEX, 40% for CBOE, 39% for PCX, and 36% for PHLX. Since many specialists on the floor exchanges are also competitive market makers at the ISE, we attribute the ISE's narrower bid-ask spread to intra-exchange competition among multiple market makers. The relative ranking of the four floor-based exchanges further shows that current order flows also affect the incentives of an exchange in providing binding quotes. Market makers facing more order flows have stronger incentives to provide binding quotes.

Over time, higher quote quality also attracts order flow. Consistent with its leading quote quality, since its inception the ISE has rapidly been gaining market share. By mid-2003, the market share of the ISE had become the largest in options trading volume, excluding the Standard and Poor's (S&P) index options which are solely licensed to the CBOE. Its rapid rise in market share highlights the economic benefits of technology innovation and careful microstructure design, and has spurred a new wave of technology innovation and structural reforms among both old and new options exchanges.

Compared to the vast market microstructure literature on the stock market, there has been little research on the market microstructure and price discovery of the options market. The few known empirical microstructure studies on the options market include Battalio, Hatch, and Jennings [2004]; Chakravarty, Gulen, and Mayhew [2004]; de Fontnouvelle, Fishe, and Harris [2003]; Holowczak, Simaan, and Wu [2006]; Mayhew [2002], and Neal [1987, 1992]. None of these studies directly addresses the issue of price discovery among different options exchanges.

## THE MARKET MICROSTRUCTURE OF THE OPTIONS EXCHANGES

Option prices provide information about the underlying security that is not readily available from the primary security market. The price quote of a stock represents a mean valuation, but the prices of options underlying the stock—with the whole spectrum of strike prices and maturities—present a complete picture of the conditional distribution of the stock value at different possible realizations and conditioning horizons. Therefore, it is important to understand the information flow in the options market and to appreciate the fact that price discovery in the options market is not limited to the discovery of the underlying stock price. The importance of options price discovery analysis goes far beyond the stock price discovery studies among the underlying stock markets (e.g., Hasbrouck [2003]), or between stock and options markets (e.g., Chakravarty, Gulen, and Mayhew [2004] and Holowczak, Simaan, and Wu [2006]).

Market making on options also has a unique set of characteristics. First, the counterparty risk of options contracts is separate from the underlying company. In the U.S., exchange-listed options are subject to a formal clearing procedure by the Options Clearing Corporation (OCC). All options exchanges are members of the OCC. Second, underlying a single stock are hundreds of options at different strike prices and maturities. The values of these options are inherently linked by no-arbitrage relations. When a market maker adjusts the quote on one option contract, the market maker should also consider the quotes on other options underlying the same stock to avoid being locked into an arbitrage trading program.

The options market maker must also pay constant attention to the underlying stock market. Any stock quote update necessitates the updates of hundreds of options underlying the stock. For example, an informed trader who knows that a stock price will soon rise can buy the stock up to the ask size of the stock market maker. On the options market, this informed trader can simultaneously buy all the calls and sell all the puts underlying this stock. Therefore, if we think of the risk exposure of the stock market maker as her current ask size, the risk exposure of the options market maker is the summation of her ask size on all call options and her bid size on all put options underlying the stock.

The unique characteristics of the options market dictate that options market makers must possess the intricate knowledge of various no-arbitrage relations, as well as the technology to update their quotes rapidly across all options underlying the same stock. Furthermore, the increased risk exposure due to the highly correlated moves among all options underlying the same stock often necessitates the options market makers to hedge their exposures with the underlying security.

### The Microstructure of the Options Exchanges

The four traditional options exchanges—the AMEX, CBOE, PCX, and PHLX—all use the familiar floor-based model for trading options. With floor exchanges, brokers and market makers interact face to face to execute orders for different options. The four floor-based exchanges use two slightly different structures. The AMEX and the PHLX apply a specialist structure resembling that used in the stock market. The CBOE trades options under a Designated Primary Market Maker (DPM), a modification of the open outcry structure used in the futures pit. The PCX also follows a similar modified outcry structure and trades options under a Lead Market Maker (LMM). The responsibilities of the DPM or LMM include disseminating quotes, providing liquidity to thin markets by trading on his own account, and representing public limit orders. The roles are similar to those of a specialist. The difference is that options traded under a DPM may also be traded by other market makers. However, the DPM maintains the right to a certain percentage of the public order flow (Mayhew [2002]).

In contrast to the four floor-based exchanges, market making on the ISE is fully electronic and is not on a physical floor. Market makers transmit their quotes via their quoting engines. These quotes are consolidated via a centralized consolidating system. Interfaces on a variety of platforms are provided to allow broker-dealers to link their order delivery systems to ISE's order management system.

Despite its fully electronic setup, the ISE is not an alternative trading system (ATS) or an electronic communication network (ECN) where customers trade against one another via electronic limit and market orders. Nor is the ISE a dealer market like the Nasdaq, where broker-dealers trade with their own customers. Instead, the ISE is an SEC-registered exchange that trades listed options products via auction principles. Customers send their orders to broker-dealers. Broker-dealers route these orders to any of the five options exchanges. Market makers at these five exchanges provide competing bid and ask quotes on a common set of stock options. Transactions on all five exchanges are subject to a formal clearing procedure by the OCC. The key structural difference between the ISE and the four floor-based exchanges is that all the transactions at the ISE are centralized and cleared electronically, without the need for the broker-dealers and market makers to gather at a certain physical floor and to face each other.

### Market Making and Trading at the ISE

The ISE is similar to the other options exchanges in that they all share the same basic auction principle. The ISE is differant because of the technology and the microstructure details of its market making and trading procedures. The ISE has three classifications of members, all of whom are registered broker-dealers. The classifications are Primary Market Maker (PMM), Competitive Market Maker (CMM), and Electronic Access Member

(EAM). In the ISE system, floor brokers are not needed because orders are input by broker-dealers directly at the point-of-sale in the electronic order book.

The ISE divides stock issues into several bins. Each bin is overseen by one PMM and several CMMs.[1] Most PMMs and CMMs are operated by large, global financial institutions with a significant capital base and substantial trading experience. Within each bin, one PMM and several CMMs submit quotes on the same set of options via their electronic terminals. The quote-consolidating machine consolidates the quotes and posts the best available bids and offers in each options series. Unlike other exchanges, which display the prices offered by the specialist in the options series, the quotes posted at the ISE represent the most competitive bid and offer from all these market makers. Each consolidated quote price and size can come from one market maker, or the aggregation of several market makers. Market makers and customers only observe the consolidated quote screen, not the exact source(s) of the quotes. Furthermore, trade counterparty information is not visible to anyone in the ISE marketplace. Both parties of a trade receive confirmations without learning the identity of the counterparty.

The PMM in each bin is a market maker with significant market-making responsibilities, including overseeing the opening, providing continuous quotations in all their assigned stock options, and ensuring that customer orders are not automatically executed at prices inferior to those available at other options exchanges. At the beginning of each trading day, the PMM determines the opening price based on the balance of the limit-order book. During the day, the PMM has the responsibility to provide continuous quotations in his assigned stock options and to guarantee best execution. If a customer buy-order comes in and the current best ask from the ISE market makers is higher than the best ask from the other options exchanges, the PMM has the obligation to either lower his own ask quote to the national best, or buy the option from the best ask in order to sell it at the same price to the customer.

In exchange for this responsibility, the PMM receives preferential treatment for order flow allocation when he provides the best bid or ask with the other CMMs. For example, if one CMM and the PMM are at the best quote when an order comes in, the PMM receives 60% of the order and the CMM receives 40%. When two CMMs and the PMM are at the best quote, the PMM receives 40% of the order and the two CMMs split the remaining 60% of the order. When three or more CMMs are at the best quote together with the PMM, the PMM receives 30% of the order and the CMMs split the 70%. Furthermore, the PMM receives all the small odd lots (orders for five or less contracts) when he is at the best quote.

CMMs are market makers who quote independently and add depth and liquidity to the market. Each CMM is required to provide continuous quotations for no less than 60% of the stock options in their assigned group. When several CMMs are at the best price, the orders are allocated among them in proportion to their quote size. For example, if CMM A posts the best quote with a quote size of 300 contracts, and CMM B posts the best quote with a quote size of 100 contracts, CMM A will receive 3/4 of the order and CMM B will receive 1/4 of the order.

In contrast to the market makers (PMMs and CMMs), EAMs are broker-dealers who represent agency and/or proprietary orders on the exchange. They cannot enter quotations or otherwise engage in market making on the exchange and they enter the market by providing market or limit orders. All customers who want to trade in listed options need to go through a registered broker-dealer. The customer posts margin with the broker-dealer and the broker-dealer posts margin with the OCC. When all are at the best price, EAM limit orders take priority over market maker quotes and are filled first.

Quoting and trading on the ISE proceed as follows: One PMM and several CMMs provide quotes through their own electronic quote engine on each options contract. These quotes are sent electronically to a central quote-consolidating machine. The quote-consolidating machine generates a consolidated quote book which shows the best bid, aggregate bid size at the best bid, best ask, and aggregate ask size at the best ask. The consolidated quote book is the only information public to both market makers and EAMs.

On the other side, the EAMs enter their market or limit orders through their electronic terminals. These orders are consolidated to generate an order book. The order book and the quote book meet in the trading engine to generate transactions. The transaction follows three layers of priority. The first layer of priority is price. Only the best quote or limit order meets the market order. Furthermore, if the best quote from the ISE market makers and the limit-order book is inferior to the national best, the PMM has the obligation to execute the market order at the national best price. The second layer of priority is the identity of the quote or limit-order provider. Limit orders from EAMs receive top priority and are filled before quotes from the market makers. Then, the PMM receives better allocation treatment than the CMMs. The third layer of priority is quote size. CMMs split their share of the order based on their relative quote size.

The ISE differs from traditional options exchanges in the number of market makers who can effectively drive quotes. On the traditional exchanges, only one market maker essentially drives quotes because market makers rarely compete against one another on the same floor within the same exchange. On the ISE, one PMM and several CMMS send in independent and competitive two-sided quotes for each option series. Because only the aggregate quote-book is public information, the market makers submit quotes anonymously. Such an independent, anonymous environment nurtures competition among the market makers (Simaan, Weaver, and Whitcomb [2003]). Furthermore, the special design of the priority rule encourages competition not only for the best price, but also for a larger quote size and, therefore, enhances market depth.

## DATA AND ECONOMETRICS

We extract the quotes and trades data on stock options from the electronic message feeds of S&P ComStock XpressFeed. The feeds contain updates on both quotes and transactions, including both price and size. The options data provider, OPRA, communicates to the public all of the transactions and quotations from each options exchange through the facilities of its processor, the Securities Industry Automation Corporation (SIAC). Each transaction and quote update is reported to OPRA as a *message*. The options markets generate such messages for a substantial number of products. As of 2002, there were approximately 3,900 equity securities and indexes underlying listed option products, and more than 178,000 individual option series. Trade and quote data are generated continuously for each options product listed on each options exchange during the hours that markets are open. Quote message traffic comprises most of the options message traffic. For example, in February 2000, the average number of quotes per day was 37.5 million, while the average number of trades per day was 183,000, averaging a quote-to-trade ratio of over two hundred.[2]

### Sample Selection

We select options contracts that are traded on all five exchanges and across all 20 business days in January 2002. Based on summary statistics data from OCC, we pick 50 stocks that had the highest options trading volume during January 2002. Then, at each day and for each stock issue, we select the most actively traded option series based on the number of trades. Since our objective is to compare the quotes from the five options exchanges, we further require that the option series be traded at least five times on each of the five exchanges. This last criterion dramatically reduces the sample choice. Of the 50 stocks, only 39 have option series that satisfy our criteria for at least one day.

Historically, most options were assigned to trade on a single exchange. An allocation plan went into effect in 1980 that assigned options to exchanges via a lottery system, with no multiple listing being allowed. The allocation plan was abolished and multiple listings were allowed in 1990. Exchanges chose not to cross-list previously listed options, however, until late 1999 following separate investigations by the U.S. Justice Department and the SEC, and class actions filed against the exchanges alleging anti-competitive practices (Mayhew [2002]). Even so, some options trade more heavily on one exchange than on another due to their historical roots. By requiring that the options in our sample trade at least five times a day on each of the five exchanges, we focus on a sample of options for which market makers on all the exchanges have the incentive to provide competitive quotes. By controlling the incentives on order flow, we can attribute price discovery, and other quote quality differences among the five exchanges, mainly to the exchanges' different technology and microstructure designs.

Exhibit 1 provides the list of the 39 selected stocks, together with the number of days that we find an option series on the stock that satisfies our selection criteria, and the daily averages on the number of trades and trading volume for the selected option series underlying each stock issue. We report the averages both per exchange and across all exchanges. Over the 20 business days in January 2002, we selected 382 option series. The last row reports the grand average of the statistics over the 382 option series. The stocks are listed in descending order in terms of the aggregate options trading volume on each stock issue. The aggregate options trading volume information is from the OCC.

The most actively traded options are on QQQ, the Nasdaq-100 tracking stock. In January 2002, the most actively traded options on QQQ average 409 trades and 12,958 contracts per day. For the selected 382 option

## EXHIBIT 1
**Sample List of the Stock Issues used in the Analysis**

| Root | ND | Average Number of Trades | | | | | | Average Trading Volume | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | AMEX | CBOE | ISE | PCX | PHLX | All | AMEX | CBOE | ISE | PCX | PHLX | All |
| QQQ | 20 | 97 | 53 | 63 | 184 | 12 | 409 | 5453 | 3694 | 1861 | 1788 | 161 | 12958 |
| TYC | 19 | 33 | 108 | 55 | 42 | 28 | 266 | 909 | 1998 | 1444 | 594 | 586 | 5531 |
| INT | 18 | 101 | 72 | 34 | 40 | 11 | 257 | 5228 | 2246 | 1270 | 1496 | 514 | 10755 |
| MSF | 20 | 15 | 142 | 27 | 39 | 30 | 253 | 1056 | 2535 | 1337 | 1077 | 812 | 6817 |
| CSC | 19 | 55 | 111 | 43 | 48 | 10 | 266 | 3708 | 4914 | 2936 | 594 | 651 | 12804 |
| AOL | 19 | 10 | 74 | 13 | 40 | 18 | 156 | 1673 | 1381 | 432 | 470 | 621 | 4576 |
| ORC | 19 | 13 | 77 | 20 | 44 | 19 | 173 | 548 | 3026 | 590 | 613 | 353 | 5131 |
| IBM | 20 | 28 | 59 | 38 | 30 | 12 | 167 | 737 | 1064 | 653 | 685 | 381 | 3519 |
| GE | 4 | 11 | 106 | 12 | 8 | 8 | 145 | 557 | 2545 | 247 | 75 | 342 | 3764 |
| EMC | 20 | 29 | 110 | 17 | 36 | 27 | 219 | 1366 | 2737 | 582 | 407 | 968 | 6060 |
| SUN | 17 | 17 | 32 | 28 | 132 | 23 | 232 | 1115 | 1364 | 1135 | 2556 | 783 | 6953 |
| C | 4 | 9 | 133 | 26 | 14 | 15 | 196 | 412 | 2411 | 876 | 206 | 236 | 4141 |
| DEL | 2 | 7 | 58 | 15 | 6 | 30 | 114 | 315 | 686 | 352 | 608 | 378 | 2338 |
| NOK | 7 | 15 | 64 | 13 | 19 | 8 | 120 | 689 | 1001 | 530 | 395 | 120 | 2735 |
| QCO | 9 | 5 | 44 | 23 | 18 | 26 | 116 | 234 | 637 | 593 | 158 | 911 | 2532 |
| AMA | 15 | 13 | 15 | 24 | 54 | 11 | 117 | 454 | 479 | 686 | 448 | 152 | 2220 |
| WFC | 3 | 39 | 14 | 15 | 8 | 16 | 92 | 1174 | 217 | 214 | 91 | 206 | 1900 |
| HAL | 4 | 34 | 145 | 45 | 11 | 8 | 243 | 1537 | 2183 | 724 | 165 | 155 | 4763 |
| TXN | 12 | 14 | 60 | 26 | 11 | 13 | 124 | 893 | 1231 | 782 | 198 | 311 | 3416 |
| SEB | 17 | 24 | 85 | 17 | 13 | 13 | 152 | 587 | 885 | 300 | 87 | 223 | 2082 |
| MER | 3 | 36 | 13 | 25 | 24 | 11 | 108 | 664 | 355 | 635 | 178 | 221 | 2053 |
| JPM | 5 | 11 | 41 | 15 | 7 | 9 | 82 | 525 | 314 | 405 | 351 | 950 | 2545 |
| CPN | 3 | 13 | 16 | 17 | 15 | 8 | 69 | 1755 | 684 | 333 | 438 | 1044 | 4254 |
| JNP | 18 | 20 | 42 | 18 | 58 | 22 | 159 | 316 | 358 | 437 | 431 | 273 | 1813 |
| PFE | 1 | 32 | 18 | 21 | 7 | 5 | 83 | 2647 | 1656 | 1282 | 288 | 467 | 6340 |
| YHO | 13 | 23 | 30 | 22 | 28 | 8 | 111 | 466 | 569 | 584 | 370 | 198 | 2187 |
| AMD | 5 | 10 | 38 | 19 | 71 | 24 | 161 | 296 | 380 | 281 | 342 | 277 | 1576 |
| AMG | 11 | 38 | 55 | 29 | 18 | 11 | 151 | 733 | 974 | 437 | 150 | 95 | 2390 |
| MO | 1 | 55 | 14 | 10 | 5 | 7 | 91 | 1575 | 384 | 94 | 18 | 53 | 2124 |
| EBA | 3 | 29 | 52 | 33 | 7 | 12 | 134 | 351 | 432 | 388 | 195 | 183 | 1549 |
| BRC | 18 | 16 | 39 | 19 | 8 | 13 | 93 | 496 | 598 | 478 | 78 | 323 | 1971 |
| VRT | 6 | 22 | 18 | 34 | 16 | 7 | 96 | 519 | 214 | 571 | 333 | 87 | 1724 |
| JDS | 2 | 15 | 62 | 57 | 26 | 64 | 222 | 807 | 1065 | 1619 | 164 | 1492 | 5146 |
| NVD | 18 | 21 | 22 | 17 | 11 | 14 | 85 | 376 | 173 | 209 | 120 | 217 | 1094 |
| MU | 2 | 10 | 8 | 12 | 46 | 10 | 85 | 415 | 44 | 290 | 267 | 142 | 1156 |
| T | 1 | 7 | 70 | 16 | 84 | 22 | 199 | 26 | 238 | 100 | 578 | 190 | 1132 |
| WMT | 1 | 6 | 26 | 26 | 5 | 5 | 68 | 103 | 121 | 145 | 19 | 5 | 393 |
| PG | 1 | 5 | 11 | 5 | 5 | 9 | 35 | 201 | 100 | 30 | 105 | 60 | 496 |
| GLW | 2 | 19 | 77 | 28 | 18 | 13 | 154 | 4331 | 1932 | 615 | 357 | 188 | 7423 |
| AVG | 10 | 30 | 66 | 28 | 43 | 17 | 183 | 1389 | 1612 | 854 | 626 | 439 | 4920 |

*Notes: The first column titled "Root" lists the root ticker symbol for each stock. The second column titled "ND" denotes the number of days that we find an option series on the stock that satisfies our selection criteria. We also report the daily averages of the number of trades and trading volume for the selected option series under each and all ("All") of the five options exchanges. The last row reports the grand average across all selected option series.*

series, the ranking in terms of number of trades is from high to low—CBOE, PCX, AMEX, ISE, and PHLX. The ranking in terms of trading volume is CBOE, AMEX, ISE, PCX, and PHLX. The different rankings for the PCX under these two measures indicate that, on average, the trade size is smaller on the PCX than on the other exchanges.

### Quote and Trade Book Construction

We extract the quotes and trades on the selected option series. Our time precision is one second. We bundle trades that happen on the same exchange at the same second and transaction price. For quote updates, if we observe more than one quote update on a certain contract from a certain exchange within the same second, we pick the last one in the sequence of the electronic message. Then, we expand the quote updates into a second-by-second quote book. In this expanded book, quotes remain the same until the next update.

Using quotes from the five options exchanges, we also construct a series of national best bids and offers (NBBO). We define the national best bid as the maximum of the available bid quotes from the five options exchanges and the national best ask as the minimum of the available ask quotes from the five options exchanges. For each exchange, we also have a time-stamped series of transactions that include both the transaction price and the transaction size.

### Vector Error Correction Model and the Information Share

When different exchanges provide competitive quotes on the same security, these quotes are cointegrated because they are noisy representations of the same fundamental "true" value. Although each series of bid or ask quotes can be nonstationary, the differences between the quotes from different exchanges are stationary, representing temporary deviations from the long-run equilibrium relation. Engle and Granger [1987] propose a vector error correction model (VECM) that accommodates the cointegrating relation.

In our application, let $p_t = [p_{1t}, p_{2t}, \ldots, p_{nt}]^{\mathsf{T}}$ denote the vector on the logarithm of the quoted prices from different exchanges. We can then write the VECM of order $k$ as

$$\Delta p_t = A_1 \Delta p_{t-1} + A_2 \Delta p_{t-2} + \cdots + A_k \Delta p_{t-k} + \gamma(z_{t-1} - \mu_z) + u_t \quad (1)$$

where $\Delta p_t$ represents second-by-second price changes (log returns) and $z_t$ denotes the pair-wise difference between different quote series,

$$z_t = [p_{1t} - p_{2t}, p_{1t} - p_{3t}, \cdots, p_{1t} - p_{nt}]^{\mathsf{T}} \quad (2)$$

with $\mu_z$ denoting the mean difference. The last term $u_t$ represents the innovation vector with covariance matrix $\Omega$. The coefficients $A_i$, $i = 1, 2, \ldots, k$ are $(n \times n)$ square matrices that capture how previous price changes impact future price changes. The coefficient $\gamma$ is a $((n-1) \times 1)$ vector that corrects the forecasts based on how much the price level from one series deviates from the levels of other series. This error-correction term captures the idea that all price series converge to the same true value for the option contract.

Based on the VECM in Equation (1), Hasbrouck [1995] proposes an information share (*IS*) measure that defines the relative contribution of the different price series to the price discovery of the underlying true price. To define this measure, Hasbrouck assumes that the underlying true price follows a random walk and thus represents the permanent component of the price changes. By this assumption, any transient movements of the price series are regarded as temporary deviations from the underlying true value. The IS measure decomposes the variance of the permanent component into components attributable to each of the different price series. It measures how each price series contributes to the variation of the true price movements. A series with a higher information share is said to discover more of the underlying true price movement.

To compute the information share, we need to separate the permanent price movements from the transient movements and attribute the permanent movements to different price series. For this purpose, we write the moving average representation of the VECM as

$$\Delta p_t = B_0 u_t + B_1 u_{t-1} + B_2 u_{t-2} + \cdots, \; B_0 = I \quad (3)$$

where the price change on each series is represented as an aggregate response to all past innovation shocks. Given the parameter estimates on the VECM in Equation (1), we can calculate the moving average coefficients, $B_k$, by forecasting the system subsequent to a unit perturbation.

With the moving average representation, our primary interest is the cumulative impulse response function,

$$C_k = \sum_{i=0}^{k} B_k \tag{4}$$

The first column of the $C_k$ matrix describes the price responses of the $n$ series subsequent to a shock in the first price series, and so on. Each shock contains both a transient component, which we regard as the deviation from the true value, and a permanent component, which we regard as the movement of the true price. The transient component dies away as time passes while the permanent component remains. Thus, we can measure the response of the permanent component by taking the limit,

$$C = \lim_{k\to\infty} \sum_{i=0}^{k} B_k \tag{5}$$

In the limit, the rows of $C$ are identical because the permanent responses to one shock are the same for all price series. If we use $c$ to denote any row of $C$, the $i$th element of $c$ measures the contribution of shocks from the $i$th price series to the permanent component. Thus, the variance of the common permanent component is given by

$$\sigma_w^2 = c\Omega c^{\mathrm{T}} \tag{6}$$

If the covariance matrix $\Omega$ is diagonal, we can write the variance of the permanent component as

$$\sigma_w^2 = \sum_{i=1}^{n} c_i^2 \Omega_{ii} \tag{7}$$

where the contribution from each price series $i$ is given by $c_i^2\Omega_{ii}$. In this case, the information share of the $i$th series is defined as

$$IS_i = \frac{c_i^2 \Omega_{ii}}{\sigma_w^2} \tag{8}$$

which measures the proportion of the variance of the permanent component that is contributed by the $i$th series. The larger this proportion, the more the $i$th price series contributes to the price discovery of the permanent component.

When the covariance matrix $\Omega$ is not diagonal, shocks from different series interact with one another, and the information share is no longer uniquely defined. We compute the lower and upper bounds of the information share by considering the Cholesky factorization of all the rotations of the disturbances. Nevertheless, since we estimate the model at very high resolution (second-by-second), the off-diagonal terms of $\Omega$ are small. Hence, the lower and upper bounds are very close to each other.

In estimating the model, we pool the bids and asks from the five options exchanges and estimate the VECM in Equation (1) with $n = 10$. We specify a lag of ten minutes (600 seconds). To reduce the size of the parameter set, we apply polynomial distributed lags (Greene [1993]) over lags of 1–10, 11–20, and 21–30 (seconds), and then apply moving averages on lags of 31–60, 61–120, 121–300, and 301–600. To compute the impact of the permanent component in Equation (5), we let $k$ = 10,800 (three hours). When we experiment with different lags and different averages, the results are qualitatively similar. To compute the lower and upper bound of the information share for each options exchange, we rotate the matrix while holding fixed the bid–ask pair from each exchange. For robustness, we also estimate the VECM separately for the five bids and the five asks, and perform the information share analysis separately for bids and asks.

## Quote Spread and Executability

The magnitude of bid–ask spreads is a simple and direct measure of transaction cost when all transactions occur at the quotes. When trades do not always occur at the quotes, the bid–ask spread reveals the aggressiveness of a specific exchange in providing binding quotes. With the second-by-second quote book, we estimate the average spread between the ask and the bid quotes on each option series. Since market liquidity often varies across different times of day, we divide each day into half-hour periods and compute the average bid–ask spreads for each exchange for each half-hour period. Within each half hour, the average is a simple time average based on the second-by-second quote book.

To determine the executability of the quotes, we also match the quote book with the trade book for each exchange, and measure the proportion of times when a transaction happens inside, on, and outside the quote spread. If most trades occur exactly at the posted quotes, we say that the quotes are executable. If most trades occur inside the quote spread, the quotes are not really executable. This happens when an exchange avoids its market-making responsibility by providing wide bid–ask spreads but agreeing to execute trades at better prices. And there are probably matching errors due to report delays if a large proportion of transactions occur outside the quote spread.

## QUOTES AND TRADES IN THE STOCK OPTIONS MARKET

We compare the quoting behavior of the five options exchanges in terms of the information share, the quote spread, and the quote executability. We then trace the quoting behavior difference to the differences in microstructural designs and trading activities.

### The Information Share of the Options Quotes

We estimate the VECM each day for each selected option series. From the estimated model, we compute the lower and upper bounds of the information share for each options exchange. We first estimate the model using all ten series of the bids and asks from the five options exchanges. We also estimate the model using the five bid series alone and then using the five asks alone. The results from all three estimations are similar, showing the robustness of our findings. For expositional clarity, we base our discussion mainly on the estimation results of the ten-dimensional VECM. We then separately address the similarities and differences of the estimations from the five bid series and the five ask series.

Given an estimated VECM, the tightness of the lower and upper bounds on the information share depends on the off-diagonal terms of the covariance matrix $\Omega$. The bounds are tight when $\Omega$ is close to a diagonal matrix. Exhibit 2 reports the sample average of the estimates on the covariance matrix $\Omega$. For clarity, we separately report the correlation matrix $\rho$ and the standard deviation $\sigma$ of each innovation. The covariance is given by the product of the two: $\Omega_{ij} = \rho_{ij}\, \sigma_i \sigma_j$.

The correlation estimates are large between the bid and ask quotes from the same exchange, but the correlation estimates between quotes from different exchanges are small at 0.03 or less. Since our focus is on the aggregate information share from the bids and asks of each exchange, we only rotate the matrix across different exchanges. Hence, the large correlation within an exchange does not affect the spread between the lower

## EXHIBIT 2

**Average Estimates of the Innovation Correlation Matrix and Innovation Volatility**

| Exchange | Quote | AMEX | | CBOE | | ISE | | PCX | | PHLX | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ρ | | bid | ask | bid | ask | bid | ask | bid | ask | bid | ask |
| AMEX | bid | 1 | 0.61 | 0.03 | 0.02 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| | ask | 0.61 | 1 | 0.02 | 0.02 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| CBOE | bid | 0.03 | 0.02 | 1 | 0.48 | 0.01 | 0.01 | 0.03 | 0.02 | 0.01 | 0.01 |
| | ask | 0.02 | 0.02 | 0.48 | 1 | 0.01 | 0.01 | 0.02 | 0.02 | 0.01 | 0.01 |
| ISE | bid | 0.01 | 0.01 | 0.01 | 0.01 | 1 | 0.18 | 0.01 | 0.01 | 0.01 | 0.01 |
| | ask | 0.01 | 0.01 | 0.01 | 0.01 | 0.18 | 1 | 0.01 | 0.01 | 0.01 | 0.01 |
| PCX | bid | 0.01 | 0.01 | 0.03 | 0.02 | 0.01 | 0.01 | 1 | 0.53 | 0.01 | 0.01 |
| | ask | 0.01 | 0.01 | 0.02 | 0.02 | 0.01 | 0.01 | 0.53 | 1 | 0.00 | 0.01 |
| PHLX | bid | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.00 | 1 | 0.58 |
| | ask | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.58 | 1 |
| σ | | 0.36 | 0.36 | 0.45 | 0.45 | 0.48 | 0.47 | 0.43 | 0.45 | 0.37 | 0.37 |

*Notes: Entries report the sample average of the correlation matrix ($\rho$) and the standard deviation ($\sigma$) of the innovation on each of the ten quote series for the estimated VECM. The averages are over all the selected option series for the 20 business days in January 2002.*

and upper bounds of the information share estimates. The small correlation estimates between innovations from different exchanges dictate that the lower and upper bounds of the information share are very tight.

Exhibit 3 reports the summary statistics of the upper and lower bounds of the information share estimates for the ten quotes from the five options exchanges. Bids and asks from the ISE generate the highest average information share, regardless of whether the comparison is based on the lower or upper bound. The mean upper-bound estimate for the information share attributable to the ISE is 30%, 17.9% from bids and 12.1% from asks. The mean lower bound estimate is 27.2%, 16.2% from bids and 11% from asks.

Bids and asks from the CBOE generate the second highest average information share. The mean upper bound is 21.6%, 15.6% from bids and 6% from asks. The mean lower bound is 18.7%, 13.4% from bids and 5.3% from asks. Closely following the CBOE is the PCX, which has an average upper bound for the information share at 21.1% and an average lower bound at 18.6%. The AMEX is next at 18.5% for the upper bound and 16.3% for the lower bound. The least informational quotes are from the PHLX, with an average upper-bound estimate at 14.9% average lower-bound estimate at 13.4%.

The mean information share estimates reveal an interesting difference between the bids and asks from each exchange. For all five exchanges, the information share estimates from the bids are higher than that from the asks of the same exchange. For the AMEX, CBOE, and PCX, the information share estimates from bids are more than double the corresponding estimates from asks. The bid–ask information share difference suggests that market makers update their bid quotes differently from the way they update their ask quotes.

Exhibit 3 also shows that the standard deviations of the information share estimates are large. The large standard deviation estimates indicate that the information share estimates vary greatly across different days and different option series. The maximum and minimum estimates tell a similar story. The minima of the estimates are zero for all ten quotes, which indicates that for all the five exchanges, we have observed an option series on a day when the exchange contributes almost nothing to the information discovery, at least on one side of its quote.

To illustrate the dispersion of the information share estimates, we plot the histogram of the estimates in Exhibit 4, with the upper bounds in the left panel and

## EXHIBIT 3

**Information Share Estimates of Options Quotes from Different Exchanges**

and the

| Exchange | Quote | Upper Bounds | | | | Lower Bounds | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Mean | Std | Max | Min | Mean | Std | Max | Min |
| AMEX | bid | 0.126 | 0.121 | 0.633 | 0.000 | 0.110 | 0.114 | 0.632 | 0.000 |
| | ask | 0.059 | 0.083 | 0.580 | 0.000 | 0.053 | 0.079 | 0.578 | 0.000 |
| CBOE | bid | 0.156 | 0.121 | 0.560 | 0.000 | 0.134 | 0.114 | 0.524 | 0.000 |
| | ask | 0.060 | 0.079 | 0.513 | 0.000 | 0.053 | 0.074 | 0.496 | 0.000 |
| ISE | bid | 0.179 | 0.116 | 0.645 | 0.000 | 0.162 | 0.111 | 0.634 | 0.000 |
| | ask | 0.121 | 0.096 | 0.452 | 0.000 | 0.110 | 0.091 | 0.438 | 0.000 |
| PCX | bid | 0.146 | 0.131 | 0.699 | 0.000 | 0.127 | 0.121 | 0.678 | 0.000 |
| | ask | 0.066 | 0.087 | 0.474 | 0.000 | 0.060 | 0.084 | 0.473 | 0.000 |
| PHLX | bid | 0.089 | 0.105 | 0.608 | 0.000 | 0.079 | 0.099 | 0.607 | 0.000 |
| | ask | 0.060 | 0.092 | 0.656 | 0.000 | 0.055 | 0.090 | 0.655 | 0.000 |

*Notes: Entries report the summary statistics of the upper-bound and lower-bound estimates of the Hasbrouck information share. The information share statistics are computed based on a VECM of the ten bid and ask quote series from the five options exchanges. We estimate the models at each day for each of the selected option series during January 2002. "Mean" denotes the sample average, "Std" denotes the standard deviation, "Max" denotes the maximum, and "Min" denotes the minimum. For each exchange, the first row reports the information share attributable to the bid quotes and the second row reports the information share attributable to the ask quotes.*

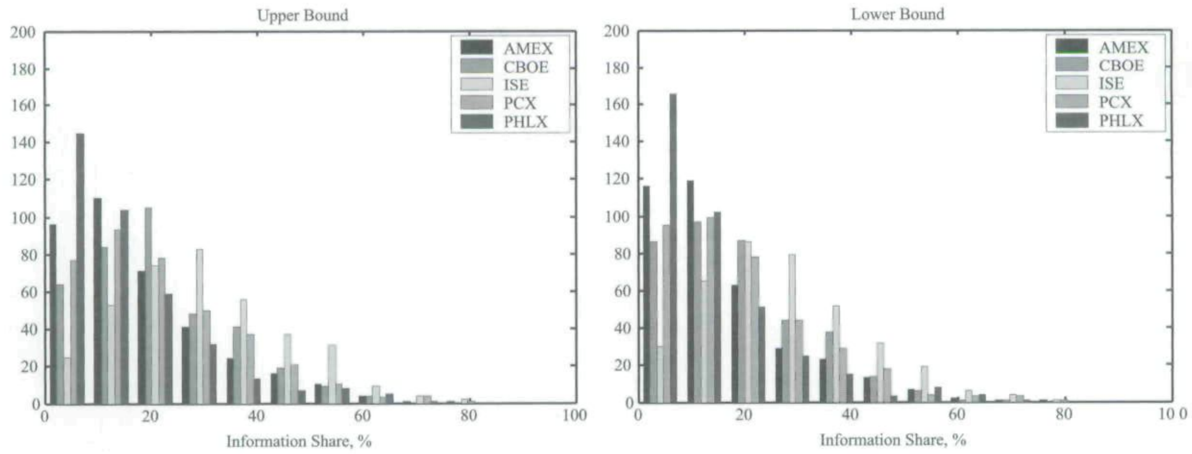
lower bounds in the right panel. To reduce graphic clustering, we aggregate the contribution of the bids and the asks from each exchange. The five bars in each group are, from left to right, the AMEX, CBOE, ISE, PCX, and PHLX.

The histograms on upper and lower bounds show similar patterns. At the low end of the information share estimates, the highest frequency is from the PHLX (the fifth bar), which is followed by the AMEX (the first bar). The lowest frequency comes from the ISE (the third bar). As we move to higher information share estimates, the ISE frequency bar rises. The ISE bar reaches its highest frequency around a 20%–30% information share, and becomes dominant in frequency at information share estimates higher than 20%. Therefore, despite the large dispersion of the estimates, the histogram clearly shows the relative ranking of the five exchanges in their respective contribution to the discovery of the permanent price component.

The ranking of the average information share estimates separates three major microstructure designs among the five exchanges. On top of the ranking is the ISE, where one PMM and several CMMs provide quotes independently and anonymously to compete internally for the order flow directed to the exchange. The second group includes the CBOE and the PCX, both of which trade options under a modified version of the open-outcry structure, where one DPL/LMM works with several market makers on the floor to provide the quotes and divide the order flow directed to the exchange. The least informative quotes come from the specialist system adopted at the AMEX and the PHLX, where one specialist provides the quotes. Comparing the information share ranking with the differences in the microstructure designs, we conclude that intra-exchange competition enhances the informativeness of the options quotes, and that quote source anonymity enhances this competition.

For robustness, we also re-estimate the VECM separating the five bid series and the five ask series. With a lower-dimensional system, the convergence speed of the estimation becomes much faster and the results also show more stability. Nevertheless, the findings are qualitatively the same. Exhibit 5 summarizes the average estimates of the correlation, standard deviation, and information share. The first panel shows that minimal cross-correlations exist among quotes from different exchanges. Hence, the lower- and upper-bound estimates of the information share are tight. The second panel shows that innovations from the ISE quotes are the most volatile as they have the largest standard deviation estimates. The standard deviation estimates are the lowest for quotes from the AMEX and the PHLX, with the estimates for the CBOE and the PCX in the middle. The ranking again separates the three different microstructure designs. The third and fourth panels show the same ranking for the information share estimates as we have found earlier, regardless of whether we estimate the model using bids or asks.

## EXHIBIT 4
**Information Share Histogram**




*Notes: We compute the information share each day on each chosen option series based on the estimates of the VECM of ten quote series from five option exchanges. For each option exchange, we report the aggregate contribution from bids and asks. Within each group, the five bars denote the five options exchanges—from left to right, the AMEX, CBOE, ISE, PCX, and PHLX.*

EXHIBIT 5

**Price Discovery Estimates from Bids alone and from Asks alone**

| Estimates | Bids | | | | | Asks | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | AMEX | CBOE | ISE | PCX | PHLX | AMEX | CBOE | ISE | PCX | PHLX |
| Correlation Matrix ρ | | | | | | | | | | |
| AMEX | 1 | 0.03 | 0.01 | 0.01 | 0.01 | 1 | 0.02 | 0.01 | 0.01 | 0.01 |
| CBOE | 0.03 | 1 | 0.01 | 0.03 | 0.01 | 0.02 | 1 | 0.01 | 0.02 | 0.01 |
| ISE | 0.01 | 0.01 | 1 | 0.01 | 0.01 | 0.01 | 0.01 | 1 | 0.01 | 0.01 |
| PCX | 0.01 | 0.03 | 0.01 | 1 | 0.01 | 0.01 | 0.02 | 0.01 | 1 | 0.01 |
| PHLX | 0.01 | 0.01 | 0.01 | 0.01 | 1 | 0.01 | 0.01 | 0.01 | 0.01 | 1 |
| Standard Deviation σ | | | | | | | | | | |
| | 0.36 | 0.45 | 0.48 | 0.44 | 0.37 | 0.36 | 0.45 | 0.47 | 0.45 | 0.37 |
| Information Share *IS*, Lower Bound | | | | | | | | | | |
| Mean | 0.17 | 0.20 | 0.26 | 0.19 | 0.13 | 0.17 | 0.18 | 0.30 | 0.17 | 0.13 |
| Std | 0.15 | 0.15 | 0.15 | 0.15 | 0.14 | 0.16 | 0.14 | 0.16 | 0.15 | 0.15 |
| Max | 0.78 | 0.77 | 0.85 | 0.86 | 0.80 | 0.87 | 0.70 | 0.86 | 0.83 | 1.00 |
| Min | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Information share *IS*, Upper Bound | | | | | | | | | | |
| Mean | 0.19 | 0.23 | 0.29 | 0.21 | 0.14 | 0.18 | 0.20 | 0.33 | 0.19 | 0.14 |
| Std | 0.16 | 0.16 | 0.16 | 0.16 | 0.14 | 0.16 | 0.15 | 0.17 | 0.16 | 0.15 |
| Max | 0.78 | 0.80 | 0.86 | 0.87 | 0.82 | 0.87 | 0.71 | 0.87 | 0.83 | 1.00 |
| Min | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

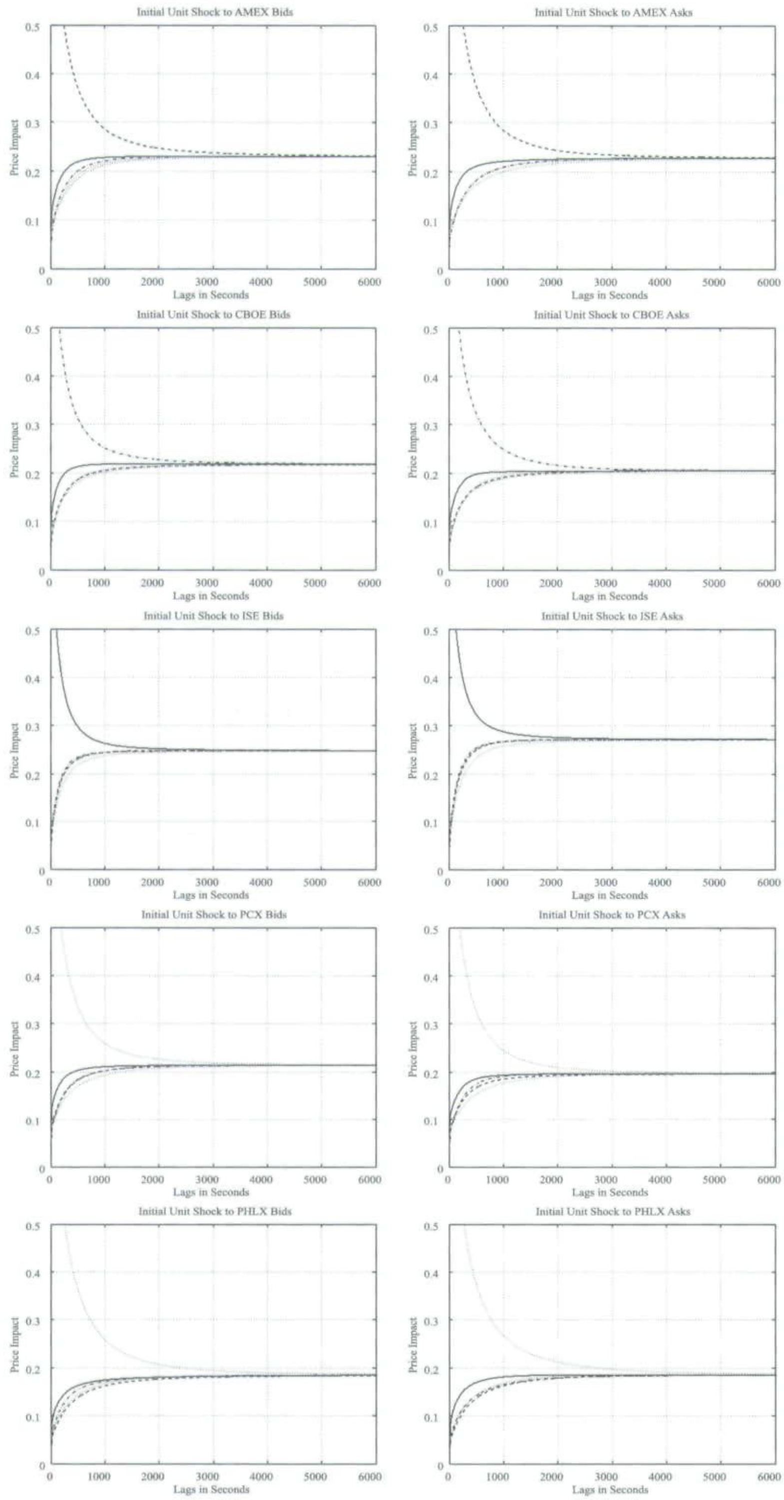
*Notes: Entries report the price discovery results based on the five bid series alone from the five options exchanges in the columns under "Bids" and from the five ask series alone in the columns under "Asks." The first two panels report the sample average of the correlation matrix (ρ) and the standard deviation (σ) of the innovation on each of the five series in the estimated VECM. The third and fourth panels report the summary statistics (mean, standard deviation, maximum, minimum) of the upper-bound and lower-bound estimates of the Hasbrouck information share.*

## The Impulse Response Function of the VECM

Also informative is the cumulative impulse response function ($C_k$) defined in Equation (4), which measures the response of each series to a unit shock from a certain series $k$ periods ago. Based on the estimates of the more stable five-dimensional VECMs, Exhibit 6 plots the impulse responses as a function of time lags, $k$, with panels on the left side estimated from the bids and panels on the right side estimated from the asks. At each time lag $k$, the response $C_k$ is a $(5 \times 5)$ matrix. Each column of the matrix captures the responses of the five series to a unit shock from one series. In Exhibit 6, each panel plots the elements of each column of the response matrix and thus captures the response to one source of shocks. The sources of the shocks are, from the top to bottom panels, the AMEX, CBOE, ISE, PCX, and PHLX, respectively. Within each panel, the five lines denote the responses of the five exchanges to a common source of shock. Since we estimate the model separately on different option series at different dates, the lines represent the sample averages of the estimates from all chosen option series across the 20 business days in January 2002.

By construction, at $k = 0$, the impact is unity on one exchange (where the shock occurs) and zero on the other exchanges. In the long run, the impacts of each shock are identical for all exchanges. Thus, the five lines in each

## EXHIBIT 6
**Cumulative Impulse Response Function**




*Notes: We compute the cumulative price impacts based on the estimates of the five-dimensional VECM. We estimate the models daily for each option contract with one-second resolution. The plots are grand averages across all chosen option series over the 20 business days in January 2002. The five options exchanges are represented by dashed lines (AMEX), dash-dotted lines (CBOE), solid lines (ISE), and dotted lines (PCX and PHLX).*

panel converge to the same level as $k$ increases. This convergence is a consequence of cointegration. Exhibit 6 shows that the convergence speed and level differ for different options exchanges. The behavior of the ISE quotes is the most prominent. For a unit shock from the other exchanges, the ISE quotes (the solid line in all panels) respond the fastest and converge to the stationary state the earliest. When the unit shock is on the ISE quotes (the two panels in the third row), it has a larger permanent impact on the market than do unit shocks from other exchanges. Unit shocks on the bid quotes from the ISE, AMEX, CBOE, PCX, and PHLX generate permanent impacts of 24.8%, 23.1%, 21.8%, 21.4%, and 18.5%, respectively. Unit shocks on the ask quotes from the ISE, AMEX, CBOE, PCX, and PHLX lead to permanent impacts of 27.2%, 22.8%, 20.5%, 19.7%, and 18.5%, respectively.

With the correlation estimates between shocks from different exchanges close to zero, the ranking of the information share is determined by the product of the permanent impact percentages and the corresponding innovation variance estimates, which are reported in the second panel of Exhibit 5. Quote updates from the ISE not only have the largest permanent impact per unit movement ($c$), but also have the largest total variance ($\sigma$). Therefore, ISE quotes contribute the most to the price discovery of the permanent component. Quote updates from the AMEX generate larger permanent impacts per unit movement than do quote updates from the CBOE and the PCX. Nevertheless, quotes from the AMEX do not vary as much, and as a result, the average information share estimates for the AMEX are lower than the estimates for the CBOE and the PCX. Intuitively, these results suggest that quote updates from the AMEX contain a large proportion of permanent movements, but the AMEX does not update its quotes as aggressively as the CBOE and the PCX.

### Linking the Information Share Difference to Market Shares and Trading Activities

All the selected option series trade at least five times per day on each of the five exchanges; nevertheless, both the aggregate trading activity and the relative market share of each exchange vary significantly across different stock issues and also across different option series (Exhibit 1). In this section, we investigate how the information share difference across different exchanges relates to the aggregate and relative trading activities on each option series.

Since quotes from the ISE generate, on average, the highest information share estimates, we use the information share estimates on the ISE as the benchmark, and define the average information share difference between the ISE and the other four exchanges as

$$\bar{\mathcal{L}} = \frac{1}{4}\sum_{i=1}^{4}\mathcal{L}_i = \frac{1}{4}\sum_{i=1}^{4}(IS_{ISE} - IS_i), \quad i = AMEX, CBOE, PCX, PHLX \tag{9}$$

We study whether the average information share difference on each option series is related to the relative and aggregate trading activities of the option series. We consider four trading activity measures on each option series: 1) ISE market share in number of trades, 2) ISE market share in cumulative trading volume, 3) the logarithm of the total daily number of trades, and 4) the logarithm of the total daily trading volume on the option series. Exhibit 7 reports the correlation estimates (and $p$-values in parentheses) between the average information share difference $\bar{\mathcal{L}}$ and the four trading activity measures.

When the trading activities of a certain contract concentrate on one exchange, we expect that this exchange has stronger incentives to keep its quotes updated and to lead in price discovery. From another perspective, the trading of a certain contract is concentrated at one exchange possibly because that exchange provides the most informative quotes. Both arguments imply a positive correlation between market share in trading activities and the information share. However, the correlation estimates do not support these arguments. The correlation estimate between the average information share difference and ISE market share in number of trades is 0.03 which is not significantly different from zero. The correlation with the market share in terms of trading volume is not distinguishable from zero.

Aggregate trading activities on an option series can also affect the quoting behavior on that option series. When an option series is very active and generates large order flow, the five exchanges have stronger incentives to compete and provide the best quotes on this contract to attract order flow. The incentive for an inactive contract is smaller since the total order flow on that contract is small. Therefore, stronger competition in the more actively traded option series can reveal more vividly the

## EXHIBIT 7

**Correlations Between Information Share Differences and Relative and Aggregate Trading Activities**

| | Market Share of ISE | | | | Aggregate Trading Activity | | | |
|---|---|---|---|---|---|---|---|---|
| | Number of Trades | | Trading Volume | | Number of Trades | | Trading Volume | |
| Lower Bound | 0.03 | ( 0.55 ) | 0.00 | ( 0.94 ) | 0.16 | ( 0.00 ) | 0.14 | ( 0.01 ) |
| Upper Bound | 0.03 | ( 0.59 ) | 0.00 | ( 0.97 ) | 0.17 | ( 0.00 ) | 0.15 | ( 0.00 ) |

*Notes: Entries report the correlation estimates between four trading activity measures on each option series and the average information share difference between the ISE and the other four options exchanges. We also report the p-values of the correlation estimates in parentheses. A small p-value indicates that the correlation estimate is significantly different from zero.*

microstructural differences of different exchanges. To test this conjecture, we also estimate the correlation between the ISE's average price difference from the other exchanges and the options' aggregate trading activity. The correlation estimates are between 0.14 and 0.17. The $p$-values (in parentheses) show that the correlation estimates are highly significant.

The results in Exhibit 7 suggest that the ISE's lead in price discovery is stronger on the more actively traded option series. If more actively traded option series lead to stronger competition and stronger competition reveals the structural differences of different exchanges more clearly, then the results in Exhibit 7 indicate that the ISE's lead in price discovery is due to its difference in microstructural design, not due to other factors such as historical client relations. It is highly unlikely that the ISE's lead would be due to historical client relations because the ISE has only been operating for a short time and therefore has less of a traditional client base.

### Quote Spreads

The information share estimates reveal how much quotes from each exchange contribute to the permanent component of price movements. Nevertheless, an informative quote does not necessarily lead to a transaction if the bid–ask spread is wide. The magnitude of the bid–ask spread is a simple and direct measure of transaction cost when transactions occur at the quote. When trades do not always occur at the quote, the bid–ask spread reveals the aggressiveness of an exchange in providing binding quotes.

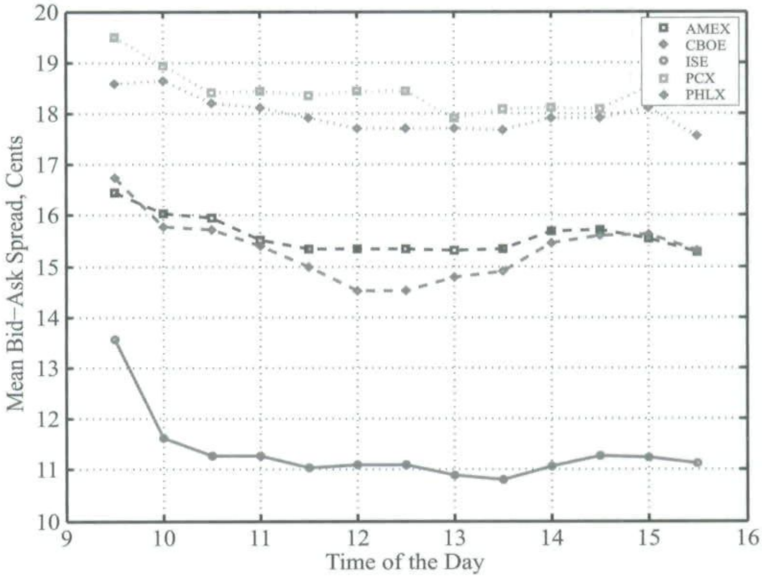
Exhibit 8 plots the average bid–ask spreads for quotes from the five options exchanges across different half-hour intervals of the day. The average is on all the selected option series during the 20 business days in January 2002. The average bid–ask spreads from the five options exchanges fall into three groups. Quotes from the ISE (the solid line) have the narrowest average spread at about 11 cents. Quotes from the CBOE and the AMEX (the two dashed lines) rank second with an average spread of about 15 cents. Quotes from the two smaller exchanges (the PCX and PHLX, the two dotted lines) show the widest average spread at around 18 cents.

From all exchanges, we also observe wider mean bid–ask spreads in the morning when the market has just opened. The spread declines as trades proceed, flattening out by noon. Similar intraday patterns have been documented for stocks in, e.g., Brock and Kleidon [1992]; Chan, Christie, and Schultz [1995]; Lee, Mucklow, and Ready [1993], and McInish and Wood [1992]. The information story in Easley and O'Hara [1992] predicts such intraday patterns.

We can trace the narrower bid–ask spread of the ISE quotes to its distinct microstructural design. Quotes from the ISE are consolidated quotes from multiple market makers, but quotes from the four floor-based exchange are mostly dominated by one market maker. Many times, the specialists on the four floor-based exchanges are also competitive market makers on the ISE. Therefore, if the specialist provides the same quotes to both exchanges, the consolidated quotes from the ISE will dominate the single-source quote from the other four exchanges. If the specialist provides different quotes to different exchanges, empirical evidence (Simaan, Weaver, and Whitcomb [2003]) shows that a specialist is likely to provide more aggressive quotes when his or her identity is not known to the public. The specialist's identity is public informa-

# EXHIBIT 8

**Mean Bid–Ask Spreads for Quotes from the Five Options Exchanges**




*Notes: This exhibit shows the average bid–ask spreads for quotes from the five options exchanges at half-hour intervals. The five options exchanges are represented by square-dashed line (AMEX), diamond-dashed line (CBOE), circle-solid line (ISE), square-dotted line (PCX), and diamond-dotted line (PHLX).*

tion on the four floor-based exchanges, but at the ISE market makers and customers only observe the consolidated quote book, not the source underlying each quote. Both arguments imply that the ISE should generate narrower quotes than the other four exchanges.

The quote-spread ranking of the four floor-based exchanges shows that historical market share of options trading activities can also play a role in the average spread. Market makers at the two larger exchanges (AMEX and CBOE) receive a larger proportion of order flow and thus have a stronger incentive to provide binding quotes at all times. But when the order flow becomes small, market makers at the two smaller exchanges (PCX and PHLX) may simply stay out of the market by posting wider bid–ask spreads.

## Quote Executability

By matching the quote book with the trade book, we also analyze the executability of the quotes from each exchange. If transactions often occur outside the quote, either the quote is not firm or trades are reported with a delay. If transactions often occur inside the quoted spread at an exchange, either the exchange is giving preferential treatment to a certain group of clients, or it is posting noncompetitive quotes but agreeing to execute trades at a better price than the posted spreads. Therefore, comparing the percentage of trades inside and outside the quoted spread provides important information on the executability of the quote.

We compute the percentage of the transactions at an exchange that occur on, inside, or outside the bid–ask quotes. Panel A in Exhibit 9 summarizes the results. Transactions at the ISE have the highest percentage (83.99%) of executions exactly on the bid or ask. The next best is the AMEX, which has 57.1% of its transactions executed at its bid or ask. The percentage drops to 40.09% for the CBOE, 39.2% for the PCX, and 35.99% for the PHLX.

Transactions executed outside the bid–ask range are very rare across all exchanges. However, a significant proportion of the trades are executed inside the quoted spread. This percentage is 13.86% for the ISE, 38.19% for the AMEX, and over 50% for the other three exchanges. When we further compare the inside trades with the NBBO in Panel B of Exhibit 9, we find that most of these inside trades happen at the NBBO. The percentage ranges from 65.53% for the ISE to 81.45% for the PCX.

Currently, the SEC implements a no trade-through rule on the options exchanges. Under this rule, all transactions should happen at the NBBO, regardless of the

## EXHIBIT 9

**Percentage of Trades Outside (On, Inside) the Bid-Ask Quote**

| Exchanges | AMEX | CBOE | ISE | PCX | PHLX |
|---|---|---|---|---|---|
| *A. Percentages Out Of Total Trades* | | | | | |
| Outside BA | 3.74 | 4.36 | 1.95 | 2.72 | 4.07 |
| On BA | 57.10 | 40.09 | 83.99 | 39.20 | 35.99 |
| Inside BA | 38.19 | 55.28 | 13.86 | 57.18 | 58.99 |
| *B. Percentages Out Of Inside Trades* | | | | | |
| Outside NBBO | 8.02 | 10.49 | 10.56 | 7.89 | 7.95 |
| On NBBO | 77.43 | 74.37 | 65.53 | 81.45 | 79.11 |
| Inside NBBO | 14.55 | 15.14 | 23.91 | 10.67 | 12.94 |

*Notes: Entries in Panel A report the percentage of trades at each exchange that are outside, on, and inside that exchange's bid–ask quote range. For trades that are inside the quote range, Panel B reports the percentage that are outside, on, and inside the national best bid and offer (NBBO). We average the estimates across all trades on the selected option series during January of 2002 at each options exchange.*

quotes at each exchange. Thus, exchanges with the most quotes at the NBBO will also see the largest percentage of transactions executed at exactly the ask or bid, whereas exchanges with quotes that stay mostly outside of the NBBO will see a large proportion of their transactions executed inside the quote. At the time of our study, this rule was not yet implemented. Nevertheless, our results suggest that most exchanges offer to execute trades at or close to the NBBO as a way of attracting order flow.[3] For example, the PCX programmed an *automatic step-up* feature into its automatic execution system for small customer orders. An LMM at the PCX is able to customize his aggressivesness based on the NBBO and the size of the order. There are six different settings that range from fully automatic NBBO execution, to one tick step up, and to no step up.

## RECENT DEVELOPMENTS IN THE STOCK OPTIONS MARKET

Our analysis shows that the microstructure design at the ISE generates options quotes that are the most informative, the most binding, and also the most executable. Over time, this quoting quality has attracted order flow to the ISE. By mid-2003, the ISE had seized the largest market share in the trading volume of individual stock options in the U.S.

The success of the new options exchange shows that technology innovations and careful market microstructure designs not only improve the efficiency of market making, but also generate significant economic gains for the innovator. Stimulated by the ISE's success, other exchanges have also been actively pursuing technology innovation and structural reform. A popular reform is to create an automated trading system that supplements traditional floor-based trading. An automated system electronically aggregates quotes from many market makers and thus enhances intra-exchange competition. For example, the CBOE launched an automated trading platform called CBOEdirect® in 2001. In 2003, the CBOE debuted its Hybrid Trading System that integrates the traditional open-outcry trading with automated trading. On October 6, 2003, the PCX launched a new trading platform, PCX Plus. Similar to the ISE platform, the PCX Plus trading engine aggregates quotes from potentially hundreds of market makers. Furthermore, new trading rules and trade allocation parameters for PCX Plus reward aggressive quoting and size, thereby encouraging price improvement and execution depth.

On February 6, 2004, yet another exchange, the Boston Options Exchange (BOX), started its first day of trading equity options. The BOX and the ISE are similar in that they are both fully electronic and are both registered exchanges without a trading floor. Their microstructure designs are also similar: They share the idea of electronically aggregating quotes from many market makers to enhance competition. While there are many subtle differences between the two exchanges, the key difference is how their methodologies govern the priority of orders and quotes on their order books. The ISE prioritizes customer orders ahead of broker-dealer, proprietary, and market maker orders. In contrast, the BOX does not differentiate order priority on the basis of order category. On the ISE and the four floor-based exchanges, customer orders joining the bid or offer only go behind other customer orders at the same price, based on time priority. On the BOX, all orders trade in pure price-time priority, regardless of order category.

Technology innovation and microstructure overhaul require heavy capital investment, which has stimulated consolidation in the options exchanges. In 2005, the Archipelago Exchange (ArcaEx) acquired the PCX in order to lever its technology and expertise in automated equity trading for use in the options market. In March 2006, the New York Stock Exchange (NYSE) merged with ArcaEx to form the NYSE Group. In October, the NYSE Group launched its options trading platform. In April 2007, the NYSE Group merged with Euronext to form NYSE Euronext. In the same month, the ISE entered into a merger agreement with the European futures and options exchange (Eurex), which is owned by Deutsche Börse and the Swiss Exchange. Meanwhile, the ISE has also expanded its business into stock trading through a new stock exchange platform.

These consolidation activities reveal two trends in derivatives trading. First, the global consolidation makes 24-hour trading a virtual certainty in many derivative products. Second, integration of derivatives market making with market making in the underlying security will prove to be a persistent trend. The integration facilitates the hedging of derivatives positions for options market makers. Due to the multitude of options contracts for each underlying security and the relatively low options trading activities, options market makers often need to hold overnight positions. Therefore, it is important for derivatives market makers to manage their risk exposure by managing their derivatives inventories and by hedging with the underlying security. An integrated market can potentially reduce the hedging costs of the market makers and allow them to be more aggressive in making the options market.

## CONCLUSION

In the U.S., multiple exchanges with distinct market microstructure designs compete to provide quotes and attract order flow on a common set of stock options. We find that the fully electronic exchange system at the International Securities Exchange, where several market makers provide quotes independently and anonymously to compete for order flow within the exchange, generates options quotes that are the most informative, the most executable, and have the narrowest bid–ask spreads. Over time, its leading quote quality has attracted order flow to the exchange, moving the exchange quickly from a new start-up company to the top market-share holder in options trading activities on individual stocks. Its rapid rise in market shares highlights the economic benefits of technology innovation and careful market microstructure design, and has spurred a new wave of technology innovation and structural reforms among both old and new options exchanges.

## ENDNOTES

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[1]At the time of our study, the ISE divided stock issues into ten bins and allowed up to 16 CMMs in each bin. Later, as the list of stock issues expanded for options trading, the ISE started a second market with additional bins for less actively traded options. For each bin in the second market, there is still one PMM, but the number of CMMs is no longer limited.

[2]SEC Release No. 34-43621; release date: November 27, 2000.

[3]Orders can also be executed inside the NBBO when limit orders from the EAMs go inside of the quoted spreads to meet the market orders.

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