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Volume 94, Issue 2, November 2009
ISSN 0304-405X
JOURNAL OF
Financial
ECONOMICS
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Published by ELSEVIER
in collaboration with the
WILLIAM E. SIMON GRADUATE SCHOOL
OF BUSINESS ADMINISTRATION,
UNIVERSITY OF ROCHESTER
Available online at www.sciencedirect.com
ScienceDirect

Journal of Financial Economics 94 (2009) 171–191

Contents lists available at ScienceDirect

Journal of Financial Economics

journal homepage: www.elsevier.com/locate/jfec

Option markets and implied volatility: Past versus present ☆

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ARTICLE INFO

Article history:
Received 5 May 2008
Received in revised form
5 August 2008
Accepted 9 September 2008
Available online 16 July 2009

JEL classification:
G13

Keywords:
Options
Implied volatility

ABSTRACT

Traders in the nineteenth century appear to have priced options the same way that twenty-first-century traders price options. Empirical regularities relating implied volatility to realized volatility, stock prices, and other implied volatilities (including the volatility skew) are qualitatively the same in both eras. Modern pricing models and centralized exchanges have not fundamentally altered pricing behavior, but they have generated increased trading volume and a much closer conformity in the level of observed and model prices. The major change in pricing is the sharp decline in implied volatility relative to realized volatility, evident immediately upon the opening of the CBOE.

1. Introduction

Option markets existed long before option pricing models. For centuries prior to the development of the Black-Scholes model, option buyers and sellers negotiated prices at which voluntary trade occurred. Did modern, centralized exchanges and formal pricing models fundamentally change the way options are priced? Which is more important in explaining the success of modern equity option markets, sophisticated mathematical models or centralized exchanges?

This paper addresses these questions by comparing implied volatility derived from equity option prices from the nineteenth and twenty-first centuries. I identify seven empirical regularities concerning implied volatility from individual equity options in modern markets, and I ask if these stylized facts exist in the over-the-counter option markets from the 1870s. I find that the same empirical regularities emerge during both periods and conclude that option markets during these two eras, despite all the nominal differences, behave fundamentally the same.

A goal of this paper is to evaluate the relative importance of economic models and financial institutions to economic behavior. Black and Scholes published their landmark option pricing paper in 1973, and the first centralized equity option exchange opened its doors the same year. As shown in Fig. 1, option trading immediately exploded. How much credit should go to the liquidity available on an organized exchange, and how much credit should go to the existence of a no-arbitrage model for pricing and hedging? The analysis in this paper suggests that the regime shift in option trading activity did not correspond to a regime shift in all aspects of option pricing. Introduction of the model formalized and refined the valuation and hedging processes that option traders were already pursuing. I conclude that the introduction of option exchanges was a direct cause of activity in options, while advances in option modeling played a key supporting role.

The paper is related to work by MacKenzie and Millo (2003), who describe the evolution of modern option exchanges. They explore how the Black-Scholes model legitimized options and provided a necessary foundation

☆ I thank Gerald Dwyer, Paul Harrison, Serguey Khovanskiy, Donald MacKenzie, Carl Mason, and Eugene White (the referee) for providing comments that substantially improved the paper. This paper reflects the opinions of the author and not those of Société Générale.

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0304-405X/$ - see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.jfineco.2008.09.010

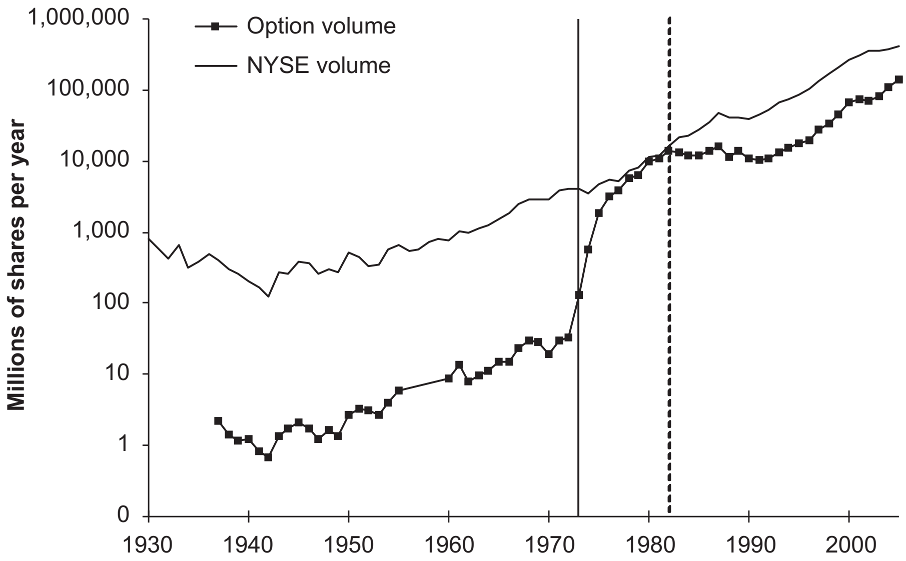

Fig. 1. Annual stock and single-stock option trading activity, 1930–2005. The figure shows the number of shares traded annually on the New York Stock Exchange and the shares of stock represented by equity options traded annually. The solid vertical line marks 1973, the year that CBOE opened. The dashed vertical line marks 1983, the year that equity index options began trading. Data are from Gastineau (1988), Kruizenga (1956), Malkiel and Quandt (1969), the New York Stock Exchange, and Options Clearing Corporation.

for the dramatic success of derivatives markets. They conclude that the model is a prime example of the way in which economics is "performative," meaning the way in which economic research can shape the markets that it describes. Similarly, Ritter (1996) and Thomas (2002) elaborate on a particular advance in derivatives modeling that changed financial market behavior. In this paper, I examine empirically how option pricing behavior changed (or did not change) over time and interpret the results in light of the performativity concept. Some sharp changes in pricing behavior can be discerned; in particular, implied volatility far exceeded realized volatility in the nineteenth century, but this gap has since decreased significantly. I present evidence that implied volatility conformed much more closely to realized volatility as soon as trading began on the CBOE. I conclude that the opening of the exchange was the major driver in the shift in option prices toward levels more consistent with the Black-Scholes model.

In terms of specific results, the first contribution of this paper is to show that empirical regularities regarding implied volatility are qualitatively the same in the nineteenth and twenty-first centuries. In both eras, implied volatility typically exceeded realized volatility, was substantially serially correlated, featured significant comovement among stocks, and was higher for stocks with relatively high realized volatility. An implied volatility skew is present and displays significant common movement in both eras. The empirical regularities and pricing behavior are clearly not a function of modern theoretical advances (see Figs. 2 and 3).

The second contribution is to quantify specific ways in which the pricing behavior of the equity option market has changed over time. For example, implied volatility is more responsive to realized volatility shocks and tends to move more closely together in modern markets. A more striking finding is the magnitude of the decline in implied volatility. Consider a one-month option on a stock with an annualized volatility of 30%. Using a common factor model, I estimate that the equilibrium at-the-money implied volatility for such a stock has fallen from 54% in the nineteenth-century OTC market to 36% on a modern exchange.

The paper is organized in the following manner. The first section describes the testable hypotheses and the related empirical literature. The second section provides relevant background for the institutional structure of the equity option market in both the historical and modern eras. The third section describes construction of the implied volatility used in the analysis. Section 4 presents the main empirical analysis. Section 5 focuses on quantifying the gap between implied and realized volatility and explaining how it has changed over time. The final section provides concluding commentary. The appendix provides evidence on the accuracy of the implied volatility interpolation procedure used on the 1870s data.

2. Testable hypotheses and related literature

The seven empirical regularities I examine are formulated as testable hypotheses H1–H7. They are:

H1. At-the-money (ATM) implied volatility tends to exceed realized volatility.
H2. The cross-section of implied volatility matches the cross-section of realized volatility.
H3. In the time series, implied volatility is systematically related to realized volatility.
H4. Implied volatilities are substantially serially correlated.
H5. Changes in ATM implied volatility are positively correlated across stocks.

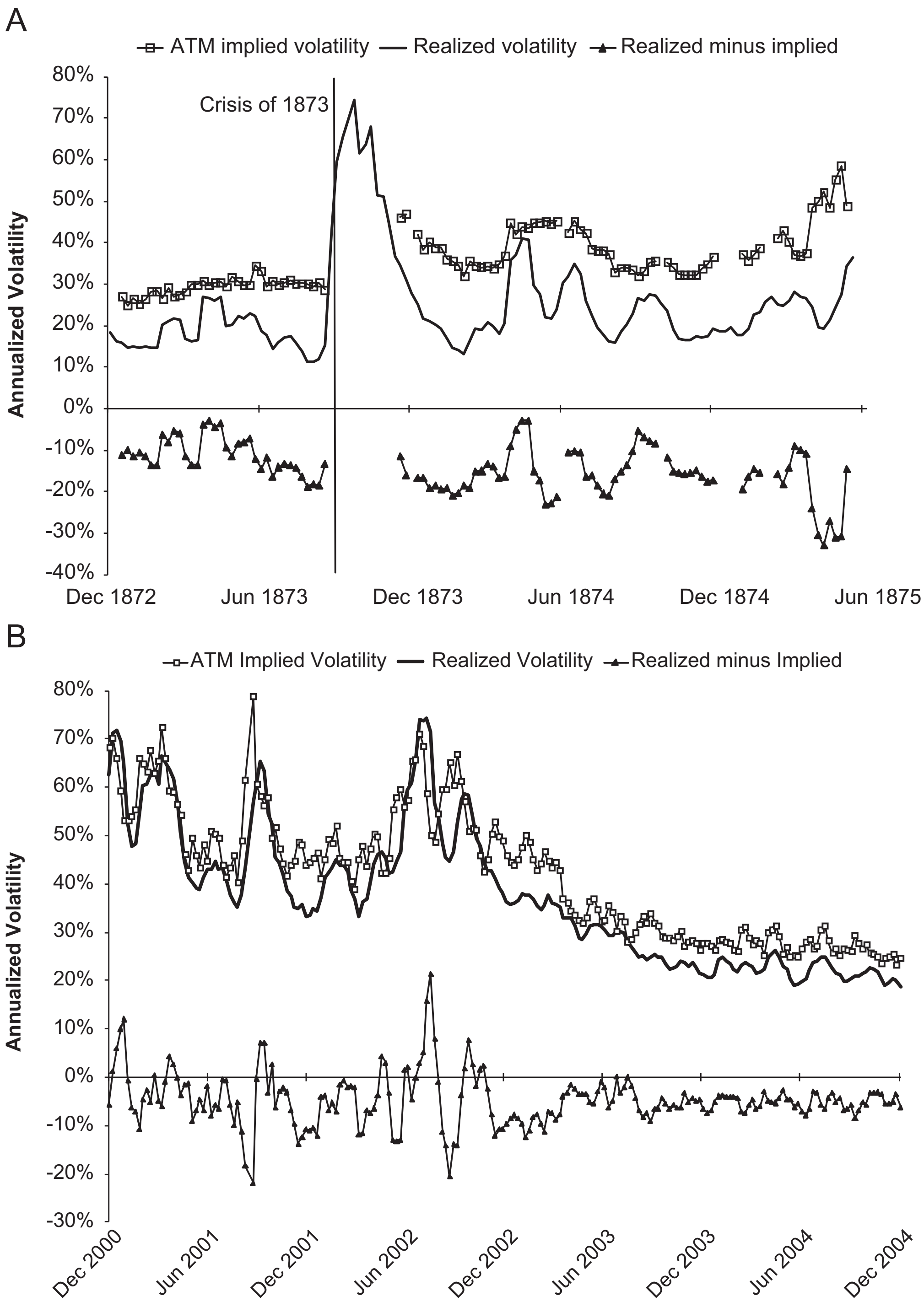

Fig. 2. Implied and realized volatility. The figure shows at-the-money (50 delta) implied volatility and trailing one-month realized volatility, averaged cross-sectionally at each date. Panel A displays data from January 1873 to June 1875. Panel B displays data from January 2001 to December 2004.

H6. Changes in implied volatility are negatively correlated with changes in the price of the underlying stock.
H7. Changes in implied volatility skew are positively correlated across stocks.

These empirical regularities are well known to derivatives researchers, and most have been repeatedly documented in modern samples. Black and Scholes (1972) provide early evidence supporting H1 and H2. Chiras and Manaster (1978) show the validity of H2. Schmalensee and Trippi (1978) and Sheikh (1993) support H3–H6. Latané and Rendleman (1976) and Merville and Pieptea (1989) provide evidence that H5 is true. Related to H7, Rubinstein (1985) concludes that the slope of the volatility skew tends to be the same across stocks at any point in time, but that the skew has changed sign over time. Bakshi, Kapadia, and Madan (2003) find evidence for comovement in implied volatility skews of individual stocks, also suggesting H7.

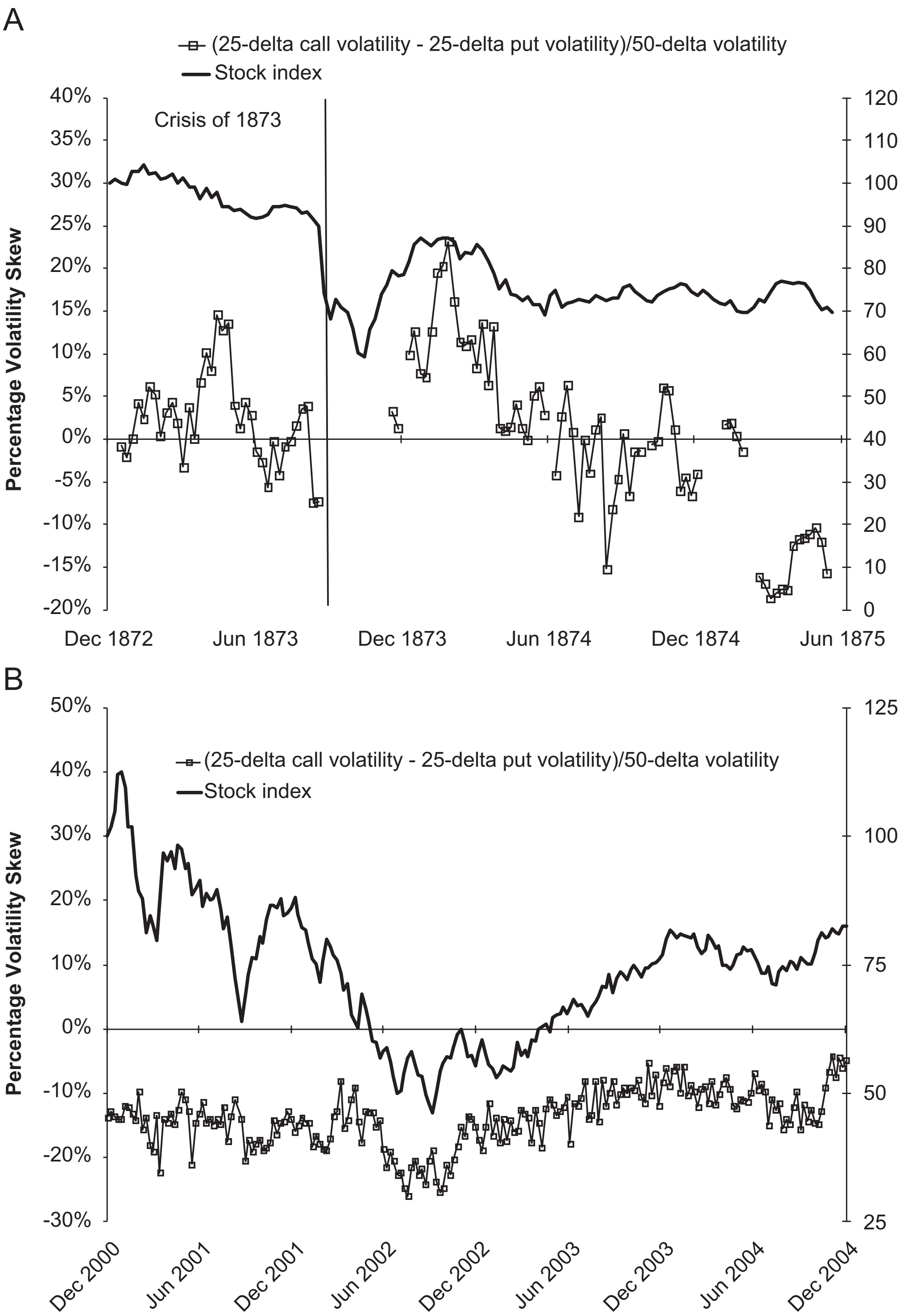

Fig. 3. Implied volatility percentage skew and stock index. The figure shows implied volatility percentage skew, averaged cross-sectionally at each date. Percentage skew for each stock is computed as the 25-delta call implied volatility minus the 25-delta put implied volatility, divided by the 50-delta volatility. The figure also displays an equally weighted index of stock prices for the stocks used in the analysis. Panel A displays data from January 1873 to June 1875. Panel B displays data from January 2001 to December 2004.

Recent research has sought to refine the early empirical work and to provide economic explanations for the observed pricing behavior. For example, Bakshi and Kapadia (2003) conclude that H1 is consistent with a priced market-volatility risk premium in individual equity options. Stivers, Dennis, and Mayhew (2006) suggest that H6 more strongly reflects a top-down volatility feedback effect than a bottom-up leverage effect.

Kairys and Valerio (1997) also study equity option data from the 1870s and conclude that options were expensive relative to a modern theoretical model. However, the results are not benchmarked against results from modern data, even though modern-day options often appear similarly overpriced by this metric. Further, the analysis is cast in terms of prices, even though option prices are often standardized into implied volatility for ease of comparison.

With respect to methodology, this paper is related to the work of Harrison (1998) and Mauro, Sussman, and Yafeh (2002). Harrison explores the similarities between statistical properties of stock price changes during the eighteenth and twentieth centuries and concludes that equity market behavior has changed relatively little over the centuries. Mauro, Sussman, and Yafeh find that emerging-market bond yields move together far more in the 1992–2000 period than during the 1870–1913 period.

3. The option market: then and now

An active, over-the-counter option market existed during the latter part of the nineteenth century. The structure of the market was well defined. Wealthy individuals such as Russell Sage sold blocks of puts and calls to brokers who resold them to small speculators. This arrangement reduced counterparty credit risk, because small speculators with unknown credit were allowed to purchase, but not sell, options and were required to pay for them in advance. The options were known as "privileges" because the purchaser of a call on a stock, for example, had the privilege of calling for the stock at the strike price, or not calling for it, at his option.

Writing in 1846, a journalist stated that option trading was practiced regularly in Paris, but that it was not as common in the United States. The author was nonetheless familiar with options, describing a trade involving the purchase of a call and the simultaneous sale of one-half the notional value of the underlying—initiating a very modern, delta-neutral, long-gamma position to benefit from large moves of the underlying in either direction, while remaining neutral to small price changes.[1] Medbery (1870) provides a detailed discussion of institutional arrangements by which stocks, gold, and privileges on both were traded, suggesting that they were common instruments by that time.

Despite the activity in the market, option trading was generally considered socially undesirable. The Illinois legislature in 1874 made it illegal to write option contracts on commodities, gold, or stock.[2] Other legislatures followed in the 1880s and 1890s with variations against option trading and futures trading, often spurred by the idea that commodity speculation could be blamed for the woes of farm interests. Emery (1896, pp. 197–199) documents legislation in Arkansas, California, Georgia, Iowa, Michigan, Mississippi, Missouri, Ohio, South Carolina, Tennessee, and Texas. In an editorial advising people not to speculate, the *New York Times* neatly summarizes a widespread view: "As for bucket-shops, puts, calls, straddles, options, double privileges, and the friendly persons who insert advertisements beginning ...'thousands are making fortunes in Wall-street,' whether to deal with them depends on whether you have any money you do not want."[3] The editorial reflects a common practice of lumping options, bucket shops, and financial scams into one list of unwholesome practices. Indeed, in some cases, these activities were indistinguishable.

Exchanges repeatedly banned option trading from their premises to deflect criticism of gambling away from their main trading activities. As an example, consider the Chicago Board of Trade (CBOT). Lurie (1979) details the political struggles over privilege trading at the CBOT during the nineteenth century. An 1865 CBOT rule stated that transactions in privileges were not recognized by the exchange or the Committee of Arbitration. A resolution adopted in 1876 prohibited privilege transactions on the exchange, and a resolution the following year threatened fraud charges against members trading privileges with innocent parties, i.e., non-members. In 1895, the president of the Board urged that privilege trading be banned; although the members voted down the revised rule, the room where privileges were typically traded was closed. The exchange also adopted a rule that conducting futures trades resulting from privilege transactions was cause for expulsion. The exchange membership enacted a 1900 rule prohibiting all privilege transactions by members, in the exchange or elsewhere, with offenses punishable by expulsion from membership. The penalty of expulsion was removed in 1905, as the exchange reverted to a "don't ask, don't tell" policy as in 1865.

Kruizenga (1956) documents the 1885 addition to the New York Stock Exchange Constitution banning offers to buy or sell options at the Exchange, with a penalty of $25 associated with such activity. Privilege traders side-stepped the ban of trading on the floor by doing business in the Exchange's smoking room. This large room was just off the Exchange floor and just off New Street, where curb trading took place. The Exchange occasionally enforced the ban, evicting option traders who carried on their business in that room.[4]

Distinguishing between legitimate speculation and gambling on stock prices might appear a superficial distinction to modern eyes, but the delineation was an important legal issue that affected market development. While it might have been efficient for options to be cash settled rather than physically settled, such "payment for differences" made them gambling contracts, which were unenforceable by the courts. New York courts treated options like other contracts (unless it was clear that stock was never intended to change hands), but Illinois courts were more likely to treat any option contract as invalid after the 1874 statute noted above. Banner (1998) details the social and cultural environment as it shaped securities regulation and market structure, and Dos Passos (1968

[1] "Stock-Gambling." February 1846. The United States Magazine and Democratic Review, 18 (92), p. 89.

[2] *Illinois Revised Statutes* (1874), Chapter 38, Section 130, p. 1295. The language was modified in 1913 to refer explicitly to contracts settled in cash. See McMath (1921, pp. 10–11).

[3] *New York Times*, September 22, 1878, p. 6, "Points about Stock Speculation."

[4] See *New York Times*, September 18, 1907, p. 4, "Privilege Brokers Expelled," and *New York Times*, November 30, 1910, p. 20, "Puts and Calls No More."

[1882], pp. 444–455) recounts the legal issues as they stood in the late 1800s.

The focus of the market was on primary issuance of options. A potential purchaser of options could choose to buy an out-of-the-money put or an out-of-the-money call. All options were American style and could be exercised at any time prior to expiration. There was no organized trading of previously issued options, but brokers advertised that they were willing to conduct cash market transactions, on commission, during the life of the options or at expiration. Options were sometimes traded after issuance, but this was usually associated with the potential default of an issuer. When an option issuer could not be found to take or deliver stock, and it was suspected that he intended to default, the options were treated as distressed securities and traded at a discount to the market value of an otherwise identical option without the default risk. Mixon (2005) describes a spectacular example of potential option default during the Panic of 1884.

The standard option contract was for 100 shares of the underlying stock, and it expired one month after issuance. The standard price of such an option was fixed at $106.25, or $1 per share plus commission. The language of the contract was simple, defining an American option on a particular stock. For example, Hickling (1875) includes the following text as an example of a call option:

> New York, January 10th, 1875
>
> The bearer may call on the undersigned for one hundred shares of Atlantic and Pacific Telegraph Company capital stock, at $19\frac{1}{2}$, at any time within 30 days from date. The bearer is entitled to all dividends paid during that time.
>
> Expires Feb. 10th, 1875
>
> Signed——————————

The example highlights the dividend protection feature of the contracts; any dividends paid during the life of the option went to the ultimate holder of the stock. The feature reduced the effective strike price of the options by the amount of the dividend. Merton (1973) notes that this method of dividend protection does not exactly offset the effect of the dividend, but the resultant "mispricing" is quite small.

Mechanical aspects of modern option exchanges are widely understood. Standardized contracts are on 100 shares of stock, expire on a rolling basis, and are issued by the Options Clearing Corporation. They are traded on several centralized exchanges. Options are not generally dividend protected, and secondary trading of options is a key focus of the exchange's business.

On modern option exchanges, an option contract is specified with a given strike price, and the price of the option (the premium) is negotiated between buyer and seller. In nineteenth-century option markets, the convention was reversed. Option contracts were sold for a fixed price, but the strike price was negotiated between buyer and seller. A call might be quoted as "1 1/8," for example, meaning that the strike price for the option was $1 1/8 above the market price for the underlying. Similarly, a put quoted at "1 1/8" was understood to be struck at $1 1/8 below the market price of the underlying. The fact that the strike price was the one free variable in the contract may have simplified any rules of thumb used by option sellers.

Higgins (1902) computes typical monthly fluctuations (i.e., volatilities) for a number of stocks, adds a cushion for interest expense, counterparty risk, and fair profit, and suggests that options should be struck that distance from the market price. (Higgins acknowledged that options were generally struck much closer than his extremely conservative examples suggested. He also allowed that option trades, in practice, were not guided by formal actuarial methods such as the one he proposed.) This "dealer mark-up" on volatility is similar in spirit to, but much simpler computationally than, the Black-Scholes implementation examined by Green and Figlewski (1999).

4. Data

4.1. Historical sample

Indicative markets for one-month options, provided by put and call brokers, were published in the *Commercial and Financial Chronicle* (*CFC*) most weeks from January 1873 through June 1875. Brokers provided indicative ranges at which individuals could purchase puts and calls for roughly a dozen stocks. The universe of stocks was not constant but generally covered the actively quoted stocks. As described above, the price of options was fixed, and the variable term of the contract was the strike price. The quotes in the paper were for the distance from the spot price at which a call or a put would be struck. Although ads for the put and call brokers continued intermittently after this period, no other similar, systematic reporting of indicative prices appears available. Kairys and Valerio (1997) and Mixon (2008) have previously examined the data from this time period.

I identify 17 stocks in the sample that often had option quotes when the broker quotes were in the newspaper. Table 1 displays the names of the stocks in the sample, as well as the symbol used to denote the stocks in subsequent tables. Many of these stocks had option quotes throughout the sample, while some of them were quoted for some periods but not others. For example, options on the preferred stock of the Chicago & Northwestern Railroad were quoted regularly prior to the Crisis of 1873, but not at all after. Options were quoted regularly on Northwestern common stock after the crisis, but not before. (Both instruments were traded pre- and post-crisis.)

Given the contract terms, option price, midprice of the stock, and the relevant interest rate, I compute an implied volatility and option delta for each option in the sample. Interest rates for prime commercial paper, also collected weekly from the *CFC*, are used as the riskless discount rate. There was no liquid market for short term Treasury securities at this time. I have performed robustness tests on the analysis, and qualitative results of the paper are not

Table 1
Underlying Stocks.
The table displays company names and associated stock symbols used in this article for notational compactness. Stocks for the historical sample are ordered in the typical ordering found in the quotations from the *Commercial and Financial Chronicle*. Stocks for the modern sample are ordered by the total number of option contracts traded on the Chicago Board Options Exchange during the sample period of 2001–2004.

Historical sample (1873–1875)		Modern sample (2001–2004)	
Symbol	**Firm name**	**Symbol**	**Firm name**
NYC&H	New York Central & Hudson River	MSFT	Microsoft
LS	Lake Shore & Michigan Southern	CSCO	Cisco Systems
C&RI	Chicago, Rock Island & Pacific	TWX	Time Warner
ERIE	Erie Railway	GE	General Electric
PM	Pacific Mail Steamship Co.	INTC	Intel Corporation
NW	Chicago & Northwestern	IBM	IBM
NWP	Chicago & Northwestern pref.	C	Citigroup
WU	Western Union Telegraph	ORCL	Oracle Corporation
O&M	Ohio & Mississippi	TYC	Tyco International
UNP	Union Pacific	DELL	Dell Computer
WAB	Toledo, Wabash & Western	QCOM	QUALCOMM
CCIC	Columbus, Chicago & Indiana Central	EMC	EMC Corporation
BH&E	Boston, Hartford & Erie	HPQ	Hewlett-Packard
SP	Milwaukee & St. Paul	NOK	Nokia ADR
SPP	Milwaukee & St. Paul pref.	TXN	Texas Instruments
H&SJ	Hannibal & St. Joseph	JPM	JPMorgan Chase
HAR	New York & Harlem	WMT	Wal-Mart
		PFE	Pfizer
		LU	Lucent Technologies
		YHOO	Yahoo! Inc.

particulary different if the call money interest rate is used (details available on request). To account for the possibility of early exercise, I use a 100 step binomial tree to compute the implied volatilities and deltas. The midpoint of the indicative strike price range is the strike for the calculations. Kairys and Valerio interpret these quote ranges (e.g., puts quoted as 3/4@1) as bid and ask quotes. I deviate from this practice for two reasons. First, my reading of advertisements and brokerage literature suggests that the retail customers targeted in these ads would never have been offered the opportunity to write options and hence would never have seen bid quotes for options.[5] Second, while the "@" symbol is sometimes used to separate bid and ask quotes, writers during this period also used the symbol to denote approximate ranges.[6] Based on these reasons, I interpret the notation as a range of ask quotes rather than bids and asks.

To facilitate comparison of the data over time, I first standardize the implied volatilities for each stock to represent hypothetical 25-delta puts, 25-delta calls, and 50-delta options. In modern OTC option markets, contracts are often specified in terms of delta. So-called risk reversals are common trades including the purchase of a 25-delta call and the sale of a 25-delta put; they are quoted as the difference in the implied volatility of the put and the implied volatility of the call.

To carry out this standardization, I compute the delta for the put and the call and assume a linear relation between deltas and implied volatilities. In other words, I assume a linear volatility skew in delta. I first convert the put deltas into call deltas and linearly interpolate to find the 25-, 50-, and 75-delta call volatilities. (I test the appropriateness of the linearity assumption on modern data and conclude that linearity in delta is a defensible approximation near 50 delta even when the limitations of the 1870s data are imposed; details are in the appendix). The 25-delta put volatility equals the 75-delta call volatility. For ease of presentation, the terms "at-the-money" or "ATM" and 50-delta are used interchangeably for the remainder of the paper. I will also refer to the "volatility skew" to mean the 25-delta call volatility minus the 25-delta put volatility, divided by the 50-delta volatility. Because puts are valuable if the underlying asset declines in price, while calls are valuable if the underlying asset rises in price, the relative valuation of the two types of options translates directly into the skewness of the implicit distribution for the asset price at expiration.

If quotes are available for only the put or the call, but not both, that date is excluded from the sample. The Boston, Hartford & Erie Railroad was a low-priced, high-volatility stock. Of the 31 dates for which option quotes on this stock are available, data are eliminated on six dates for which an interpolated volatility is less than zero.

[5] E.g., an ad for Lapsley & Bazley from the *CFC*, January 25, 1873, p. 132, states that "$100 plus commission will purchase a first class contract ... no further risk or outlay is incurred beyond the amount you decide to risk... All 'puts' and 'calls' negotiated by us are signed by bankers and brokers of acknowledged responsibility and credit."

[6] For example, "Money continues very easy on call loans, and the rates have ranged from 3@5 per cent. ..." (*CFC*, March 21, 1874, p. 290) and "The stock market has been without decided movement of importance until to-day, when a bear movement set in, led by Wabash, ... which sold down to 25, and carried down the balance of the list to the extent of 1/2@2 per cent." (*CFC*, December 19, 1874, p. 632).

4.2. Modern sample

Stocks for the modern sample were chosen to form a comparable sample to the historical data: the 20 stocks with the most active options. Specifically, I take the 20 stocks (excluding exchange-traded funds) with the highest total number of option contracts traded on the Chicago Board Options Exchange during the period 2001–2004. Table 1 displays the names of these stocks and the ticker symbol for each stock. For the analysis that follows, I compute the implied volatility for 50-delta options, 25-delta puts, and 25-delta calls and sample them on the last trading day of each week. The weekly observation interval matches the interval for the historical sample.

Contract-level data were obtained from iVolatility.com. End-of-day implied volatility and option delta are provided for each contract. Derived data are computed using an American option pricing model incorporating discrete dividends. I interpolate the contract-level data to construct constant maturity, constant moneyness implied-volatility indexes. I first interpolate implied volatility from listed contracts for each expiry. The analysis assumes that implied volatility is a linear function of call delta between the two contracts with deltas bracketing the target delta. I use data from out-of-the-money options only, converting observed out-of-the-money put deltas into in-the-money call deltas using the approximation $1 + \text{put delta} = \text{call delta}$. I then linearly interpolate the variance (squared implied volatility) from the two expiries bracketing the target 30 days until expiration. Expiries with seven or fewer days until expiration are excluded. If the two closest expiries are further than 30 days away, I extrapolate rather than interpolate.

In a few instances, there is no option with a strike price less than the spot price. The main example is Lucent Technologies, which fell to the \$1–\$2 range from mid-2002 until mid-2003. Rather than exclude the stock or extrapolate implied volatility beyond the strike price range, I record these observations as missing for these dates (71 observations). In a handful of other instances, obvious data errors are removed. The errors affect a small number of observations: for example, in the ATM data, I exclude 20 of 4,089 potential observations because of data errors, representing less than half of 1% of the total.

Table 2
Implied and realized volatility.
The table displays means for implied and realized volatility for each stock in the sample. Implied volatility is the average 50-delta implied volatility for a given stock and is in the column labeled "IV." Realized volatility is the average Parkinson (1980) sample standard deviation over the trailing four weeks of daily data, sampled on dates for which the implied volatility is available, and it is in the column labeled "RV." The column "OBS" displays the number of observations available for each stock.

Historical sample (1873–1875)				Modern sample (2001–2004)			
Firm	OBS	IV	RV	Firm	OBS	IV	RV
NYC&H	101	14.0	7.0	MSFT	208	33.2	27.8
LS	105	18.9	12.6	CSCO	209	49.9	43.2
C&RI	101	16.3	8.1	TWX	209	42.2	38.4
ERIE	100	45.1	25.8	GE	209	30.1	27.3
PM	104	43.7	32.6	INTC	207	44.0	38.5
NW	65	37.7	25.9	IBM	209	29.8	23.7
NWP	27	19.4	6.9	C	208	29.8	27.2
WU	104	22.0	16.1	ORCL	209	50.8	45.4
O&M	105	45.3	23.5	TYC	209	44.8	40.4
UNP	105	45.3	30.9	DELL	206	37.8	35.5
WAB	105	50.7	31.0	QCOM	208	50.1	44.8
CC&IC	99	96.2	41.2	EMC	207	58.0	54.4
BH&E	23	251.4	88.6	HPQ	208	42.9	37.6
SP	96	39.0	22.9	NOK	207	48.8	35.1
SPP	31	22.6	7.0	TXN	207	50.7	47.4
H&SJ	65	60.9	31.3	JPM	208	35.9	31.3
HAR	48	15.8	9.1	WMT	208	27.2	23.7
				PFE	209	27.1	25.6
				LU	136	69.1	56.0
				YHOO	208	60.6	53.5
Average		49.7	24.7	Average		43.1	37.8

5. Empirical results

5.1. Results

This section presents the results of a battery of empirical tests. For each of the hypotheses described above, I verify that the empirical regularity appears in the modern data set and examine whether it appears in the historical data set. A key element of the analysis is the comparison of the results across the two periods to gauge whether the pricing behavior has markedly changed. Overall, I find that the empirical regularities of modern option markets are not new: precisely the same qualitative behavior existed more than a hundred years before Black-Scholes and the CBOE. Nonetheless, I find evidence that option market pricing has changed in some ways. Implied volatility appears to be more responsive to shocks to realized volatility, and idiosyncratic factors appear to affect option prices less. Implied volatility has also fallen substantially relative to realized volatility.

H1. Implied volatility (ATM) tends to exceed realized volatility.

Table 2 displays basic statistics relating to implied and realized volatility. For each stock, the average at-the-money implied volatility is shown, as well as the average realized volatility. Because of data limitations for the historical sample, realized volatility is computed using the Parkinson (1980) range-based estimator of variance over the trailing four weeks of daily data. While the realized volatility itself is computed using daily data, the realized volatility average is computed using only the values from dates on which the implied volatility is available for that stock.

Comparing the results across the two samples, it is clear that the "volatility gap" between implied and realized volatility has narrowed dramatically between the two periods. In the historical sample, the average implied volatility across all stocks is 49.7%, while the realized volatility is less than half that amount at 24.7%. In the modern sample, the average implied volatility across all stocks is 43.1%, and the average realized volatility is 37.8%. The average implied volatility exceeds the average realized volatility for every stock in the table. This result is little changed if trailing volatility is replaced with subsequent realized volatility. Robustness tests (available on request from the author) suggest that any problems due to infrequent trading in the 1870s data do not alter this conclusion.

H2. The cross-section of implied volatility matches the cross-section of realized volatility.

Hypothesis H2 is a basic restriction on rational option pricing. If options are priced correctly on a relative basis, then higher-volatility stocks should have more expensive options. The cross-section of implied volatility should closely match the cross-section of realized volatility. An alternative is that the cross-section of implied volatility bears little relation to the cross-section of realized volatility. If hopeful speculators in the nineteenth century were merely placing cheap bets on "hot" stocks, they might have bid up option prices without connection to the underlying realized volatility. I test hypothesis H2 by considering the relation between average implied volatility and average realized volatility.

For the nineteenth-century sample, I estimate the relation

$$\ln(\overline{\sigma}_{it}) = \underset{(0.164)}{0.528} + \underset{(0.091)}{0.938}\ln(\overline{\sigma}^r_{it}), \quad R^2 = 0.876 \tag{1}$$

where standard errors are below the parameter estimates. For the modern sample, the results are similar:

$$\ln(\overline{\sigma}_{it}) = \underset{(0.058)}{0.104} + \underset{(0.056)}{0.973}\ln(\overline{\sigma}^r_{it}), \quad R^2 = 0.944. \tag{2}$$

In both instances, the notation indicates that the time-series average implied volatility for stock i ($\overline{\sigma}_{it}$) is regressed on the time-series average realized volatility for stock i ($\overline{\sigma}^r_{it}$), where both are expressed in log terms. Although the sample sizes are small (17 and 20 observations, respectively), the relation is quite strong. It is difficult to reject the null hypothesis that the slope coefficient should be unity in the regressions. The fact that the intercept is larger in the historical regression again emphasizes the fact that the spread between implied and realized volatility was much larger in the past. One can also pool the two samples and estimate the regression, then test for equality of the coefficient vectors across the two time periods. I find evidence that the intercept declined significantly in the modern sample (t-statistic of -2.12) when I allow the slope and intercept to vary (the t-statistic for a different slope across the two samples is 0.21).

H3. Implied volatility is systematically related to realized volatility.

H4. Implied volatilities are substantially serially correlated.

First, I ask if implied volatility varies directly with recent realized volatility across firms. I find that if realized volatility for stock A is less than realized volatility for stock B, then implied volatility for stock A is also less than implied volatility for stock B.

I estimate the pure cross-sectional regression

$$\ln(\sigma_{it}) = a + b\ln(\sigma^r_{it}) + \varepsilon_{it}, \tag{3}$$

where σ_{it} is the at-the-money implied volatility for stock i on date t, and σ^r_{it} is the trailing realized volatility for stock i, measured on date t. The results are shown in Table 3. The slope coefficient is around 0.75 for both the historical and modern samples, indicating a substantially positive relation. There is no obvious value to hypothesize for the slope, but intuition suggests that the sign should be positive. The combination of the fact that realized volatility is a month-long trailing average, including old data, with the mean reversion of instantaneous volatility, makes it unsurprising that the coefficient is lower than the cross-sectional coefficient described in the regression on averaged data in the test of H2.

Next, I concentrate on explaining implied volatility levels within a single firm. I find that implied volatility for stock A is lower when realized volatility for stock A is

Table 3
Implied/realized volatility panel regressions.

The table displays panel regression results for a regression of log implied volatility on the log of trailing realized volatility. Standard errors are reported below each coefficient.

	Historical sample			Modern sample		
	$N = 1,384$			$N = 2,268$		
Individual effects	No	Yes	Yes	No	Yes	Yes
Time effects	No	No	Yes	No	No	Yes
Realized volatility	0.727	0.409	0.426	0.753	0.569	0.578
(s.e.)	(0.012)	(0.013)	(0.014)	(0.009)	(0.011)	(0.012)
$\overline{R}^2$	71.2%	88.3%	90.8%	74.7%	81.9%	90.0%
Realized volatility	0.038	0.051	0.041	0.212	0.240	0.291
(s.e.)	(0.005)	(0.005)	(0.006)	(0.016)	(0.016)	(0.016)
Lagged implied volatility	0.964	0.936	0.946	0.695	0.533	0.482
(s.e.)	(0.006)	(0.009)	(0.008)	(0.018)	(0.020)	(0.020)
$\overline{R}^2$	98.8%	98.8%	99.2%	84.8%	86.0%	92.1%

lower. To implement this test, I build on the regression above to estimate a fixed-effects regression with individual effects:

$$\ln(\sigma_{it}) = a_i + b\ln(\sigma^r_{it}) + \varepsilon_{it}. \tag{4}$$

The results are also shown in the top of Table 3, and the slope coefficient remains significantly positive in both samples. Nonetheless, the estimated slope declines to around 0.5, but the R^2 rises from the 70–75% range to the 80–90% range. The substantial increase in explained variation reflects the marked differences across stocks in terms of volatility. The decline in the realized-volatility slope coefficient emphasizes the contrarian nature of realized volatility as a predictor of implied volatility. To elaborate, realized volatility often reverts from historically extreme levels, and implied volatility often reflects this fact. A shock that increases realized volatility, but is expected to be transitory, increases implied volatility less than realized volatility. Implied volatility often forecasts a more moderate value when realized volatility is at an extreme reading, and the regression results are consistent with this interpretation.

Finally, I go on to include dummy variables for each of the time periods represented in the data. This specification addresses the issue of whether the previous results are simply picking up aggregate movements (time-series variation in the data):

$$\ln(\sigma_{it}) = a_i + a_t + b\ln(\sigma^r_{it}) + \varepsilon_{it}. \tag{5}$$

Results are again shown in the top of Table 3, and the estimated slope coefficients indicate very little in the way of misspecification: estimates vary only slightly when time effects are added to the regression.

The bottom of Table 3 provides another clue about how the pricing behavior of the market has evolved. The regression relates the level of implied volatility to both the lagged implied volatility for that stock as well as the most recent realized volatility. It is useful to keep in mind the timing of the data in the regression. The lagged implied volatility, of course, is the market price a week prior to the date for the current value. Realized volatility, on the other hand, is sampled at the same point in time as the implied volatility, using daily data over the previous four weeks. The realized volatility is therefore “fresher” than the lagged implied volatility.

The most general fixed-effects specification, including individual and time effects, is

$$\ln(\sigma_{it}) = a_i + a_t + b_1\ln(\sigma^r_{it}) + b_2\ln(\sigma_{it-1}) + \varepsilon_{it}. \tag{6}$$

The regression coefficients on the lagged implied volatility are very close to unity in the historical sample, but they fall sharply to the 0.5–0.7 range in the modern sample. Correspondingly, the estimated coefficients on realized volatility are quite small but significantly positive in the historical sample (around 0.05), and they are much higher in the modern sample (around 0.25). In both periods, the fit of this regression is quite good, with explained variation over 90%. The particular specification matters little for the overall results.

In the data from the 1870s, implied volatility for a given stock was responsive to shocks to realized volatility, but the previous level of implied volatility was far more important in determining the current level of implied volatility. The lagged implied volatility captures any firm-specific, idiosyncratic variation that is not captured in the sample mean, and it is very effective in capturing the variation of the data. In contrast, the data from the twenty-first century shows much less sensitivity to the recent level of implied volatility, with substantial weight placed on realized volatility in determining the current level of implied volatility. In other words, I find that the option market is now much more sensitive to current fundamentals than it was in the days before organized exchanges.

H5. Changes in ATM implied volatility are positively correlated across stocks.

H6. Changes in implied volatility are negatively correlated with changes in the price of the underlying stock.

Table 4 displays the correlations among at-the-money implied volatility changes. Panel A shows correlations for 11 of the most active stocks in the historical sample. This selection balances the desire for a bigger sample of observations with the desire for the largest number of stocks in the sample. To preserve comparability, each of the correlations is computed using data from the same observation dates. If an observation is missing for a given stock, I delete all observations for that date. All of the correlations are positive, and the average is 0.38. A number of the values appear small, with several below 0.10.

Panel B displays correlations for all stocks in the modern sample, and the results are not surprising. Implied volatilities of stocks in the same industry tend to have high correlations with each other. For example, JP Morgan and Citigroup volatilities have a correlation of 0.71. Implied volatilities of stocks in distinct industries are much less likely to have a high correlation (e.g., the lowest value in the table is for Pfizer and Oracle, at 0.19). Overall, the correlation matrix indicates a strong, positive contemporaneous relation among implied volatilities of stocks, averaging 0.41.

The analysis can be refined to decompose the relations into systematic and idiosyncratic influences. I estimate market model regressions of changes in 50-delta implied volatility on changes in the cross-sectional average of 50 delta implied volatility. I trim the cross-sectional average by excluding the largest and smallest observation at each date to produce a more robust measure of central tendency. Details on the choice of trimmed means versus untrimmed means are available on request. The regressions are of the form

$$\Delta\ln(\sigma_{it}) = \alpha_{0i} + \beta_{0i}\Delta\ln(\overline{\sigma}_{it}) + \varepsilon_{it}. \tag{7}$$

I estimate the regression separately on each of the stocks in both samples and display the results in Table 5. Coefficients are estimated using ordinary least squares (OLS), and standard errors use Davidson and MacKinnon’s (1993) method for MacKinnon and White’s (1985) HC3 covariance matrix estimator.

The regressions demonstrate strong evidence that there is a systematic, marketwide factor in implied

Table 4
Correlation matrix for implied volatility changes.
Panel A displays the correlation matrix for weekly log changes in ATM implied volatility during the 1873–1875 sample. Panel B displays the correlation matrix for weekly log changes in ATM implied volatility during the 2001–2004 sample.

	NYC&H	LS	C&RI	ERIE	PM	WU	O&M	UNP	WAB	CC&IC
Panel A: Historical sample										
LS	0.55									
C&RI	0.43	0.55								
ERIE	0.15	0.29	0.15							
PM	0.12	0.30	0.01	0.60						
WU	0.47	0.63	0.59	0.21	0.36					
O&M	0.23	0.40	0.53	0.24	0.29	0.51				
UNP	0.13	0.31	0.15	0.55	0.63	0.36	0.34			
WAB	0.09	0.41	0.36	0.44	0.48	0.40	0.56	0.55		
CC&IC	0.01	0.26	0.30	0.07	0.23	0.37	0.48	0.29	0.54	
SP	0.35	0.54	0.56	0.27	0.37	0.70	0.62	0.44	0.55	0.51

	MSFT	CSCO	TWX	GE	INTC	IBM	C	ORCL	TYC	DELL
Panel B: Modern sample										
CSCO	0.49									
TWX	0.51	0.40								
GE	0.37	0.30	0.40							
INTC	0.63	0.41	0.50	0.42						
IBM	0.63	0.35	0.44	0.47	0.62					
C	0.54	0.46	0.51	0.53	0.55	0.54				
ORCL	0.41	0.23	0.35	0.29	0.46	0.40	0.31			
TYC	0.34	0.29	0.46	0.31	0.36	0.35	0.43	0.23		
DELL	0.55	0.50	0.41	0.40	0.58	0.54	0.56	0.45	0.30	
QCOM	0.53	0.39	0.55	0.28	0.56	0.42	0.48	0.36	0.36	0.56
EMC	0.55	0.37	0.36	0.24	0.53	0.55	0.47	0.32	0.34	0.42
HPQ	0.37	0.39	0.44	0.30	0.40	0.35	0.33	0.28	0.31	0.42
NOK	0.48	0.22	0.37	0.29	0.55	0.47	0.45	0.37	0.39	0.44
TXN	0.52	0.34	0.49	0.34	0.60	0.51	0.49	0.49	0.27	0.57
JPM	0.44	0.39	0.47	0.42	0.37	0.50	0.71	0.34	0.44	0.48
WMT	0.49	0.40	0.48	0.50	0.47	0.46	0.50	0.26	0.36	0.44
PFE	0.37	0.21	0.37	0.36	0.29	0.39	0.44	0.19	0.39	0.27
YHOO	0.45	0.23	0.45	0.27	0.43	0.47	0.39	0.33	0.34	0.36

	QCOM	EMC	HPQ	NOK	TXN	JPM	WMT	PFE
EMC	0.43							
HPQ	0.38	0.39						
NOK	0.45	0.47	0.25					
TXN	0.62	0.54	0.44	0.48				
JPM	0.44	0.37	0.36	0.37	0.43			
WMT	0.42	0.35	0.36	0.43	0.42	0.45		
PFE	0.34	0.35	0.30	0.39	0.35	0.40	0.44	
YHOO	0.41	0.52	0.39	0.43	0.41	0.40	0.29	0.29

Table 5

Market model regressions for implied volatility changes.

The table displays the results of regressing weekly changes in single-stock at-the-money implied volatility on weekly changes in the cross-sectional average of at-the-money implied volatility. The cross-sectional average is trimmed, excluding the highest and lowest value each week. *t*-Statistics in the table are based on HC3 heteroskedasticity-consistent standard errors from Davidson and MacKinnon (1993). The regression estimated is

$$\Delta \ln(\sigma_{it}) = \alpha_i + \beta_i \Delta \ln(\overline{\sigma}_{it}) + \varepsilon_{it}.$$

.

Historical sample				Modern sample			
Firm	β	$t(\beta)$	$\overline{R}^2$	Firm	β	$t(\beta)$	$\overline{R}^2$
NYC&H	0.13	(1.89)	2.0	MSFT	1.03	(15.53)	54.2
LS	0.23	(1.15)	5.4	CSCO	0.89	(11.11)	36.5
C&RI	0.19	(2.45)	9.1	TWX	0.99	(13.46)	50.3
ERIE	0.69	(2.52)	24.4	GE	0.83	(7.93)	33.3
PM	0.76	(2.82)	26.9	INTC	1.06	(15.97)	59.5
NW	0.58	(2.93)	43.4	IBM	1.13	(14.80)	54.8
NWP	−0.06	(−0.70)	−0.8	C	1.18	(16.40)	53.3
WU	0.42	(2.08)	13.2	ORCL	0.70	(7.66)	26.9
O&M	0.54	(3.11)	25.4	TYC	1.26	(7.56)	33.6
UNP	1.05	(3.70)	42.6	DELL	1.13	(15.23)	52.1
WAB	0.87	(7.09)	42.4	QCOM	1.04	(12.37)	51.6
CC&IC	0.64	(2.16)	17.7	EMC	1.16	(15.14)	50.0
BH&E	−0.18	(−1.26)	3.7	HPQ	0.74	(8.07)	26.6
SP	0.61	(3.37)	33.2	NOK	0.84	(10.78)	40.6
SPP	0.15	(1.38)	1.6	TXN	1.09	(15.75)	57.0
H&SJ	0.48	(3.80)	31.9	JPM	1.11	(12.19)	45.4
HAR	0.20	(1.25)	6.0	WMT	0.77	(9.52)	41.7
				PFE	0.80	(7.62)	29.5
				LU	0.93	(4.71)	16.7
				YHOO	0.81	(11.48)	42.7
Average	0.43	(2.34)	19.3	Average	0.98	(11.66)	42.8

Table 6

Implied volatility asymmetry.

The table displays the results of regressing weekly changes in single-stock at-the-money implied volatility on weekly changes in the cross-sectional average of at-the-money implied volatility and on the weekly stock return orthogonal to the market return. The cross-sectional average is trimmed, excluding the highest and lowest value each week. Indicated significance in the table is based on HC3 heteroskedasticity-consistent standard errors from Davidson and MacKinnon (1993). The regression estimated is

$$\Delta \ln(\sigma_{it}) = \alpha_{0i} + \beta_{0i} \Delta \ln(\overline{\sigma}_{it}) + \gamma_{0i} \Delta s_i + \varepsilon_{it}.$$

.

Historical sample				Modern sample			
Firm	$\Delta \ln(\overline{\sigma}_{it})$	Δs	$\overline{R}^2$	Firm	$\Delta \ln(\overline{\sigma}_{it})$	Δs	$\overline{R}^2$
NYC&H	0.15*	−0.64	3.2	MSFT	1.05*	−1.17*	62.5
LS	0.24	−0.73*	9.4	CSCO	0.90*	−0.61*	44.1
C&RI	0.21*	−1.12	17.0	TWX	0.97*	−0.69*	56.9
ERIE	0.60*	−1.02*	50.4	GE	0.86*	−1.39*	49.6
PM	0.77*	−1.00*	40.1	INTC	1.05*	−0.56*	63.6
NW	0.49*	−0.92*	54.1	IBM	1.14*	−1.42*	64.7
NWP	0.05	−1.13*	50.4	C	1.20*	−1.63*	66.4
WU	0.41	0.39	13.2	ORCL	0.74*	−0.62*	36.2
O&M	0.42*	−0.98*	39.9	TYC	1.11*	−1.19*	62.8
UNP	1.02*	−0.71*	51.9	DELL	1.16*	−0.95*	60.7
WAB	0.78*	−0.71*	58.7	QCOM	1.01*	−0.77*	66.3
CC&IC	0.48*	−0.99*	73.3	EMC	1.17*	−0.50*	56.0
BH&E	−0.14	−0.04	−1.3	HPQ	0.75*	−0.53*	31.1
SP	0.54*	−1.15*	44.7	NOK	0.86*	−0.44*	45.8
SPP	0.07	−1.16	9.2	TXN	1.08*	−0.61*	66.0
H&SJ	0.42*	−0.72*	57.4	JPM	1.10*	−1.20*	57.9
HAR	0.18	0.22	4.1	WMT	0.79*	−1.57*	65.4
				PFE	0.80*	−1.65*	56.5
				LU	0.93*	−0.49*	20.5
				YHOO	0.81*	−0.20*	43.9
Average	0.39	−0.73	33.9	Average	0.97	−0.91	53.8

* indicates parameter significance at the 5% level.

volatility changes in both samples. In the historical sample, 11 of the 17 stocks display *t*-statistics for the slope coefficients that are well above two. Nonetheless, the evidence also indicates a strong influence of idiosyncratic movements for the individual implied volatilities: seven of the stocks have adjusted R^2 values below 10%. In the modern sample, the evidence is very strong for a systematic factor: every stock has a *t*-statistic greater than four for the slope coefficient, and more than half of the stocks feature *t*-statistics greater than ten. On average, the R^2 for the historical sample is 19.3%, while the average for the modern sample is 42.8%. There is clear evidence that a single factor can explain a significant amount of variation in implied volatility, but the influence of idiosyncratic factors was much higher during the 1870s. This is an interesting result, given that stocks plummeted en masse during the dramatic crash in September 1873. Clearly, idiosyncratic factors (such as order flow) must have been highly important in determining a stock's implied volatility during the nineteenth century.

Table 6 presents regression results for a simple model relating log changes in implied volatility to contemporaneous stock price changes:

$$\Delta \ln(\sigma_{it}) = \alpha_{0i} + \beta_{0i} \Delta \ln(\overline{\sigma}_{it}) + \gamma_{0i} \Delta s_{it} + \varepsilon_{it}. \tag{8}$$

In this regression, the variable Δs_{it} represents the log stock price change (over a weekly interval) that is orthogonal to marketwide effects. That is, Δs_{it} is the residual from a regression of the log stock price change on the return of an equally weighted index of all the stocks in the sample (a market model regression). Using the residual puts the focus squarely on the idiosyncratic part of the stock price change. Systematic movements in implied volatility are captured by the index of implied volatility, and non-systematic movements are captured by the stock price change orthogonal to the market's movements.

In the sample of data from the nineteenth century, the coefficients imply an increase in implied volatility of around 0.75% when the associated stock price drops 1%. The twenty-first-century data show a response of approximately 1%. Even after accounting for systematic, marketwide changes in implied volatility, idiosyncratic stock price changes and volatility move inversely.

H7. Changes in implied volatility skew are positively correlated across stocks.

The analysis in this section tests if there is a significant systematic factor driving changes in single-stock implied skewness. Because of data limitations in the historical sample, the skew for stock *i* is defined as the 25-delta call volatility minus the 25-delta put volatility, divided by the

Table 7
Market model regressions for implied volatility skew changes.

The table displays the results of regressing weekly changes in single-stock implied volatility skew on weekly changes in the cross-sectional average of the implied volatility skew. The cross-sectional average is trimmed, excluding the highest and lowest value each week. Volatility skew is computed as the 25-delta call volatility minus the 25-delta put volatility, divided by the 50-delta volatility. Both sets of regressions adjust for AR(1) errors. The regression estimated is

$$\Delta skew_{it} = \alpha_{1i} + \beta_{1i}\Delta\overline{skew}_{it} + \varepsilon_{it}.$$

.

Historical sample				Modern sample			
Firm	β	$t(\beta)$	$\overline{R}^2$	Firm	β	$t(\beta)$	$\overline{R}^2$
NYC&H	2.11	(5.80)	29.6	MSFT	1.00	(6.34)	34.4
LS	1.67	(7.85)	45.5	CSCO	0.96	(6.67)	32.8
C&RI	0.59	(3.09)	8.0	TWX	1.06	(6.18)	29.1
ERIE	0.56	(2.40)	8.2	GE	1.34	(5.74)	28.3
PM	0.95	(4.18)	24.8	INTC	1.03	(7.93)	48.9
NW	0.72	(3.64)	18.8	IBM	0.87	(6.88)	32.4
NWP	0.38	(2.92)	20.3	C	1.23	(6.05)	30.8
WU	1.12	(5.85)	33.3	ORCL	1.06	(5.07)	25.6
O&M	1.73	(5.49)	27.9	TYC	0.98	(5.66)	27.2
UNP	1.39	(5.70)	25.2	DELL	0.97	(5.76)	34.9
WAB	1.08	(6.10)	30.4	QCOM	0.73	(7.20)	38.2
CC&IC	0.74	(3.14)	11.9	EMC	1.37	(4.81)	36.3
BH&E	2.46	(2.59)	18.4	HPQ	1.37	(7.59)	41.3
SP	0.77	(3.84)	15.8	NOK	0.95	(4.79)	34.1
SPP	0.67	(3.30)	23.5	TXN	0.76	(5.40)	30.3
H&SJ	1.02	(4.03)	28.5	JPM	0.76	(4.13)	19.8
HAR	0.43	(2.60)	16.3	WMT	0.98	(7.35)	36.2
				PFE	1.22	(7.10)	36.6
				LU	0.33	(0.42)	10.9
				YHOO	0.59	(3.66)	28.2
Average	1.08	(4.27)	22.7	Average	0.98	(5.74)	31.8

50-delta volatility. I construct an index of implied skew using the cross-section of stocks available on a given date, trimming the highest and lowest values for robustness. This index is positive for positively skewed implied distributions and negative for negatively skewed distributions.

The market model regression of changes in skew on changes in cross-sectional average skew is

$$\Delta skew_{it} = \alpha_{1i} + \beta_{1i}\Delta\overline{skew}_{it} + \varepsilon_{it}. \tag{9}$$

Results of the estimation are shown in Table 7. Because of evidence of serially correlated errors in many of the regressions, an AR(1) error specification is included in the estimations. Every regression but one features a highly significant and positive slope coefficient, with t-statistics averaging greater than five in value. The regressions account for a noticeable amount of variation, with adjusted R^2 values averaging 23% and 32% in the historical and modern samples, respectively. There is strong evidence that changes in implied skewness feature a common element.

5.2. Discussion

The battery of tests presented here indicates that all of the empirical facts about implied volatility that define today's equity option markets were also found in option markets long before the modern era. The cross-section of implied volatility generally matches the cross-section of realized volatility in the same fashion. Likewise, the time-series properties of implied volatility also match across time periods. Systematic changes in at-the-money implied volatility and in implied volatility skews appear to have been a feature of option prices for centuries.

Examination of Fig. 1 reveals the dramatic increase in equity option trading after 1973. The results of the empirical tests in this paper show that there was not an equally dramatic change in the qualitative features of option pricing. I conclude that the regime shift in option trading was not paired with a regime shift in all aspects of option pricing. The success of modern option markets did not occur because of a sea change in option pricing.

One interesting difference between the two samples of data relates to the implied volatility skew. During the 1870s, the average volatility skew shifted from negative to positive and back again. It is well known that the volatility skew is decidedly negatively sloped these days. Even though the percentage volatility skew presented here varies in magnitude, its value remains steadfastly below zero. During the 1970s and 1980s, the sign of the typical single-stock volatility skew varied in sign. By the 1990s, the negative skew was entrenched, and it remains entrenched to this day.

Bollen and Whaley (2004) conclude that order flow has significant effects on the implied volatility skew in indexes and single stocks, suggesting that shifts in order flow might be quite important in understanding the long-term evolution of the volatility skew. Fig. 1 shows how the growth of equity option trading slowed after the introduction of index options in 1983. The associated shift in option trading behavior as index options became available for portfolio managers and investors might be important in understanding the changing behavior of the volatility skew for single stocks, and further research can shed light on this conjecture.

A key finding of the paper is the dramatic decline in implied volatility, relative to realized volatility, between the two eras. In principle, the very high implied volatility in the nineteenth century could have been due to perceived risk. For example, the historical sample consists almost entirely of stocks in a single industry (railroads), and the general macroeconomic environment was quite different—after all, the Crisis of 1873 occurred in the middle of the sample! This fact motivates the following section's event analysis, which is focused on the period around the opening of the CBOE.

6. Reality meets theory

The discussion thus far indicates that nineteenth-century option markets behaved extraordinarily similarly to twenty-first-century option markets. The empirical puzzles relating to implied volatility are not modern inventions. The observation that the pricing behavior of the market has not been fundamentally altered suggests that the underlying market structure might not have changed much, either. This section focuses on the biggest change in pricing across the two eras—the diminishing gap between implied and realized volatility—to explore what changed about the market and when it changed. The overall conclusion in this section is that implied volatility has declined relative to realized volatility over the years, and the biggest portion of the decline occurred immediately after the CBOE opened.

The first part of this section compares the panel of nineteenth century data to the twenty-first-century data to determine the existence and magnitude of any systematic, marketwide shift in the implied/realized volatility relation across the two eras. The second part explores a long time series of implied and realized volatility for a representative stock. The two decades of data span the OTC option market of the early 1970s, the opening of the CBOE, the bear market of the 1970s, the bull market of the 1980s, and the crash of 1987. The specific focus of the time-series analysis is on determining what events or periods were associated with changes in the implied/realized relation.

6.1. *Volatility gap: nineteenth vs. twenty-first centuries*

The idea behind the analysis in this section is that the average "implied volatility forecast error" between implied volatility and subsequent realized volatility represents systematic compensation for being short volatility, as well as any "inefficiency" in the market. Defining the error in this manner is not predicated on the idea that at-the-money implied volatility should equal the expected realized volatility in an "efficient" market; rather, the deviation is simply a useful, easy-to-understand benchmark. Evaluating the pricing relation for this forecasting error over the two historical periods allows a rigorous examination of how equity option market pricing has evolved. The methodology used is the two-pass regression test developed by Fama and Macbeth (1973).

The first step is a time-series regression for each stock to compute the factor loading (β_i) of the stock onto the average percentage implied volatility forecast error across stocks. The dependent variable in the regression is the percentage implied-volatility forecast error for a given stock, measured as the log of at-the-money implied volatility minus the log of subsequent realized volatility. The independent variable is the common factor, constructed as a cross-sectional average of the percentage implied-volatility forecast errors (log at-the-money implied volatility minus log realized volatility over the subsequent four weeks) on each date.

The second step is a cross-sectional regression of the percentage volatility forecast errors on the betas computed in the first step. This cross-sectional regression is computed for each date in the sample. The final step is computation of the time-series averages of the constant terms and the slope coefficients from each of these cross-sectional regressions. I utilize a Newey and West (1987) covariance matrix estimator with four lags to compute standard deviations of the estimates.

The estimated relation for the historical sample, with t-statistics below the parameter estimates, is

$$\ln(\text{implied}_{i,t}) - \ln(\text{realized}_{i,t+1}) = \underset{(2.52)}{0.223} + \underset{(3.97)}{0.357} \times \beta_i, \tag{10}$$

while the estimated relation for the modern sample is

$$\ln(\text{implied}_{i,t}) - \ln(\text{realized}_{i,t+1}) = \underset{(3.45)}{0.134} + \underset{(1.08)}{0.047} \times \beta_i. \tag{11}$$

Under the null hypothesis that there is a single common factor driving the gap between implied volatility and subsequent realized volatility, the intercepts in these equations should be zero and the coefficient on the factor loading should be positive. The estimates show that this ideal value of zero for the intercept is probably untrue for either sample, but the value has declined by half across the two periods. The change appears economically significant. For the early sample, the intercept alone suggests a mark-up of, say, 10–50 volatility points over realized volatility, whereas the intercept in the modern sample suggests an increase of closer to 3–5 volatility points. Perhaps this "inefficiency" is attributable to the lack of a secondary market in the pre-modern period. Brenner, Eldor, and Hauser (2001) show that a lack of liquidity induces a lower price for options than would otherwise prevail. The result suggests that illiquidity should lower, not raise, the price of options, and that liquidity concerns do not explain the difference in pricing across the two eras.

Further, compensation for a unit of the common factor has declined from 0.36 to just 0.05, although the latter value is not even significant in the modern sample. In equilibrium, the market compensates participants for systematic risk that they do not wish to hold without compensation. If the market is more evolved, with participants willing to take both sides of the market, compensation for that risk falls. It appears that the enhanced ability to sell options has had a significant effect on the market's required compensation for being short volatility. With more participants willing and able to sell options, volatility risk has become less of a burden and requires less compensation.

To describe these estimates in more human terms, we can solve for the fitted value of implied volatility for a stock with a volatility rate of 30% per year and a common factor beta of 1.0. In the nineteenth century, the fitted value for the implied volatility is $\exp(\ln(30\%)+(0.223+0.357)) = 54\%$. In the twenty-first century, the fitted value is $\exp(\ln(30\%)+(0.134+0.047)) = 36\%$. Therefore, the market required a volatility markup of 24 volatility points in the nineteenth century, but the required volatility markup for the stock has fallen to six volatility points in today's market. A more conservative comparison assumes that the relevant factor beta is 0.5 for the historical sample and 1.0 for the modern sample, given the higher comovement of implied volatility in the modern sample. These parameters yield fitted values of 45% and 36%, respectively, still representing an economically significant decline in option prices.

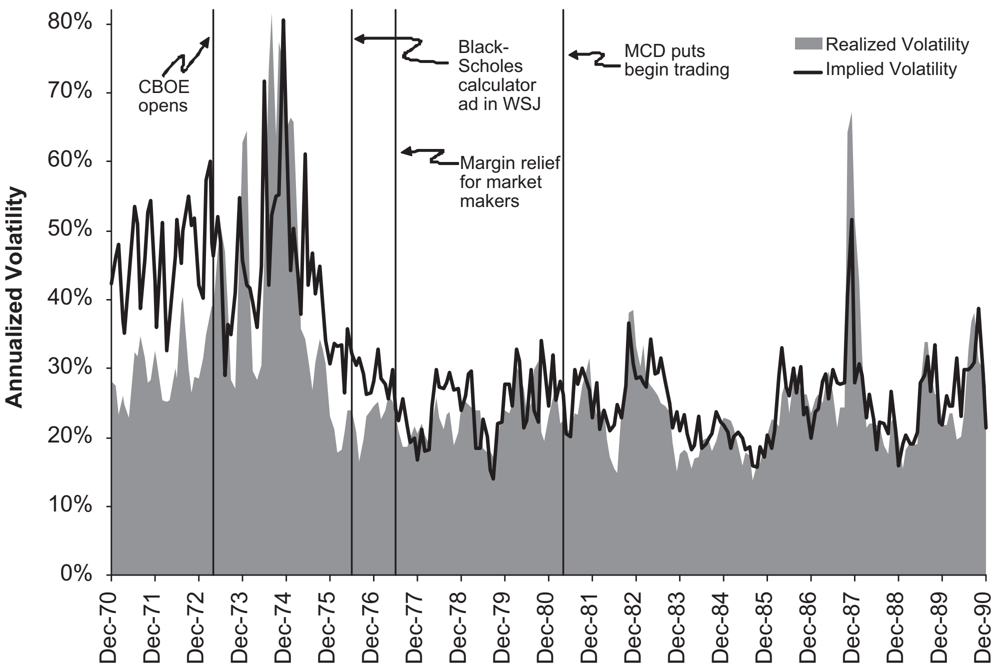

Fig. 4. Implied and realized volatility for McDonald's, 1971–1990. The figure displays implied volatility for nearby, near-the-money call options and the trailing 50-day standard deviation of log price changes of McDonald's stock. The figure also marks several key dates in option trading history.

The conclusion that the price of volatility risk has evolved over time has relevance to today's market. If the required compensation for volatility risk has declined because more participants are willing to bear it, then the explosion in the number of hedge funds that are implicitly or explicitly willing to sell volatility could drive this compensation even lower than current levels.

6.2. *Volatility gap: twentieth century*

When did implied volatility move toward levels consistent with the Black-Scholes model? Was it in the early 1970s, before the CBOE opened (suggesting that the change was due mostly to dissemination of the model)? Or was it over a long period as exchanges matured and trading frictions diminished? I provide an initial exploration of the question by examining the evidence for one of the original 16 stocks for which options began trading on the CBOE in 1973.

Fig. 4 displays a long time series (1971–1990) of implied and trailing realized volatility for McDonald's equity. For dates prior to the exchange opening, the chart shows implied volatility for calls advertised in *Barron's*, the *New York Times*, and the *Wall Street Journal*. For subsequent dates, the implied volatility is from the nearby, out-of-the-money call option with at least 30 days until expiry (or its closest substitute), computed from newspaper prices. Realized volatility is computed using daily data over a 50-trading-day trailing window. Several potentially relevant dates are marked with vertical lines. The opening of the CBOE, the publication of the famous Black-Scholes Texas Instruments calculator ad in the *Wall Street Journal*, a reduction of the Reg T margin (from 50% to 25%) for option market makers, and the introduction of puts on McDonald's stock are all marked. Securities and Exchange Commission (1978, pp. 678–684) provides more discussion on market-maker margin requirements.

Examination of the figure suggests that the premium on implied volatility diminished swiftly after the CBOE opened, but not before. The sharply elevated volatility of the mid-1970s bear market complicates the analysis slightly, but visual examination provides little evidence that a break in pricing occurred at a time other than the exchange opening. The gap averaged 16.2% before the opening and 1.2% afterwards. A simple regression of the volatility gap on event dummies defined as above confirms a significant decline after the opening of the CBOE (Newey-West t-statistic $= -4.6$). There is some evidence of a decline after the reduction in margin requirements for market makers (t-statistic $= -2.3$), but this occurred simultaneously with a stabilization in the stock price and volatility after a year-long price decline of over 40%, suggesting that the margin relief might have been a coincidence.

7. Conclusion

On the surface, option markets in the nineteenth century bear little resemblance to their modern counterparts. In the past, transactions in options took place on the street or in small, dingy offices. Stock and commodity exchanges repeatedly banned trade in them. A handful of wealthy stock market speculators sold options, but most individuals were allowed only to purchase options. Puts and calls were vilified as clever scams to extract money from hopeful speculators and rubes of small means. In the twenty-first century, derivatives are considered legitimate investment tools. Seven national exchanges in the United States feature trade in equity options. Market makers stand ready to buy or sell options at continuously quoted prices.

It is tempting to conclude that option markets remained a small, niche business for hundreds of years because traders lacked a no-arbitrage model for pricing and hedging. This characterization is incomplete and overstates the reliance of markets on mathematical models. Even sophisticated concepts such as delta hedging of options were intuitively understood by traders more than a century ago. For example, in explaining why London's OTC option market was more active than New York's, the *Wall Street Journal* noted in 1902 that "the practice of sellers of privileges in London, as the result of long experience, is, if they sell a call, to immediately buy half the stock against which call is sold, or, if they sell a put, to sell half the stock immediately, finding that in the long run this course works out a profit. This is not the usual practice here, where privileges are sold generally with some special object in view."[7] Mathematical rigor allowed traders to refine their practices, but it did not create a market out of thin air.

The analysis in this paper demonstrates that equity option markets displayed precisely the same empirical regularities in the nineteenth century as they do in the twenty-first century. Stylized facts relating implied volatility to realized volatility, stock prices and other implied volatilities, are present in both eras. Nineteenth-century option markets functioned remarkably similarly to modern ones. Modern pricing models and centralized exchanges changed the culture, language, and perception of option trading, but they did not fundamentally alter pricing behavior in the option market. Nonetheless, markets have changed in some ways, and the analysis quantifies this evolution. Implied volatility moves more than it used to in response to realized volatility shocks, and the general level of option prices has declined toward levels consistent with Black-Scholes.

Despite the sophistication of modern option markets, Bates (2008) concludes that imperfections resulting from institutional structure are a source of the empirical puzzles regarding option pricing. He suggests that the capacity constraints and risk limits of the relatively few option-writing institutions drive the equilibrium in the market away from the equilibrium implied by representative agent models. His characterization of the market structure is very similar to the market structure for the nineteenth-century option markets, where many small speculators purchased options from the large market operators who were willing to sell them. The organizational structure of option markets has evidently not changed dramatically in 130 years.

MacKenzie (2006) elaborates on several ways in which the Black-Scholes model could have affected option pricing practice. The first is "expressivity," which would be consistent with Black-Scholes merely describing pre-existing empirical regularities. This was certainly not true for the model: the empirical regularities examined in this paper do not exist in the Black-Scholes world, in which implied (and realized) volatility is a constant parameter. More meaningful is "generic performativity," meaning that the theory was used and made a difference in the market. The narrative described in MacKenzie and Millo (2003) provides evidence that this outcome occurred. The strongest impact would be by "Barnesian performativity," meaning that the model was used and actually changed reality to be more like the theory. Based on the empirical analysis presented here, I conclude that this outcome occurred, with option prices dropping sharply to be more in line with Black-Scholes prices as soon as the CBOE opened.

The results of this study sharpen the focus on the precise ways modern option pricing theory helped shape today's vibrant option markets. Figlewski (2002) points out that even simple rules of thumb eliminating only static arbitrage opportunities go a long way in explaining option prices. Traders figured out such basic pricing problems centuries ago. Observers have argued that the major factor in the success of modern option markets is because centralized exchanges enhanced liquidity. Malkiel and Quandt (1969, pp. 165–166)) conclude that "There is no central marketplace... The rather informal ad hoc nature of the present arrangements appears to be the major obstacle in the way of further development of the option market." Derivatives markets did not suddenly spring to life because of breakthroughs in financial theory or simply because exchanges opened. The actual process, described in MacKenzie and Millo (2003), appears much more interesting and complicated. The analysis presented here shows that sophisticated option pricing has a much longer history than is typically suspected.

One conclusion to draw from these results is that the history and development of option markets—before Black, Scholes, and Merton revolutionized theory—should be taken seriously. While the development of no-arbitrage pricing and hedging models yielded a rich stream of unexpected insights, the actual practice of option pricing has been remarkably constant throughout the centuries. Rather than dismiss pre-modern option trading as the province of swindlers, bucket-shop operators, and amateurs, researchers should consider the history and development of the market as an unexploited resource in understanding modern derivatives markets. Still-developing markets such as credit derivatives can be better understood in the context of the long-term development of derivatives markets.

Appendix A

This appendix provides evidence on the accuracy of the implied volatility interpolation procedure used on the 1870s single-stock option data. The analysis uses the data on single-stock option implied volatility from the modern era (2001–2004) to gauge the likely accuracy of the procedure. These modern data are rich enough to allow comparison of the 50-delta implied volatility as computed under the limitations present in the 1870s data with 50-delta implied volatility computed without imposing

[7] *Wall Street Journal*, "The use of privileges," February 19, 1902, p. 1.

Table A1
Summary of strikes and deltas in 1870s option data.

Stock	Strike (% of spot)		Delta			
	Average		Average		Standard deviation	
	Puts	Calls	Puts	Calls	Puts	Calls
New York Central & Hudson River	99.03	101.88	−0.37	0.39	0.03	0.04
Lake Shore & Michigan Southern	98.40	102.63	−0.35	0.37	0.03	0.03
Chicago, Rock Island & Pacific	98.44	102.80	−0.33	0.34	0.02	0.04
Erie Railway	94.22	106.99	−0.29	0.34	0.04	0.04
Pacific Mail Steamship Co.	94.49	108.36	−0.30	0.31	0.06	0.05
Chicago & Northwestern	96.86	105.75	−0.34	0.35	0.03	0.04
Chicago & Northwestern pref.	98.02	102.90	−0.32	0.35	0.01	0.01
Western Union Telegraph	97.75	103.87	−0.33	0.33	0.03	0.04
Ohio & Mississippi	96.62	105.22	−0.36	0.39	0.03	0.03
Union Pacific	96.26	106.29	−0.35	0.37	0.04	0.04
Toledo, Wabash & Western	94.84	107.64	−0.32	0.36	0.03	0.04
Columbus, Chicago & Indiana Central	91.04	113.10	−0.31	0.38	0.04	0.07
Boston, Hartford & Erie	83.79	116.99	−0.21	0.64	0.07	0.08
Milwaukee & St. Paul	96.29	105.77	−0.33	0.35	0.02	0.03
Milwaukee & St. Paul pref.	97.92	103.61	−0.33	0.34	0.01	0.02
Hannibal & St. Joseph	94.29	109.33	−0.33	0.36	0.02	0.04
New York & Harlem	97.84	103.13	−0.29	0.31	0.04	0.06
Average	95.52	106.37	−0.32	0.37	0.03	0.04
Median	96.62	105.75	−0.33	0.35	0.03	0.04

Table A2
Comparison of 50-delta implied volatility estimates.

	Average estimate (%)		Constrained–Unconstrained	
	Constrained	Unconstrained	Average difference	MAE
MSFT	33.7	33.2	0.5	1.3
CSCO	50.5	49.9	0.5	1.7
TWX	42.8	42.2	0.6	1.8
GE	30.5	30.1	0.3	1.2
INTC	44.5	44.0	0.4	1.3
IBM	30.2	29.8	0.3	1.0
C	30.3	29.8	0.5	1.3
ORCL	51.4	50.8	0.6	2.0
TYC	45.5	44.8	0.8	2.1
DELL	38.4	37.8	0.5	1.4
QCOM	50.6	50.1	0.5	1.3
EMC	58.9	58.0	0.9	2.6
HPQ	43.4	42.9	0.5	1.6
NOK	49.3	48.8	0.5	1.7
TXN	51.2	50.7	0.4	1.3
JPM	36.3	35.9	0.4	1.5
WMT	27.5	27.2	0.3	0.9
PFE	27.6	27.1	0.5	1.2
LU	70.7	69.1	1.6	4.2
YHOO	61.1	60.6	0.5	1.7
Average	43.7	43.1	0.6	1.6

those restrictions. I present empirical evidence and conclude that the assumption of a linear volatility skew in delta is a good first approximation for implied volatility near 50 delta, but the convexity of the volatility skew probably imparts a small upward bias to the estimates computed on the 1870s data. The convexity bias is small and does not appear large enough to overturn the qualitative conclusions of the paper.

The next section presents summary statistics for the observed 1870s option data; these summary statistics are used to calibrate the simulations on the modern data set. The following section presents comparisons of the 50-delta implied volatility constructed under the limitations of the 1870s data ("constrained estimates") and without the limitations of the 1870s data ("unconstrained estimates"). It includes an evaluation of the unbiasedness and accuracy of the linearly interpolated estimates on a stock-by-stock basis. The analysis is augmented by a more detailed examination of the period-by-period estimation errors for a single representative firm. The final section provides concluding commentary.

A.1. Experimental design

Table A1 displays average values for strike prices and deltas for the stocks in the 1870s data set. Across stocks, the median call delta is 0.35 and the median put delta is −0.33. I convert the put delta into a call delta with the approximation call delta = 1 + put delta. The last two columns in the table present the standard deviation of delta values for each of the stocks, and the evidence suggests that the deltas for the quoted options were quite stable for many of the stocks. Based on these calculations, I choose 0.35 and 0.67 as the "typical" deltas from which to construct volatility skew models in the following exercises.

A.2. Evaluation of implied volatility interpolation procedure

A.2.1. Cross-sectional evaluation

Table A2 presents evidence that the linear interpolation procedure is defensible. The table presents time-series averages of the implied volatility estimates for each stock in the sample. The column labeled "Constrained" presents the average of the estimated 50-delta volatilities computed in the following fashion. First, the 35-delta and 67-delta implied volatilities are linearly interpolated using the observed implied volatility values most closely bracketing the target values. Second, a line is fit through these points and the 50-delta implied volatility is interpolated. This method closely corresponds to the linear interpolation as applied to the coarser 1870s data set. The column labeled "Unconstrained" presents the average 50 delta implied volatility estimate constructed using the most directly applicable data. In this exercise, the unconstrained estimate is the same as the one used in the paper, and the interpolation to get the 50-delta implied volatility utilizes the observed implied volatilities closest to 50 delta. The final two columns elaborate on the differences between the two types of estimates. Positive values in the next-to-last column mean that the constrained estimate is, on average, higher than the unconstrained estimate, and that the observed data are typically convex around 50 delta. The numbers are all positive, and all but one average is less than one volatility point. The average across stocks is 0.6 volatility point. The final column in the table displays the mean absolute error (MAE) for each stock. The average across stocks is 1.6 volatility points. To put these summary statistics into perspective, the average implied volatility across these stocks is about 43%, with the average for individual stocks ranging from 27% to 69%.

Fig. A1 is a scatterplot of the second and third columns of data in Table A2, along with a quadratic regression line fit through the data. This graphical representation reinforces the conclusion that imposing the limitations of

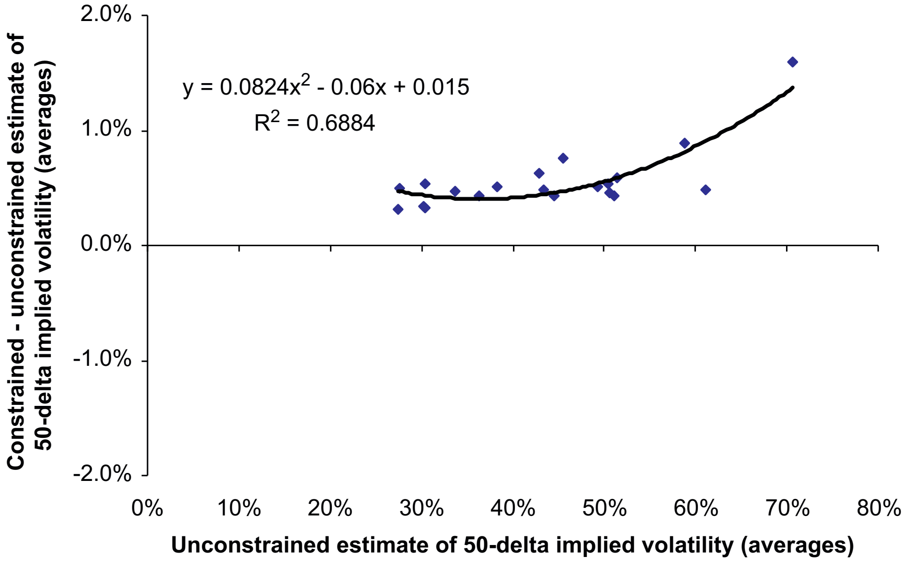

Fig. A1. Unconstrained versus constrained estimation of 50-delta implied volatility (averages).

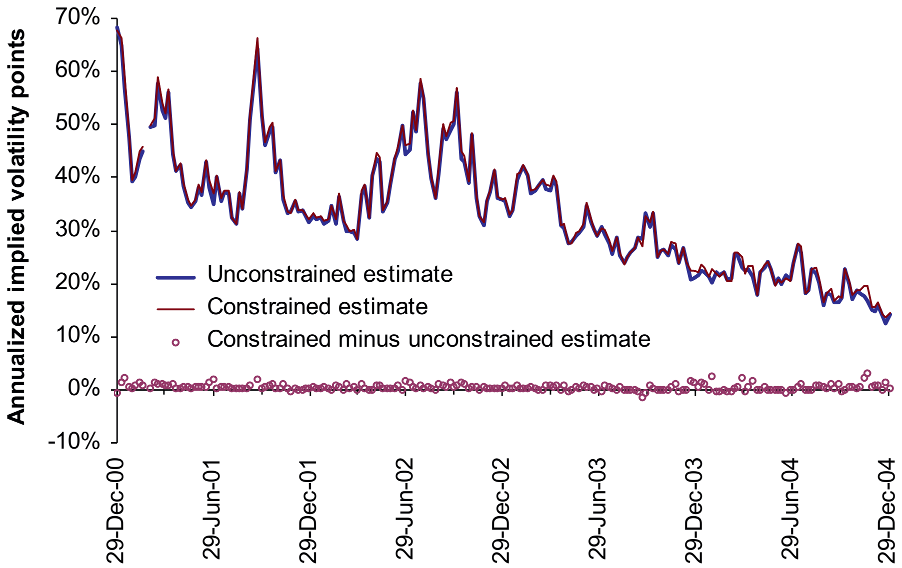

Fig. A2. Unconstrained and constrained estimates of 50-delta implied volatility for Microsoft (time series).

the 1870s data set causes the constrained estimate to be slightly higher than the unconstrained estimate. While the regression suggests that this bias is higher if the true 50-delta implied volatility is higher, this conclusion is strongly influenced by the most extreme data point. The most extreme data point represents LU (Lucent), which also had the highest MAE. Lucent was a low-priced stock over most of the sample; the price was less than $10 per share from April 2001 through December 2004 and bottomed at $0.58 per share. In fact, observations for LU were excluded during the June 2002–October 2003 period because no options with strike prices less than spot were listed. The resulting coarseness of the strike prices (set at $1 or $2.50 intervals) suggests that the implied volatility curve for LU is likely to be a poor approximation to the "true" curve during this period.

A.2.2. Time-series evaluation for a representative stock

Fig. A2 displays a time-series chart for a single stock, Microsoft (MSFT). The figure shows results from the two estimation methods for 50-delta implied volatility over the four-year period, as well as the difference between the two. Generally speaking, the two sets of values correspond quite well with each other, but the difference between them does appear to increase at times when implied volatility spikes up.

Fig. A3 presents the same data as in Fig. A2, but it is organized as a scatterplot rather than as a time series. The unconstrained estimate is measured on the horizontal axis and the constrained estimate is on the left vertical axis. The cloud of dots appears to follow the 45° line in general, suggesting that the two measures line up quite closely. A linear regression line is also plotted on the chart,

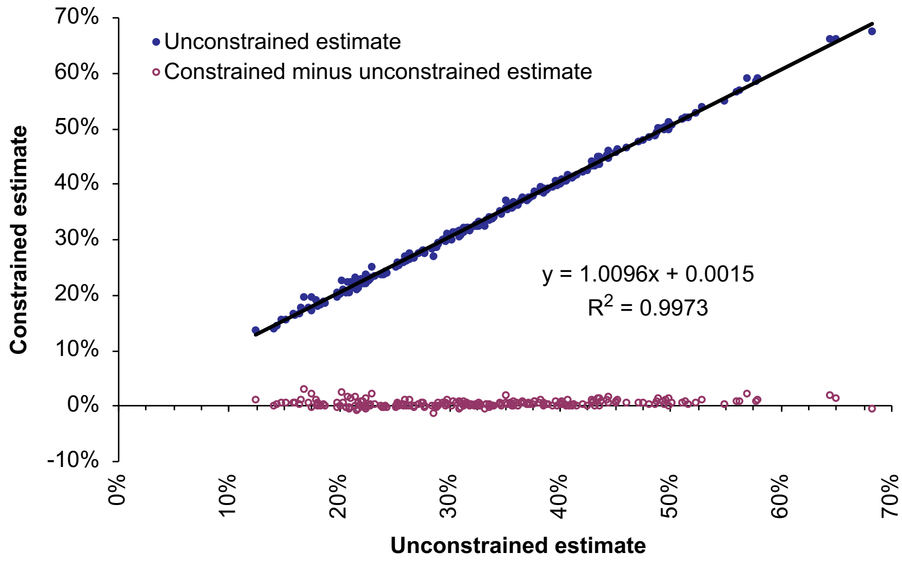

Fig. A3. Unconstrained and constrained estimates of 50-delta implied volatility for Microsoft (scatterplot).

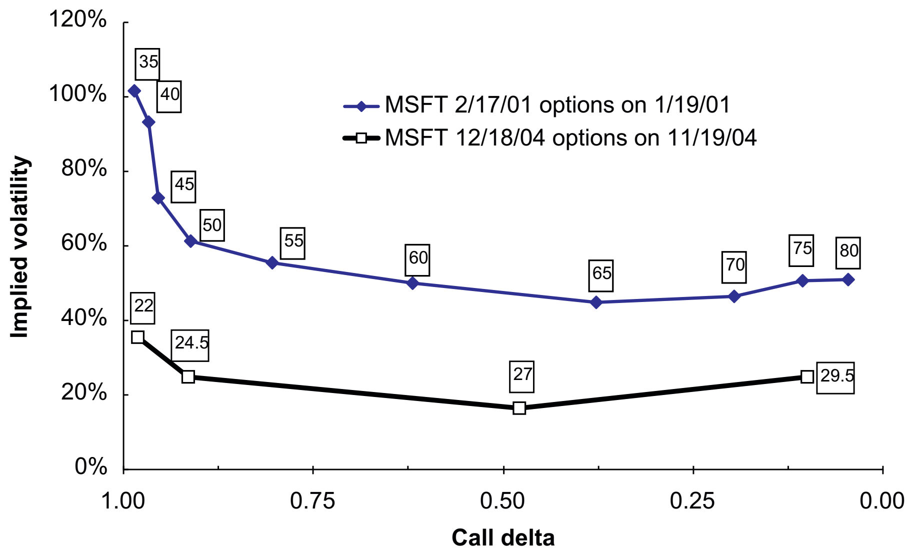

Fig. A4. Implied volatility curve for Microsoft options on representative dates.

along with the R^2 and regression equation. The regression results confirm the general closeness of the two series.

Fig. A4 provides further granularity on the interpolation. The top curve in the figure is a January 2001 observed implied volatility curve for MSFT options expiring in approximately one month; the bottom curve is an equivalent one from November 2004. At-the-money implied volatility was generally higher in 2001 than in 2004, and MSFT had at-the-money volatility of around 45% in January 2001 and around 17% in November 2004. The curves therefore illustrate two distinct environments for the interpolation.

The figure for January 2001 displays the out-of-the-money option volatility points for options with nonzero prices. For the options expiring on December 18, 2004, only one put and one call had nonzero bid values (strikes 24.5 and 27, respectively). The chart includes one option on either side, although several more strikes were listed (each of them having ask prices of $0.05 and bid prices of $0.00). In both instances, the data labels in the boxes are the strike prices associated with the options shown.

One important fact that this figure makes clear is that the observed data are still discrete and imperfect. Based on these data, I conclude that the volatility skew near 50 delta appears close to linear when there are abundant strike prices near that point. When strike prices are far apart in delta space (e.g., when implied volatility or relevant strike prices are relatively low), the observed data are not rich enough to discriminate among linear and nonlinear functional forms. The coarseness of strike price spacing could actually impose spurious convexity when neighboring data points are linearly connected. Put another way, interpolating based on the fictitious 35 and 67 delta volatilities constructed for this exercise may be a bad idea if the 35 and 67 delta vols are themselves poor approximations to the truth.

A.3. Conclusion

The linear interpolation of 50-delta implied volatility is likely to be a good approximation for the 1870s single-stock option data. The methodology is to examine the results of the interpolation procedure when the limitations of the nineteenth-century data are imposed on modern data.

I find that the interpolation procedure yields 50-delta implied volatility estimates that are reasonable, suggesting that estimates constructed from the 1870s data are defensible. Nonetheless, implied volatility skews in the modern data are convex, indicating that linear interpolation produces a small upward bias in the interpolated values. Imposing limitations on the data similar to those found in the nineteenth-century data, I find the bias to be around half a volatility point (at a time when single-stock 50-delta implied volatility averaged almost 45%).

I find it likely that any suggested bias in the implied volatility interpolation procedure is not significant enough to overturn any of the qualitative conclusions of the paper. There are two main reasons for this conclusion. First, it is important to recognize that the modern data are quite coarse at times, exaggerating the convexity in the data. The point is that the modern data are much richer than the historical data (allowing these experiments), but the modern data are still imperfect. Therefore, the simulation pursued in this appendix might present a more pessimistic view of the interpolation than is warranted. Second, and more important, the measured bias is economically small for the purposes at hand. For example, the linearly interpolated implied vols exceed trailing realized volatility by around 25 volatility points (on average) in the nineteenth-century data, and a change of less than a volatility point does not overturn the general story.

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