investigate whether other components of milk also signal to the infant to trigger different postnatal maturational programs — for example, in the gut and the nervous system. Other nuclear receptors that bind to RXR to form heterodimers and have established roles in promoting cardiomyocyte maturation[6–8] should be analysed, to determine whether γ-linolenic acid modulates signalling through heterodimers or exclusively through RXR homodimers.

In heart failure, energy metabolism in heart cells shifts away from FAO and towards metabolism of glucose[9]. It will be interesting to determine whether altered γ-linolenic acid signalling through RXR contributes to this shift, and if it can be mitigated by administration of γ-linolenic acid. Human stem-cell-derived cardiomyocytes have promising uses in disease modelling and heart regeneration, but these cells fail to mature in culture and resemble neonatal or fetal cardiomyocytes[10]. Treating these cultured cells with a combination of fatty acids enhances their ability to generate force and their oxidative capacity[11]. Could augmentation of RXR signalling, by addition of γ-linolenic acid, further improve the maturity of these cells?

Paredes and colleagues have identified an environmental cue that triggers metabolic maturation of cardiomyocytes. The mechanism they have uncovered adds to a growing body of evidence for the role of the mother–infant relationship in postnatal development. Further investigation of this interplay could help researchers to better understand how the mammalian body is remodelled in the hours and days that follow birth.

Pingzhu Zhou and **William T. Pu** are in the Department of Cardiology, Boston Children's Hospital, Boston, Massachusetts 02115, USA. **W.T.P.** is also at the Harvard Stem Cell Institute, Harvard University, Cambridge, Massachusetts.
e-mail: william.pu@cardio.chboston.org

1. Guo, Y. & Pu, W. T. *Circ. Res.* **126**, 1086–1106 (2020).
2. Paredes, A. *et al.* *Nature* **618**, 365–373 (2023).
3. Shao, M. *et al. Biomed. Pharmacother.* **137**, 111264 (2021).
4. Heyman, R. A. *et al. Cell* **68**, 397–406 (1992).
5. Sergeant, S., Rahbar, E. & Chilton, F. H. *Eur. J. Pharmacol.* **785**, 77–86 (2016).
6. Vega, R. B, Huss, J. M. & Kelly, D. P. *Mol. Cell Biol.* **20**, 1868–1876 (2000).
7. Hirose, K. *et al.* *Science* **364**, 184–188 (2019).
8. Sakamoto, T. *et al. Circ. Res.* **126**, 1685–1702 (2020).
9. Brown, D. A. *et al. Nature Rev. Cardiol.* **14**, 238–250 (2017).
10. Gomez-Garcia, M. J., Quesnel, E., Al-attar, R., Laskary, A. R. & Laflamme, M. A. *Semin. Cell Dev. Biol.* **118**, 163–171 (2021).
11. Yang, X. *et al. Stem Cell Rep.* **13**, 657–668 (2019).

The authors declare no competing interests.
This article was published online on 24 May 2023.

In retrospect

Golden jubilee for an iconic financial formula

Blanka N. Horvath

Fifty years ago, an equation called the Black–Scholes formula revolutionized finance, leading to a rapid growth of markets and stimulating quantitatively oriented minds. But, with time, its simplicity became a liability — and yet its legacy persists.

In the May–June 1973 issue of the *Journal of Political Economy*, Fischer Black and Myron Scholes introduced a model that transformed mathematical finance theory, and had a profound influence on how financial markets operate[1]. Their work followed key advances[2,3] published the same year by Robert Merton, with whom Scholes shared the Nobel Prize in Economics in 1997, just two years after Black's death. They had devised a formula that became known as the Black–Scholes equation, a succinct expression of how much investors should be charged for financial products that allow them to mitigate the risks of their investments in assets whose value can fluctuate over time. The model's impact is largely due to its simplicity, but it also stems from a curious combination of world events, and it precipitated a fascinating half-century in finance.

Nineteen seventy-three was a pivotal year in finance for reasons other than Black, Scholes and Merton's publications. The Chicago Board Options Exchange opened on 26 April, launching the world's first marketplace for trading financial contracts called options (Fig. 1). Such contracts give the owner the option of buying or selling an asset with an uncertain future value (such as a foreign currency) on a specific date for a price that is decided when the contract is drawn up. The publication of the Black–Scholes formula in a well-regarded journal was perfectly timed to yield a consensus among market participants about how much such options should cost. The simple and concise formula imbued traders with

CBOE GLOBAL MARKETS

Figure 1 | The Chicago Board Options Exchange in 1973.

the confidence and clarity necessary to trade them, thus catalysing the large-scale expansion of options markets.

To say that the world was ready for such a change is putting it mildly. In the months before the exchange opened in Chicago, Illinois, the United States had officially ended its 20-year involvement in the Vietnam War, leaving the country with widespread disillusionment. The cold war continued to escalate. And the spring of 1973 saw the climax of the Watergate scandal, the extensive media coverage of which made it a defining moment in political history, shattering the American public's trust in politics and elected officials.

These months also marked the end of the Bretton Woods system, the post-war monetary arrangement that had established the US dollar as the world's reserve currency and had fixed all foreign exchange rates to it; the dollar was, in turn, pegged to the price of gold. That the system was in trouble was already clear in 1971, when the US dollar was temporarily unpegged from the price of gold, but its demise was complete in 1973 when an attempt to revive the system of fixed exchange rates failed. The main currencies began to shift against each other, marking the beginning of an era of floating exchange rates. Finally, the 1973 oil crisis caused a sharp rise in oil prices, leading to inflation and economic instability in many countries.

Against this backdrop of unsettling geopolitics and unpredictable global markets, the Black–Scholes model provided an appealing way of thinking about investment from the perspective of risk management, and provided access to financial securities that gave investors a welcome sense of control. The formula is simple and effective. It relates the profit or loss associated with an option (its pay-off) to the fluctuating price of a risky asset and the price for which this asset will later be traded (the strike). It does so through a standard normal probability distribution that is a function of the time left before the contract ends, and of a parameter called the volatility, which is a measure of the asset value's variability. The key idea is that the method eliminates all the risk of an uncertain pay-off from buying or selling an asset with a wavering value. But arriving at this solution was far from straightforward.

Previous attempts to price options[4,5] had struggled with the question of how risk should be factored into the evaluation. The surprising answer given in Black and Scholes's paper, and also explained by Merton, is that the option price should be independent of how much risk the buyer and seller are willing to take on. The absence of a premium for risk means that the valuation formula produces the same fair price for all market participants.

This solution was so unexpected that Black and Scholes had considerable difficulty in getting their results published. The paper was (initially) rejected by the *Journal of Political Economy* some years before 1973, after which the authors submitted it to the *Review of Economics and Statistics*, with the same negative outcome. It was finally accepted after revisions that were suggested by Scholes's erstwhile doctoral advisers, Merton Miller and Eugene Fama.

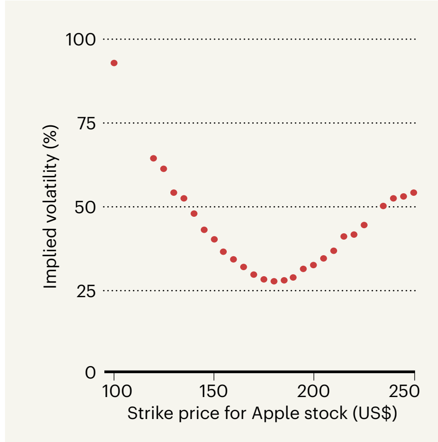

Figure 2 | Volatility in financial contracts. An option is a financial contract that gives the owner the option of buying or selling an asset at a future date for a prescribed price. Black and Scholes[1] devised an equation that relates the profit or loss associated with this option to the fluctuating price of an asset (such as a stock in the technology company Apple) and the price for which this asset will later be traded (the strike price). Using the formula to price an option should eliminate the risk of buying or selling an asset with a wavering value, the variability of which is called the volatility. However, high and low strike prices are associated with higher volatility than are intermediate prices, a trend that is known as the 'implied volatility smile' (shown) and that is not captured by Black and Scholes's model. (Figure courtesy Jayati Walia; see go.nature.com/45bcpxw)

By 1975, almost all traders were valuing options using the Black–Scholes model; the computations could be carried out easily on pocket calculators. With time, more derivative contracts (ones derived from risky underlying assets) were offered on exchanges, as well as the simple options contracts described above. In just two years, the market for derivatives had grown enormously, with total capitalization (the amount invested in the market) reaching trillions of dollars. Black, Scholes and Merton's work not only led to an explosive expansion of derivatives markets, but also prompted an appetite for developing the underlying theory further.

Although the birth of mathematical finance is often traced back to Louis Bachelier's 1900 PhD thesis[6], some suggest that the 1973 breakthroughs can be considered as its coming of age, as well as the dawn of financial engineering. At a celebration marking Merton's 75th birthday, the US economist Andrew Lo suggested that a scientific field can be considered mature only once a field of engineering has emerged from it[7]. After 1973, the relevance of mathematical-finance techniques for engineering in options markets was indisputable.

One by-product of these changes was an increased demand for specialists capable of navigating the technical complexities of the subject. Initially, such experts were predominantly mathematicians, statisticians and physicists, with computer scientists recruited as the technology advanced. This led to a breed of specialist known as quants (quantitative analysts) and, over time, universities started offering courses in this area[8]. The work of these quants, and the ongoing interaction between scientists and financial engineers, had key roles in the rapid growth of mathematical- finance literature in the following decades.

In some ways, Fischer Black can be considered one of the first quants. He studied physics at Harvard University in Cambridge, Massachusetts, but was expelled from the PhD programme owing to his frequent changes in academic fields: he shifted from physics to mathematics, and then to artificial intelligence. Later, he earned a PhD in applied mathematics, working with Marvin Minsky. After working with Scholes and Merton at the Massachusetts Institute of Technology, also in Cambridge, he joined the investment bank Goldman Sachs in 1984. There, he developed a slew of financial products and models[9–11], remaining active in research and banking until his death in 1995.

By contrast, Myron Scholes showed an early interest in economics and started investing in the stock market while he was still in secondary school. He studied economics and then earned an MBA under the supervision of Fama and Miller, who introduced him to the emerging field of financial economics. In the early 1990s, Scholes worked for the investment bank Salomon Brothers in New York City. And in 1994 he founded a hedge fund in Greenwich, Connecticut, called Long-Term Capital Management with Merton and John Meriwether, a colleague from Salomon Brothers.

Long-Term Capital Management had staggering success in its first few years. But after 1997, the Asian financial crisis and the 1998 collapse of the Russian economy triggered the fund's unexpected implosion. By that time, the fund was said to have US$4.8 billion in equity, and its misadventure propelled the United States — and even the world — so close to financial disaster that the US Federal Reserve felt impelled to step in. Just one year after Scholes and Merton received the Nobel prize, their fund became one of the first and most prominent examples of risk potential in the investment industry.

As John Hull, author of the bestselling book

Options, Futures and Other Derivatives, aptly observes[12], Black–Scholes theory is popular among traders because it has only one unobservable parameter, which is related to the volatility. This simplicity makes it appealing, but it is based on a modelling assumption about how fluctuations in the price of the asset underlying the option are distributed. At the time, this assumption seemed reasonable, but its limitations became increasingly obvious in later years.

One indication that the Black–Scholes model might be an oversimplification was that the volatility parameter implied by option prices in the market seemed to depend on the strike price of the option. Very high and very low strike prices are associated with higher volatility than are intermediate prices, and this gave rise to the term 'implied volatility smile' (Fig. 2). Volatility is also not the same for different contract durations. And varying the strike price and contract duration simultaneously results in an implied volatility surface, which has formed the focus of several decades of research in mathematical finance.

Over time, many of Black, Scholes and Merton's original modelling assumptions were deemed simplistic, and new, more complex models emerged that are better equipped to reproduce the smile. These models typically allow more-general movements of the underlying asset price than does the Black–Scholes equation. Traders can now choose to work with models that have stochastic (random) volatility, ones with 'rough' volatility or those involving jumps in asset-price movements, to name just a few.

Today, the world of finance is in a post-Black–Scholes era, in which the theory's historical importance is undisputed, but some say that the model itself can be more distortive than helpful for understanding the microstructure of markets[13]. Decades of research have gone into improving financial models; into calculating the risks connected with them; and — because all models are imperfect in some way — into understanding the implications if the models are wrong.

Considerable research now goes into teaching machines to price and hedge options in an automated way[14,15], and with more-general settings than have previously been possible[16]. Tremendous effort is also being spent on understanding how trading at extremely high frequencies affects the market[17], and how pricing strategies can be built to withstand ever-changing market environments. Finally, with the climate crisis looming, focus is shifting towards understanding and optimizing market incentives that help to protect our environment. However, although priorities have changed, it's safe to say that neither the markets nor financial research would be where they are now had it not been for Black, Scholes and Merton's extraordinary work.

Blanka N. Horvath is at the Oxford–Man Institute of Quantitative Finance, University of Oxford, OX2 6GG Oxford, UK, and the Alan Turing Institute, British Library, London, UK.
e-mail: blanka.horvath@maths.ox.ac.uk

1. Black, F. & Scholes, M. *J. Polit. Econ.* **81**, 637–654 (1973).
2. Merton, R. C. *Bell J. Econ. Mgmt Sci.* **4**, 141–183 (1973).
3. Merton, R. C. Appendix to Samuelson, P. A. *SIAM Rev.* **15**, 34–38 (1973).
4. Sprenkle, C. M. *Yale Econ. Essays* **1**, 178–231 (1961).
5. Samuelson, P. A. *Ind. Mgmt Rev.* **6**, 41–49 (1965).
6. Davis, M. & Etheridge, A. *Louis Bachelier's Theory of Speculation: The Origins of Modern Finance* (Princeton Univ. Press, 2006).
7. Lo, A. W. *Annu. Rev. Financial Econ.* **12**, 1–18 (2020).
8. Davis, M. H. A. *Mathematical Finance: A Very Short Introduction* (Oxford Univ. Press, 2018).
9. Turfus, C. & Karasinski, P. *Wilmott* **2021**, 26–33 (2021).
10. Black, F. & Litterman, R. *Financial Anal. J.* **48**, 28–43 (1992).
11. Black, F. & Litterman, R. *J. Fixed Income* **1**, 7–18 (1991).
12. Hull, J. *Wilmott* **2023**, 58–60 (2023).
13. Bouchaud, J. P. *Wilmott* **2023**, 70–72 (2023).
14. Bühler, H., Gonon, L., Teichmann, J. & Wood, B. Preprint at https://arxiv.org/abs/1802.03042 (2018).
15. Horvath, B., Muguruza, A. & Tomas, M. Preprint at https://doi.org/10.2139/ssrn.3322085 (2021).
16. Buehler, H., Horvath, B., Lyons, T., Perez Arribas, I. & Wood, B. Preprint at https://doi.org/10.2139/ssrn.3657366 (2021).
17. Avellaneda, M. & Stoikov, S. *Quant. Finance* **8**, 217–224 (2008).

The author declares no competing interests.
This article was published online on 5 June 2023.

Computational social science

People, not algorithms, choose partisan news

Eni Mustafaraj

Analysis of people's web searches and visited websites suggests that it is more likely that they are choosing to engage with partisan or unreliable news than that they are being unduly exposed to it by search-engine algorithms. **See p.342**

Believing false news or conspiracy theories on the Internet has real-world consequences. For instance, a discredited conspiracy theory known as Pizzagate gave rise to the much bigger QAnon conspiracy, which ultimately contributed to the attack on the US Capitol building in January 2021 (see https://bbc.in/3zBFFcb). It's often thought that the personalized algorithms of big platforms such as Facebook and Google facilitate exposure to problematic information[1], keeping their users in 'filter bubbles' and 'echo chambers' that distort their view of reality[2]. But scientific studies that try to measure this phenomenon are rare. On page 342, Robertson *et al.*[3] describe their attempt to quantify both exposure to and engagement with online news. They show that a person's choices trump Google Search's algorithmic recommendations in terms of their consumption of unreliable or partisan news.

Healthy democracies depend on factually accurate news, so it is crucial to determine whether algorithmic curation exacerbates people's exposure to, and tendency to consume, partisan or unreliable news stories. But how can we do this scientifically? In 2015, scientists studied Facebook's news feed, and concluded that individual choice was more effective at limiting exposure to ideologically diverse news than was algorithmic filtering[4]. However, this study was conducted by researchers at Facebook, and the data that would allow its replication were not available to scientists employed elsewhere.

This situation is the norm for research involving online platforms. When *The New York Times* revealed in 2006 how easy it was to identify individuals from their search history in an anonymized data set shared by the company AOL (see https://nyti.ms/2USiiDM), online platforms took note, and sharing data with external researchers became a rarity. To circumvent this type of data-access issue, some have called for online information spaces to be studied in the same way as one might study pollution — in an 'ecological' framework that analyses the interactions of individuals with online applications in their natural environments[5].

Robertson *et al.* have done just that. Similar to the way in which environmental scientists install sensors around the globe to collect ecological data about weather conditions and pollution, the authors asked survey participants — US citizens recruited through a third party — to install an extension on their browser that allowed the researchers to gather information about three types of data: Google Search results pages, links followed from those pages and all other URLs visited while browsing.

The authors collected these data in two waves. In the first wave, in 2018, they collected

Correction
The original version of this article described the investment bank Salmon Brothers as defunct. The bank was acquired by Citigroup in 1997 and Citigroup discontinued use of the name in 2003. There are currently efforts in progress to revive the name.