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Understanding Connections Between Market Price Liquidity and Volatility: Can Quantum-Inspired Models Help?

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Abstract

Measurement is a key element of quantum theory where only one possible outcome comes to pass, while other ones disappear. Similar phenomena have been observed in psychology, language processing, and economics. Mathematical descriptions that employ elements of quantum theory have successfully modeled effects observable outside of subatomic physics. Price and value are important concepts in finance. We distinguish between *price* as something fixed in a transaction and publicly available, while *value* is an agent's private assessment. Measurement and updates of both may happen in asynchronous timelines and the frequency of measurements might impact change. When considering derivative markets, usually the focus is on price dynamics given by a stochastic process – market liquidity is often assumed to be infinite. A more detailed consideration of liquidity in relation to price dynamics is desirable and this work outlines possible angles from quantum-inspired models. We discuss how market liquidity and volatility relate to each other in the residential real estate and stock market. We investigate quantum walks, quantum models of psychological decision making by individuals and groups, and the role that the framing of a question plays, all with the goal of an improved understanding of the link between observed price volatility and liquidity.

Keywords

liquidity, volatility, quantum inspired models, quantum cognition

Introduction

Wittgenstein once stated that "The world is all that is the case" (Wittgenstein, 1922), but our experience is also filled with things that might have been the case but aren't. The problem of hypotheticals (counterfactuals) has permeated much of Western philosophy, at least since Aristotle's analysis in *De Interpretatione*, which includes the idea (still relevant today):

> A sea-fight must either take place to-morrow or not, but it is not necessary that it should take place to-morrow, neither is it necessary that it should not take place, yet it is necessary that it either should or should not take place to-morrow. (McKeon, 1941, *De Interpretatione*, Ch. 9)

There is a long tradition of thinking related to the distinction between potentiality vs. actuality, determinism, and reasoning in hypotheticals – we will briefly review some of this shortly, as a way to motivate interest with the particular perspective from quantum mechanics: quantum mechanics enables a unique formalization of ideas regarding the distinction between potentiality and actuality, through the requirement that uncertainty, prior to a measurement, can be ontic. This work is a brief summary and commentary about the possible cross-fertilization of these insights from quantum mechanics into economics and finance.

Questions of 'how', 'what happened', 'what if', 'was it necessarily so', and 'what will be' are related and greatly predate the emergence of quantum mechanics as a dominant scientific theory. Such questions have been discussed by Western philosophers throughout the history of Western culture and philosophy, including by Augustine, Leibniz, Spinoza, Hume, and many more (Sowa, 2000, Ch 2). In its maturation from natural philosophy, Western *science* has

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often ignored or dismissed such questions. For example, Einstein wrote:

> But the scientist is possessed by the sense of universal causation. The future, to him, is every whit as necessary and determined as the past. (Einstein, 1954, *The Religious Spirit of Science*)

Einstein declares with admirable honesty that his views on necessity and determinism are motivated by a personal belief or intuition that he describes as religious. The notion that there might be all sorts of unpredictable situations, and no way of determining which will really come to pass, is not refuted by scientific demonstration: instead it is assumed that someone who does not believe in determinism is not cut out to be a scientist.

For some centuries, this was a tenable and indeed dominant scientific position, but two main developments have rendered it obsolete. The first is quantum mechanics. Rather than always guaranteeing a single outcome in a deterministic fashion, quantum mechanics gives the probabilities for different outcomes. The probability of each outcome in quantum mechanics is predicted by expressing the system as a superposition of different pure states. This is often written in the form $\sum_n a_n \psi_n(x)$ where $\psi_n(x)$ are the wavefunctions and a_n are the corresponding coefficients. In formal mathematical theory, this becomes a sum of basis vectors in a Hilbert space, written as $\sum_n a_n |\phi_n\rangle$ (see Dirac (1930, Ch 1 §5)). The probability that the system is observed to be in the state $|\phi_n\rangle$ is given by the squared amplitude $|a_n|^2$ (the modulus sign is important because the coefficients are typically complex numbers). Unless something else happens in between, a subsequent measurement of the same system will yield the same result with certainty: so in the process of measurement, the state vector collapses from the superposition $\sum_n a_n |\phi_n\rangle$ to the eigenstate $|\phi_n\rangle$. This was such a strange departure from classical mechanics, that early quantum theorists (including Einstein and Schrödinger) felt compelled to postulate a more fundamental deterministic explanation. Quantum physics predicts experimental outcomes probabilistically with high precision, however, thanks to quantum entanglement and the statistical tests motivated by John Bell's famous inequalities it has become clear that no reasonable realist local hidden variable theory can reproduce observed results (Bernhardt, 2019, Ch 5). Without measurement, quantum theory uses unitary evolution of the system but a measurement stops this evolution by a state collapse (at least in traditional measurement theory – e.g., see (Busemeyer et al., 2025). In particular, quantum theory predicts that as the frequency of measurements increases, the chance that a system remains in it's previous state increases, the so-called quantum Zeno effect (Home & Whitaker, 1997). In specific situations the opposite can be modeled in quantum theory as well, by carefully choosing the set-up: A system where change is accelerated if the frequency of measurements increases (Facchi et al., 2001).

The idea that judgments can alter beliefs is hardly new in psychology, especially in social psychology (e.g., Schwarz, 2007), but, additionally, there has been behavioral evidence for the particular way in which a (mental) state has to change as a result of a measurement in quantum theory — that is, there has been some evidence that the mental state 'jumps' to identify with the stated response, in the way assumed by quantum theory (Kvam et al., 2015; White et al., 2020). (There is also a more commonplace account: we talk about *making* our mind up, rather than *finding* our mind, and once we make up our minds, we don't like changing them – though note that this idea does not necessitate a change in the relevant preference or opinion state).

The distinction between hypotheticals and actuals is particularly apparent in economics. The actual observeable events are transactions, where two parties agree to exchange something at arms-lengths. Throughout, we will assume the simplification that one of the items exchanged is an amount of money, and so we can talk about the 'price' of a transaction in numerical terms. Together with price, the traded quantity (transaction volume) might be available in a data base. Money is designed to facilitate transactions, while in a barter economy the situation would be more complex as pairs of goods that may be exchanged would need to be analyzed, but we do not consider such economies here.

In between transactions, which is most of the time for illiquid items, agents may have different, private opinions regarding an item's 'value'. This is particularly true if the item is unique, like a house or an original piece of art. For other items, like ounces of gold, cryptocurrencies, stocks, etc., traded prices are available on an ongoing basis, but an agent may have deviating views regarding the item's value. The concept of an agent's value assessment provides an undercurrent for which directly observable data is not provided, but where concepts from quantum cognition may be applied. There are even some publicly available proxies for aggregated opinions, like market sentiment indices, put-call-ratios or consumer confidence, so that probing the undercurrent may not necessarily necessitate direct polling of agents.

In general, value is seen as a subjective, individual opinion, which is not observable. In a simple form, it denotes the potential price at which an agent may be interested in doing a transaction; a transaction happens when two parties have compatible enough assessments of value to make an exchange; and thus a price is an agreed value attached to a one-time transaction. An individual may have no prior notion of the value of an item, and asking the question itself may cause a person to form an opinion of the appropriate value which they did not possess before (Yearsley & Pothos, 2014). 'Value' as seen by an individual is not public and is only updated when an individual interested in an item or an asset class is triggered in some form.

Quantum-inspired ideas have been proposed. The quantum economic theory developed by Orrell (2020) considers modeling values as quantum information, transactions as measurements, and prices as classical information recorded from these measurements. The example of prices is central to economics, and a similar approach employing quantum states and measurements has been used to model people making decisions (Busemeyer & Bruza, 2025; Pothos & Busemeyer, 2022) and selecting the meaning of a word in context (Widdows, 2004). In each model (economic, psychological, linguistic, physical), there are several possible outcomes (a price, a decision, a word-sense, a quantum state), the state of a combined system is expressed as a superposition of these possible outcomes, and a decision/observation/collapse occurs when one of these possibilities comes to pass, with a probability predicted by the model. (The accuracy of the predictions becomes the key test of the model's fidelity.) A key notion in Orrell's model is that a quantum-like system evolves dynamically between transactions and models of value can be understood using quantum mathematical concepts, such as interference and entanglement. In some cases, the longer the system evolves between measurements, the larger the change in values can be — so when the number of comparable transactions is small, the uncertainty around what prices will finally be agreed grows.

This paper is intended as a discussion of ideas and results across a range of examples that are related to this theme. The subsequent sections discuss liquidity and price change in the housing and stock markets, respectively, which are then related to a quantum random walk model, where increasing the frequency of measurement restricts the volatility of the quantum walk. Following that psychological ideas are discussed for individual behavior and group behavior.

Fungible and Non-Fungible Assets

We need to distinguish between items that are unique, for example an original oil painting from a famous master or a Tudor house with a interesting history, and items that are fungible, i.e., that may be standardized and transacted interchangeably, because the units are identical in value and function. Examples of fungible assets include ounces of gold without numismatic value where only the quantity of chemical gold matters, stocks, or, for a more modern example, Bitcoins.

With non-fungible items, a specific piece is usually transacted infrequently, so one is often in the dark about the current potential price for the item. This is specifically the case where no comparable transactions have taken place for a longer time period and where the item does not generate cash-flows like rents or dividends, so that discounted cash-flow valuation is impossible. In such cases, one often observes that low liquidity goes hand in hand with high price volatility. Prices may jump considerably between rare successive measurements.

With fungible items, there usually are transactions happening all the time at least in smaller size. However, this does not imply that we have price certainty at all times for larger quantities of the item. Consider stocks in a publicly traded company where only a very small portion of the outstanding number of shares trade on an average day (as it is usually the case), but where someone owns a large block, maybe even a controlling stake. When trying to sell this, the achievable price is difficult to judge. Assuming there are strategic buyers, a large premium might be commanded, but absent such situations, a sale may only be possible over longer periods of time with a large price discount. Here, the publicly traded price for small quantities gives some indication of the evolution in a dynamic world, even though a measurement for large quantities has not taken place in a while.

We will take a brief look at the housing market and the stock market as examples for both types of assets before we turn to abstract modeling questions.

Housing Markets: Associations Between Liquidity and Price Change

Real estate is non-fungible and no two properties are truly interchangeable. The number of comparable properties that were transacted may be larger in cities, but even in such cases, location and individual features are crucial. In large urban agglomerations, transaction prices might be available for several pieces of residential real estate ('housing') in closer spatial proximity; for example, one flat may be facing north on a low floor of a high rise building, while a similarly sized flat may be situated on a higher floor and face south-west direction. One house may be old but in a quiet side street, while a similar sized house may be new and next to a main road. Liquidity for individual objects in rural areas may be low in general with sales only happening once in a while. Where no comparable transaction took place for a while, the owner may be in for a surprise. In this sense, one might say that "low liquidity brings volatility".

In order to obtain statements about the general development of residential real estate prices, individual house prices need to be aggregated. The well-known Case-Shiller Index looks at residential real estate prices in the United States based on repeated sales of the same property. While this takes into account specifics of individual properties, it also means that low liquidity market areas are underrepresented and renovations and new builds are problematic. Reports from the European Mortgage Federation (EMF) or the Zillow House Value Index, which uses model based valuation independent of transactions, take a different approach. Dröes and Francke (2018) analyse data from the EMF and find a strong lagged feedback mechanism between prices and turnover. They conclude in particular that part of the price momentum that is typically found in housing markets can be explained by the feedback between prices and turnover. Zheng (2015) shows that less liquid housing classes are more sensitive to unexpected liquidity shocks, with the starter housing class being very sensitive to negative liquidity shocks.

Sentiment and psychology play an important role in real estate markets with their well-known boom and bust cycles, so the use of tools from quantum cognition could be interesting. Ling et al. (2015) e.g., connect sentiment of buyers, builders, and lenders to house prices and find that a market sentiment shock is associated with house price change over the next two quarters.

In recent work, Widdows and Bhattacharyya (2024) tested a hypothesis based on the quantum Zeno effect using Zillow Housing Data. For nearly all metro areas in the USA a positive correlation between liquidity and price change could be established in the data set, see Figure 1. When there are fewer transactions, there tends to be a larger gap between the initial listing price and the eventual sale price. The impact of a particular measurement or transaction on a subsequent comparable transaction may be possible to trace in practical models (e.g., in terms of expectations of how the density of comparable transactions might impact volatility).

Stock Markets: Volatility as a Separate Asset Class

Here we discuss stocks as examples of fungible items. In contrast to housing markets, traded option prices exist along side stock prices. Thus, there is not only the statistical volatility that can be computed retroactively from the standard deviation of a historical time series of stock prices changes, but also volatility expectations implied by the option prices quoted in the equity derivatives markets.

It is just over 50 years since the introduction of the Black Scholes model for option pricing (Black & Scholes, 1973).[1] The Black Scholes model has long been hailed as transforming option trading from being akin to gambling to being an exact form of risk-management: but there is also a cost of making seriously simplifying assumptions, for example that the available liquidity is assumed to be infinite under ideal market conditions. Another problem is that the estimate of the cost required to replicate the option, as computed by the Black Scholes formula or a tree model, depends crucially on volatility.[2] This is formalized as

$$\begin{aligned} \frac{dS_t}{S_t} &= \mu dt + \sigma dW_t, \\ L_t &= \infty, \end{aligned}$$

where S_t, σ, and L_t denote stock price, volatility, and potential stock liquidity (i.e., the maximum volume that is tradable at time t without moving the price) at time t, respectively. As perfect replication of the option is possible in that model, μ can be set to the risk-fee interest rate. In the simplest case, the volatility of future stock price change is assumed to be a known number $\sigma > 0$. In elaborate models, σ is assumed as a more intricate function or a separate stochastic process, which is fitted to the information about implied volatility that can be inferred from quoted prices for options.

The spirit of the model is such that there is always a unique observable price for an asset which changes with some drift μ plus an unpredictable random component over time. In the Black Scholes model, the random change is driven by Brownian noise, i.e., the change dW_t is a normally distributed random variable with mean zero and variance dt. In this model, the stock price follows a classical random walk as the binomial distribution converges to the Gaussian distribution.

After the 1987 market crash, economists questioned the Black Scholes assumptions more critically, noting that the *implied* volatility — which measures the amount by which traders expect a stock price to vary in the future — is *not* constant and may suddenly change in an unforeseeable manner. In addition, it was observed that the distributional assumption for stock price change underlying the Black Scholes model underestimates the probability of large stock price change, which traders correct by using a volatility that is dependent on the strike price for the traded option. This gives rise to a term structure of volatility, where implied volatility depends on the time to maturity and the relative distance of the strike price from the current price of the stock. For a single stock, we typically observe that the further the strike price is from the current price, the higher the traded implied volatility. This behavior had been noted in the markets by the mid-1990s (Derman & Kani, 1994), and gradually became called the 'volatility smile' (Figure 2). Other types of volatility term structures may occur, for example in stock indices, where it is often observed that out-of-the-money call options command lower implied volatilities compared to at-the-money options.

Quantum-inspired ideas have already been considered in this area. Orrell (2022) developed a quantum oscillator model that aims to describe such dynamics of the stock market more explicitly. In basic classical economics, it is assumed that prices are single values and that the market converges to

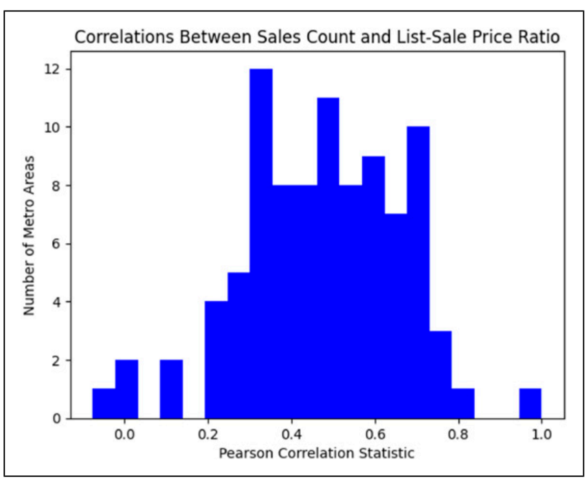

Figure 1. Evidence for the correlation between liquidity and volatility in the housing market. Nearly all regions in the USA tend to show a smaller gap between list and sale price when there are more sales

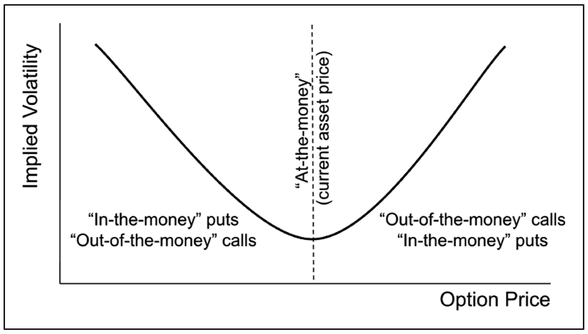

Figure 2. Schematic diagram of the volatility smile

these values instantaneously. Consider the traditional supply-demand curves in Figure 3. The classical equilibrium notion is that a rise in price stimulates more supply, but reduces demand: the volume of a commodity that is created and the price for which it is sold depend on where these supply and demand curves intersect. If a new source of supply is discovered, the supply curve may move upwards, moving the intersection between the curves to a lower price. In practice, this does not happen instantaneously, but the process of transition is not part of this model. To the extent that the value assessment of agents is considered, such a behavior may result naturally: When the price increases the number of agents whose private value assessment exceeds the current price becomes smaller, so demand for the item goes down.

Orrell argues that this whole situation can be modeled better if the dynamic momentum of the situation is part of the model, and if one abandons the notion that there is a single 'objectively' determined price and value at any point in time. Instead, his model assumes that prices change and oscillate. In his model, this is derived from the quantized entropy of the propensity curve, eventually deriving a probability that a transaction will take place within a given time-window. This is one of several 'quantum trading' models that describe the amount of a commodity owned by a trader, and the probability of this changing, using quantum oscillators and energy levels (Haven et al., 2017). In Orrell's approach the frequency of transactions, and the implied volatility of the stock, are both determined by the oscillations in a trader's perception of value, modelled by a quantum state.

More formally, Orrell's model represents a trader's perception of value as a quantum state evolving under a harmonic oscillator Hamiltonian,

$$H = \frac{1}{2}\hbar\omega\left(\hat{a}^{\dagger}\hat{a} + \hat{a}\hat{a}^{\dagger}\right), \tag{1}$$

where ω is the characteristic frequency of oscillation in the trader's value assessment, and $\hat{a}$, $\hat{a}^{\dagger}$ are the standard ladder operators (Orrell, 2022, 2024). The energy levels $E_n = \hbar\omega(n + \frac{1}{2})$ govern the propensity for a transaction to occur within a given time window: a low oscillation frequency ω corresponds simultaneously to a wide bid-ask spread and high implied volatility, both emerging from the same underlying parameter rather than being assumed separately. This stands in contrast to the Black–Scholes framework above, where volatility σ is exogenous input and liquidity L_t is assumed infinite. In Orrell's model, both quantities are endogenous consequences of market energy.

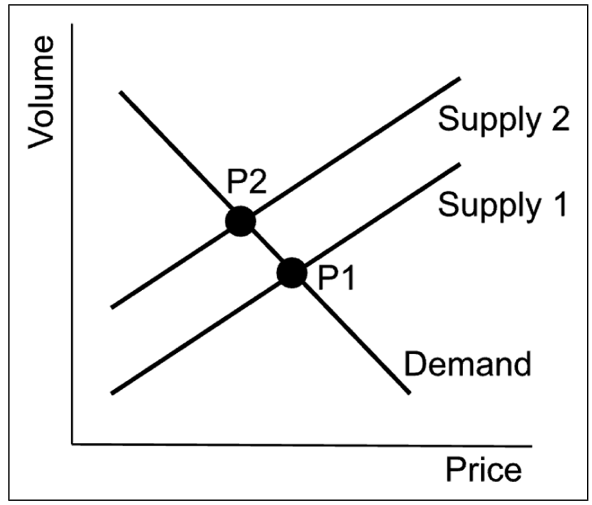

Figure 3. Traditional supply and demand curves, the intersection of which determines the price of a commodity in classical economics

The quantum walk model introduced in the next section is complementary but distinct in character. Where Orrell's oscillator is a *mechanism* model — deriving spread and volatility from an economic potential energy — the quantum walk is a *distributional* model: it describes the shape of the probability distribution over possible price positions after a given number of steps, without specifying the force driving the walker.

In Orrell's oscillator model, a low energy, or low frequency of oscillation, can lead to both large differences in opinions of value (manifested by a large bid-ask spread), and higher implied volatility (Orrell, 2024). In such a model, it is natural to expect that "low liquidity brings volatility", or at least that they are correlated: a smaller number of transactions, and higher implied volatility, are both associated with a large amount of market uncertainty. As such, a connection between σ and L results. Of course, classical models may be constructed with corresponding built-in features. But, even without specifically introduced built-in features, classically a greater density of observations would constrain error corresponding to some quantity of interest, hence reducing volatility, arising from different value perceptions.

Note, the idea that low liquidity (sometimes) results in higher volatility is consistent with the quantum Zeno effect, whereby a greater density of measurements can reduce dynamical change. We consider the quantum Zeno effect in more detail below. For now, in addition to the simple theme "low liquidity brings volatility", one has to keep in mind that in real markets several effects can be at work at the same time. Specifically, if there is news that drastically changes the perception of market participants on future prices and/or their risk taking appetite, then large investment portfolios may have to be adjusted considerably which results in higher traded volumes that go hand in hand with large price changes (higher liquidity bringing about higher volatility). At the same time, market makers, who are usually good liquidity providers are likely to widen their bid-ask spreads and reduce their quoted volume in the face of increased volatility to preserve capital. The net result of these effects may vary and possibly result in high volatility going hand in hand with increased or with decreased liquidity. In quantum theory, there have been well-understood ideas regarding the transition from a quantum Zeno to a quantum anti-Zeno effect and this is a potential source of added value from a quantum perspective here (that is, if such physical models can be translated to terms relevant to a market under study). This is not to say that classical alternatives may not be possible, however, the most immediate classical intuition only concerns higher liquidity and low volatility.

Regarding formalisation, there are several possibilities, including ones in the work referenced above. In our way of thinking, distinguishing between value and price, the main elements which are needed would be as follows: A general model would consider the observable market prices S_t together with available liquidity L_t and observable volatility σ_t over time t. In addition, it would specify the view about value V_t^k held by agent k at time t, possibly in conjunction with the financial potency (resources) R_t^k of that agent. Generally, one would expect for each point in time a distribution of individual value assessments among the agents $k = 1, \ldots, K$. We note that the concept of value may not only be applied to individual assets but, for example, also to algorithmic trading strategies. Psychological aspects are not removed just because a quantitative strategy is implemented automatically, human agents still have to apply capital to such strategies and in doing so they have to apply a concept of value to specific algorithms.

Update rules would deal with changes in V_t^k (incorporating behavioral traits) and with the interplay between the V's and (S, L). In a market without derivatives, σ would result from changes in S, but when traded option prices exist, their implied volatility gives an additional source of data. On a more advanced modeling level financial potency R_t^k, e.g. risk appetite and the possibility to receive loans, will be influenced by (S, L, σ).

Quantum-Inspired Directions

From the area of quantum-inspired models three ideas seem promising for further investigation around the interconnection between liquidity and price volatility. First, a quantum walk typically allows the generation of bi-modal distributions, such that the measurement frequency governs the distance between the peaks of the distribution. This tool may be useful for both modeling value and price dynamics. Second, we can consider an application of principles of quantum cognition to individual behavior. Third, we will discuss the aggregation to group level behavior, possibly through Ising models and state collapse, for agents taking into account the importance of the narrative and the framing of certain questions of economic conditions and asset class valuations.

Quantum Walks and Measurement

A key assumption underlying the Black Scholes model is that stock prices follow a 'random walk' pattern in lognormal space (Orrell, 2020, Ch 6; Hull, 2021; Bingham & Kiesel, 2014). It is well-known that the position reached after n steps in a classical random walk has a binomial distribution, which for large n approximates a normal Gaussian distribution.[3]

A *quantum walk* is different: the wave function can evolve over time, with a superposition of upward and downward steps, and only after being measured is the position of the walker fixed. This can lead to bimodal distributions, where the momentum of the walker's up or downward steps constructively interfere to send the walker to either extreme, rather than forming a normal distribution around the mean. (Notably, this two-tailed pattern can sometimes occur in beliefs-of-value, especially with new instruments, such as cryptocurrencies: many people reckon that Bitcoin in the future will be worth a fortune; many reckon it will be worthless.)

The simulations in Figure 4 follow the quantum walk design of Widdows and Bhattacharyya (2024), based on Orrell (2020, Ch 7). The walk operates on a composite state space $\mathcal{H}_C \otimes \mathcal{H}_P$, where $\mathcal{H}_C = \mathrm{span}\{|\uparrow\rangle, |\downarrow\rangle\}$ is a two-

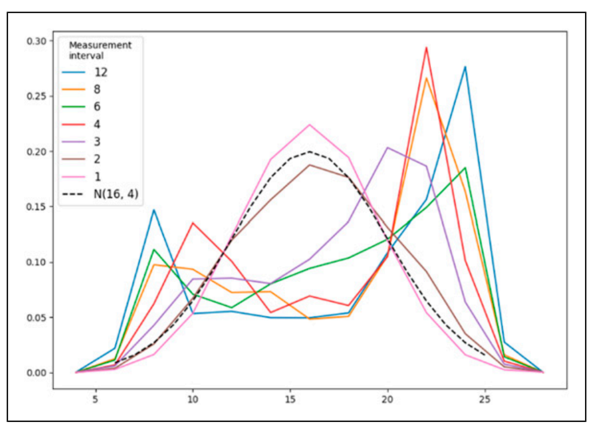

Figure 4. Quantum walks, starting at position 16, ranging for 16 steps, with different measurement intervals. The probability of the first step being forwards is set to 0.8, leading to bimodal distributions with peaked unequal tails. The larger the measurement interval, the more pronounced the two peaked pattern becomes

state coin register and $\mathcal{H}_P$ is the position register. At each step a biased coin operator

$$C = \begin{pmatrix} \sqrt{p} & \sqrt{1-p} \\ \sqrt{1-p} & -\sqrt{p} \end{pmatrix} \quad (2)$$

is applied, followed by a conditional shift moving the walker forward or backward depending on the coin state. With $p = 0.8$ and a walk of 16 steps from position 16, the interference between superposed paths produces the asymmetric bimodal distributions visible in Figure 4. Periodic measurement at interval m collapses the position to a definite value and restarts the walk, with larger m allowing more interference to accumulate before collapse.

Quantum walks show properties that deviate from those of classical random walks. For example, their diffusion rate is quadratic in time while classical Markovian random walks have a diffusion rate that is linear in time. For background on quantum walk theory more broadly, see Kempe (2003) and Venegas-Andraca (2012).

Such a quantum walk may be used to model the private value assessment and even the publicly traded price. When applying it to 'value' a key modeling choice concerns the question of what constitutes a measurement and thus leads to a collapse on one side of the binomial distribution.

Quantum Walks and Psychological Uncertainty

In considering the impact of quantum-like vs. Bayesian thinking, one could argue that the former is more likely to be black and white vs. the latter. This is because in the former case, mental states cannot be introspected, therefore any introspection (e.g., from a desire to reduce uncertainty) would force a measurement on the state and a collapse to relevant eigenstates. This is a requirement from a famous theorem in quantum theory, the Kochen-Specker theorem (e.g., Hughes, 1989, Ch 6). Such eigenstates would correspond to the extreme end points of the relevant question. For example, a trader considering whether to hold or sell a stock might represent their uncertainty in a superposition state, such that the amplitudes provide a nuanced picture regarding the probability of these actions. If the trader is forced to or wishes to examine this uncertainty state, a decision would collapse to the relevant extremes, losing any more nuanced detail. Note, this picture would apply regardless of the granularity of the corresponding internal scales. For example, one trader might represent value in terms of 5 eigenstates, from 'close to zero' to 'very high'. A measurement then collapses their internal state to one of these 5 eigenstates, with the most likely eigenstate being the one closest to the original mental uncertainty state. Such effects would alter the mental state, unless the density of eigenstates is so high that they faithfully sample the relevant value range. Similar points apply regardless of the nature of the space, e.g., value, action etc. The point applies that any attempt to access the mental state would lead to some coarsening of the underlying belief.

By contrast, a Bayesian trader would be able to introspect their mental uncertainty state without necessarily altering this state. A Bayesian trader could hold more nuanced beliefs regarding value and relevant actions, that is, if the actions are to hold some stock or sell it, a Bayesian trader would be able to have (accessible) uncertainty states corresponding to any relative weight between these two actions.

It may be surprising to talk about quantum-like vs. Bayesian traders. However, in general, work on quantum cognition shows that, both between and within individuals, there are certain characteristics which make one mode of inference more likely than the other, with a complete picture of behavior captured though a combination of quantum-like vs Bayesian thinking (Huang et al., 2025). One factor which tends to predict more Bayesian thinking is greater familiarity with the subject matter (Yearsley & Trueblood, 2018). For a diversified asset manager, we would expect that they would be unfamiliar with details of all assets but e.g. for a merger arbitrage hedge fund with a small number of large positions great familiarity may be assumed. Importantly, there is some indication that both cognitive load and (e.g., emotional) bias might lead to more quantum-like thinking (Huang et al., 2025). All these considerations do suggest that diversified investors might be more quantum-like in the way they assign probabilities, with interesting implications regarding both a more 'black and white' approach to behavior and the emergence of classical probabilistic fallacies (e.g., order effects). However, humans are expert at remembering previous alternatives and sometimes regretting decisions, e.g., "If only I had done such-and-such instead, the current situation would be better." In this aspect, human decisions are very different from single-state quantum measurements or more sophisticated quantum measurement models may be needed (see Busemeyer et al., 2025).

Overall, we suggest that a classical investor would always have a firm view, albeit a nuanced one, i.e. having a threshold below or above which to sell; since he can introspect on the belief state without changing it, he can adjust minutely without being forced to a decision. A quantum-like investor would generally be assumed to have a superposition belief state and but will collapse to a (slightly more) black and white view when a measurement is triggered, so it becomes important to specify what triggers a measurement. This may for example happen when a neighbor announces that she has sold her BTC or when some news or podcast comes up that incites introspection of the personal belief state. For a quantum-like person, checking the state can only mean measuring and so projecting; therefore, even small trigger events might lead a quantum-like person to action, especially if their set of eigenstates allows for a coarser sampling of the relevant range. So, with quantum-like investors prompting measurements on their state is more likely to lead to action.

One interesting prediction from the idea that measurements can change a system is a so-called quantum Zeno effect or, colloquially, that a watched pot never boils. Remarkably, there is some evidence that this occurs in physical systems (Home & Whitaker, 1997; Misra & Sudarshan, 1977). In behavior, Atmanspacher et al. (2004) first outlined a corresponding prediction for human perception, but the first direct empirical demonstration has been due to Yearsley and Pothos (2016). They asked participants to consider a hypothetical murder mystery. The suspect was initially assumed innocent. Across several (hypothetical) days of trial proceedings, participants received pieces of information indicating the suspect's guilt. Individually, each of these pieces of information would be quite weak, but collectively they would make a very strong case for guilt. Now, imagine a participant in that study: before seeing any evidence, their mental state would be closely aligned with the innocent eigenstate (the state corresponding to certainty that the suspect is innocent). Then, they would see one piece of evidence, which would be modeled as a small rotation of the state vector towards guilt. If, at this point, the participant is asked to decide between innocence and guilt, their mental state is likely to collapse back to the innocence eigenstate — where she started from. It is in this way that the density of intermediate judgments can increase survival probability (the probability of no-change after seeing all information, relative to the initial measurement outcome), a prediction that was empirically confirmed. Note, the idea that step by step judgments can alter belief updating is not new in psychology. Hogarth and Einhorn (1992) had considered such possibilities long before the application of quantum theory in cognition. However, in their work, the requirement that 'intermediate' measurements affect opinion change was heuristically expressed, lacking axiomatic foundation and generative value.

A 'pure' quantum Zeno effect has the property that *In the limit of continuous measurement, the evolution of the system can be completely suppressed* (Atmanspacher et al., 2004). Such an effect would be equivalent to high liquidity bringing about low volatility. However, in finance, the converse is also observed too: some days on the stock market see both heavy trading and large price variations, so the Zeno effect is *not* consistently observed. The association between high liquidity and high volatility is equivalent to anti-Zeno behavior, which can also be expressed with quantum models (Facchi et al., 2001). The transition from Zeno to anti-Zeno regimes can provide interesting angles of study and a direction of quantum-like modeling with potential added value over purely classical methods.

Quantum Modeling of Group Behavior

The bulk of applications of quantum theory in social science has been at the level of modeling the behavior of individuals (though we note that the work of Lawless (2020) concerns groups and organizations and the work of Khrennikov (2019, 2025) applies ideas from laser theory to social systems; see also the work of Baragello (Bagarello & Gargano, 2023). Consider the above examples of different investor decisions: they concern an individual's belief state which changes, as a result of committing to a decision.

Most work in quantum cognition concerns the cognitive processes of an individual and, at least in some cases, there appears to be a good match between cognitive and quantum-like processes (Pothos & Busemeyer, 2022). However, the application of these insights to groups of individuals has rarely been discussed (Bagarello & Gargano, 2023). One problem is this: if an individual investor makes a decision about a stock, then there is no particular difficulty in assuming that their mental state changes in a corresponding way. But, if a group of investors make a decision, can we validly assume that this will have at some point in time a measurable impact on some aspect of the (financial) world, consistent with quantum theory? Note that one person's decision — or even that of a larger group — does not always become accepted or change the beliefs of others.

Bachelier noted this dissonance in beliefs, saying:

> *Contradictory opinions in regard to these fluctuations are so divided that at the same instant buyers believe the market is rising and sellers that it is falling.* Bachelier (1900)

This may sound surprising, but is commonplace in politics: respondents surveyed in opinion polls give different opinions on whether their country is headed in "the right direction" or "the wrong direction", and this is typically correlated with whether the respondents' preferred party is currently in office. Combine this with some physicist's preferred understanding of the uncertainty principle as applying *only* to ensembles of identically-prepared systems (Hilgevoord & Uffink, 2024; Nielsen & Chuang, 2002, §2.2), and it is perhaps surprising that the application of quantum cognitive models to group behaviors has not been more common.

As an example related to group behavior, we consider applying a standard 'decision as projection' model to a collection of points, representing the notional views of a population of voters. The initial distribution of the views of these voters is depicted at the left of Figure 5. The diagram is deliberately somewhat dissimilar to various examples employed in quantum cognition, whereby points represent possible states-of-belief, and the axes represent questions that can be posed/decisions that can be made (Note, in a quantum model states are normalized vectors, so here we can just assume that the two-dimensional diagrams represent projections of corresponding states, which are normalized in a higher dimensionality space.) We assume there is an arc or spectrum of views between the 'red team' and 'blue team' positions: for example, someone's ideal proportion of revenue spent on a particular program. The

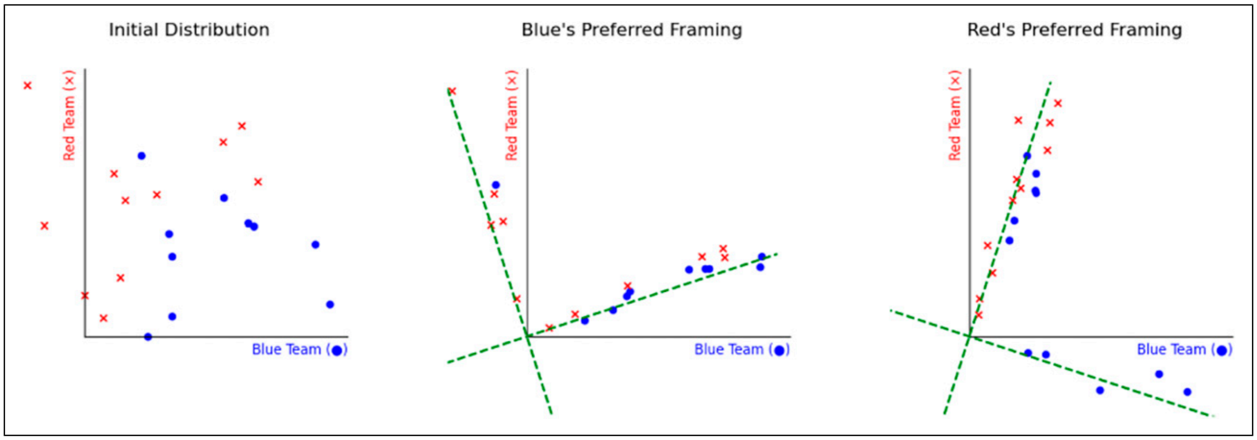

Figure 5. A notional distribution of viewpoints, and how they are likely to be 'projected' differently by choosing different axes for measurement. An initial distribution (left) represents the viewpoints of individuals with different party affiliations in an orthogonal standard base given by the horizontal and the vertical axis. Each party would like to 'frame the debate' by asking a question that unites their party, and divides the opposing party as much as possible. The preferred 'debate frames' are depicted by the dashed lines. They are assumed to be rotations to a new orthogonal pair of base vectors. In the middle picture, this basis is chosen so that nearly all the blue team is projected to the same 'side' and the Red Team is divided, and vice versa for the picture on the right. Strictly, the Lüders rule would have these projections land directly on the dashed measurement lines: in the diagram, we have just projected them close to the measurement lines, for ease of reading

distance from the origin could reflect the intensity of an individual's feelings on the issue (again, note that technically pure quantum states would all be unit vectors, and the different radial distances in Figure 5 are only used to make the diagrams easier to follow).

The individuals are already split between two different teams, an affiliation we assume is based on a variety of issues, including but not limited the one in question. (Thus, most of a team may agree on this particular issue, but there may be outliers.) Each team is trying to score points from the other team, by making their own point-of-view sound reasonable, and their opponents' extreme. This incentives the teams to ask different questions. If the blue team can choose a debate axis that is close to their team's centroid-of-opinion, nearly all the blue team will toe this party line, and indeed some of the more centrist red team members too. This splits the red team in two. The red team, of course, would like to choose an axis that unites their team, and splits their blue opponents. These scenarios are depicted in the middle and right of Figure 5.

In finance, as an example, the cryptocurrency Bitcoin (BTC) causes ardent debates between skeptics and proponents, who are often quite keen on winning new followers. While some investors would say that its long term value is zero, other would disagree, state high price targets and argue that BTC is something like gold in the digital age, with a finite supply on the BTC blockchain that is not influenced by nation states and traditional central banks, so that BTC will always be a valuable global asset. So there is a large disconnect and arguably the state of mind regarding the future value of BTC of an undecided investor, standing on the sidelines, can be seen as a superposition between these two views. This initial state evolves over time while the investor may sometimes not care about BTC or at other times listen to discussions.

Framing plays a role as BTC-advocates usually prefer a discussion about the issue of whether traditional (fiat) paper currencies can remain functional in the long run in the face of increasing public debt levels, while BTC-adversaries prefer a discussion about what BTC actually is, i.e., a distributed public ledger file on a system of peer-to-peer computer nodes with an energy consuming proof-of-work verification mechanism that was proposed in a white paper in 2008 by an unknown author. With some investor groups holding individual views that the value of BTC intrinsically is zero and other groups already invested in BTC standing to profit from persuading additional investors to join their camp, the question of how to frame the debate becomes important.

Though extremely simple, this picture effectively describes 'wedge issues' in politics. Sometimes, the reason politicians avoid answering a direct 'yes/no' question is precisely because they know that either answer will displease some of their supporters. The incentive to divide ones opponents was documented by ancient authors, including Sun Tzu and Thucydides, and the technique of carefully choosing an *ideological* wedge-question is demonstrated explicitly by Paul in Acts 23:6.

An important problem concerns the question of how to aggregate individual behavior taking into account the interaction between agents. In physics and computing, Ising models and their corresponding Hamiltonian formulation are popular for studying neighbor-neighbor interactions. A simple Ising quantum model to describe ferromagnetism in statistical mechanics is given by the Hamiltonian eigenvalue expression

$$H = -\sum_{\langle i,j\rangle} J\sigma_i\sigma_j - \mu\sum_i h_i\sigma_i$$

where σ_i and σ_j are the spin values (i.e., the eigenvalues of the corresponding local quantum spin operators) at sites i and j, J is the coupling between neighboring spins, $\langle i,j\rangle$ indicates that the sum is over nearest neighbor pairs of spins, μ is the magnetic moment, and h_i is the external magnetic field. The Hamiltonian captures the energy of a magnetic system, taking into account the alignment of spins and the effect of an external magnetic field. Ising models are known to admit significant phase transitions: under the right circumstance (such as a particular temperature threshold), measuring and fixing just a few sites can have knock-on effects to many more. The aggregation in a financial markets context can be done in different ways, e.g., as described in Cont and Bouchaud (2000) where percolation clusters act as buying or selling investors which may result in heavy-tailed price dynamics or as described in Stauffer and Sornette (1999), where clusters can shatter and aggregate continuously over time. In Shirazi et al. (2017) the cluster sizes in the interaction network vary and in times of crisis the network deviates visibly from pure randomness. When it comes to using Ising models in connection with quantum inspired models of cognition, the choice of aggregation mechanism should be co-ordinated with the quantum cognition model used.

Conclusion

Instead of the world being just "all that is the case", we start by considering the world as a vast space of possibilities, only a handful of which come to pass. Human language describes things that do not come to pass, just as well as things that do. When forming opinions, about value or other things, humans take into account the space of possibilities. We have seen that, in a variety of situations, a scarce supply of traded prices i.e. possibilities for transaction levels becoming fixed by measurements (a situation of low liquidity) leads to a high degree of uncertainty in the possible outcomes. Here the next traded price may deviate substantially from the previous one: low liquidity brings volatility.

A broad correlation between liquidity and volatility can be explained easily using classical statistics: smaller samples lead to higher uncertainty. The distinctly quantum part of our considerations is the treatment of intervening states, where different hypotheses are free to interact and interfere with one another, so long as they are not forced into a fixed state by measurement. This feature has been explored using different experimental setups, including psychological inquiries and quantum simulations, and works like Orrell (2024) and Yearsley and Pothos (2016) showing that more accurate predictions can be made by *not* assuming a fixed trajectory between observations. An additional potential source of added value from quantum-like models concerns the transition between the Zeno and anti-Zeno effect, that is, the transition from an association between high liquidity and low volatility to high liquidity and high volatility. There are corresponding physical models and so there is a potential source of inspiration regarding applications in finance.

Quantum-inspired models provide a tools that may allow the treatment of such situations. Quantum walks can, for example, model a type of dynamics which produces a bimodal distribution, where the separation between the peaks is wider when the frequency of measurement is lower (infrequent price assessment in low liquidity markets or infrequent value assessment by an individual, when triggers to update their investment occur rarely). The quantum walk model applied to price would be consistent with higher volatility (i.e., a larger deviation between last price and new price level) occurring hand in hand with lower liquidity (i.e., a low frequency of measured transaction prices). Also, it would be surprising if quantum-like random walks were applicable in all cases. What is needed is some theory concerning when we expect quantum-like vs. classical random walk, e.g., in relation to the price change of some commodity. If this can be accomplished, then it would be possible to anticipate a relation between an increase in density of transactions and a change from bimodal to unimodal dynamics vs. broad to narrow unimodal dynamics (a similar point broadly applies to how degree of monitoring interacts with belief changes).

An analytical and practical test for such models would be to describe more explicitly how the situation changes with each new measurement and when such effects occur. A particular example for the residential real estate market might be the evolution of expectations of the value of an individual house: is it possible to show that a nearby sale affected the market in a particular neighborhood, and if so, can quantum methods predict this behavior any better than classical approaches? A goal for the stock market would be a better understanding of the connection between volume, price change, and volatility. How do phase transitions between a lackluster trading environment and a market frenzy occur? When does 'judicious' choice of questions nudge polarization? When can we use the Ising model to understand the propagation of influence in a community? These are theoretically and practically important questions, as long as there is some understanding of the conditions of applicability of these quantum-like ideas.

More generally, there seem to be many fields where scarcity of reckonings leads to a wide range of beliefs and uncertainty. We hope that some of the ideas presented here will encourage more such applications.

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Notes

1. There are many kinds of financial instruments traded as 'options': the Black Scholes formula in particular addresses the case of so-called *European*-style options, which allow the bearer to buy ('call') or sell ('put') a stock for an agreed strike price p at a specific later maturity date T. There are also *American*-style options that allow the bearer to exercise an option at any time until T, and *Asian*-style options where the strike price or payout depend on average values over a period, etc.
2. Historic volatility is typically defined as the standard deviation of the (logarithmic) rate of return of price S in a recorded time series and stated on a per annum basis. However, to replicate an option future stock price volatility σ needs to be known until maturity date of the option. The term 'implied volatility', refers to the volatility that traders anticipate for the future, as evidenced by how much they are willing to pay for an option with a given maturity and strike price. If such an option price is known together with the price of the underlying stock, interest rate and dividend expectations, the Black Scholes model allows the computation of the implied volatility that corresponds to the current option price.
3. In the Cox–Ross–Rubinstein binomial tree model a stock is likely to go up or down by some percentage every day. For small time steps the tree model converges to the Black Scholes model as the classic random walk converges to a Brownian motion.

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