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Key words: performativity, bricolage, option pricing, Black-Scholes, social studies of finance.

**An Equation and its Worlds:**

*Bricolage, Exemplars, Disunity and Performativity in Financial Economics*

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Abstract

This paper describes and analyzes the history of the fundamental equation of modern financial economics: the Black-Scholes (or Black-Scholes-Merton) option pricing equation. In that history, several themes of potentially general importance are revealed. First, the key mathematical work was not rule-following but *bricolage*, creative tinkering. Second, it was, however, *bricolage* guided by the goal of finding a solution to the problem of option pricing analogous to existing exemplary solutions, notably the Capital Asset Pricing Model, which had successfully been applied to stock prices. Third, the central strands of work on option pricing, although all recognisably ‘orthodox’ economics, were not unitary. There was significant theoretical disagreement amongst the pioneers of option pricing theory; this disagreement, paradoxically, turns out to be a strength of the theory. Fourth, option pricing theory has been performative. Rather than simply describing a pre-existing empirical state of affairs, it altered the world, in general in a way that made itself more true.
Economics and economies are becoming a major focus for social studies of science. Historians of economics such as Philip Mirowski and the small number of sociologists of economics such as Yuval Yonay have been applying ideas from science studies with increasing frequency in the last decade or so. Established science-studies scholars such as Knorr Cetina and newcomers to the field such as Izquierdo, Lépinay, Millo and Muniesa have begun detailed, often ethnographic, work on economic processes, with a particular focus on financial markets. Actor-network theorist Michel Callon has conjoined the two concerns by arguing that an intrinsic link exists between studies of economics and of economies. The economy is not an independent object that economics observes, argues Callon (1998). Rather, the economy is performed by economic practices. Accountancy and marketing are among the more obvious such practices, but, claims Callon, economics in the academic sense plays a vital role in constituting and shaping modern economies.

This article contributes to the emergent science-studies literature on economics and economies by way of a historical case study of option† pricing theory (terms marked † are defined in the glossary in table 1). The theory is a ‘crown jewel’ of modern economics: ‘when judged by its ability to explain the empirical data, option pricing theory is the most successful theory not only in finance, but in all of economics’ (Ross, 1987: 332). Over the last three decades, option theory has become a vitally important part of financial practice. As recently as 1970, the market in derivatives‡ such as options was tiny; indeed, many modern derivatives were illegal. By December 2002, derivatives contracts totaling $165.6 trillion were outstanding worldwide, a sum equivalent to around $27,000 for every human being on earth. Because of its centrality to this huge market, the equation that is my focus here, the Black-Scholes option pricing equation, may
be ‘the most widely used formula, with embedded probabilities, in human history’ (Rubinstein, 1994: 772).

The development of option pricing theory is part of a larger transformation of academic finance. Until the 1960s, the study of finance was a marginal, low status activity: largely descriptive in nature, taught in business schools not in economics departments, and with only weak intellectual linkages to economic theory. Since the 1960s, finance has become analytical, theoretical and highly quantitative. Although most academic finance theorists’ posts are still in business schools, much of what they teach is now unequivocally part of economics. Five finance theorists – including two of the central figures discussed here, Robert C. Merton and Myron Scholes – have won Nobel prizes in economics.

This intellectual transformation was interwoven with the rapid expansion of business schools in the U.S. In the mid-1950s, U.S. business schools produced around 3,000 MBAs annually. By the late 1990s, that figure had risen to over 100,000 (Skapiner, 2002). As business schools grew, they also became more professional and ‘academic’, especially after the influential Ford Foundation report, Higher Education for Business (Gordon and Howell, 1959). At the same time, the importance of the finance sector in the U.S. economy grew dramatically, and increasing proportions of financial assets were held not directly by individuals but by organizations such as mutual funds and pension funds. These organizations formed a ready job market for the growing cohorts of students trained in finance.
The transformation of the academic study of finance is the subject of a fine history by Bernstein (1992), and the interactions between this transformation, the evolution of U.S. business schools, and changing capital markets have been analyzed ably by Whitley (1986a & b). However, what the existing literature has not done fully is to ‘open the black box’ of mathematical finance theory. That – at least for the theory of option pricing – is this article’s goal.

Limitation of space mean that the focus of this paper is on the mathematics of option pricing theory and on its intellectual context. The interaction between theory and practice – the processes of the adoption by practitioners of option pricing theory, and the consequences of its adoption – is the subject of a ‘sister’ paper (MacKenzie and Millo, forthcoming), although the issue of performativity means that the subject-matter of that paper will be revisited briefly below.

In this article, four themes will emerge. I would not describe them as ‘findings’, because of the limitations on what can be inferred from a single historical case-study, but they may be of general significance. The first theme is *bricolage*. Creative scientific practice is typically not the following of set rules of method: it is ‘particular courses of action with materials to hand’ (Lynch, 1985: 5). While this has been documented in overwhelming detail by ethnographic studies of laboratory science, this case-study suggests it may also be the case in a deductive, mathematical science. Economists – at least the particular economists focused on here – are also *bricoleurs*.

They are not, however, random bricoleurs, and the role of existing exemplary solutions is the second issue to emerge. Ultimately, of course, this is a Kuhnian theme. As is well known, at
least two quite distinct meanings of the key term ‘paradigm’ can be found in Kuhn’s work. One – by far the dominant one in how Kuhn’s work was taken up by others – is the ‘entire constellation of beliefs, values, techniques, and so on shared by the members of a given [scientific] community’ (Kuhn, 1970: 175). The second – rightly described by Kuhn as ‘philosophically ... deeper’ – is the exemplar, the problem-solution that is accepted as successful and that is creatively drawn upon to solve further problems (Kuhn, 1970: 175; see also Barnes, 1982).

The role of the exemplar will become apparent here in the contrast between the work of Black and Scholes and that of mathematician and arbitrageur Edward O. Thorp. Amongst those who worked on option pricing prior to Black and Scholes, Thorp’s work is closest to theirs. However, while Thorp was seeking market inefficiencies to exploit, Black and Scholes were seeking a solution to the problem of option pricing analogous to an existing exemplary solution, the Capital Asset Pricing Model. This was not just a general inspiration: in his detailed mathematical work, Black drew directly on a previous mathematical analysis on which he had worked with the Capital Asset Pricing Model’s co-developer, Jack Treynor.

As Peter Galison and others have pointed out, the key shortcoming in the view of the ‘paradigm’ as ‘constellation of beliefs, values, techniques, and so on’ is that it overstates the unity and coherence of scientific fields (Galison and Stump, 1996; Galison 1997). Nowhere is this more true than when outsiders discuss ‘orthodox’ neoclassical economics, and the nature of economic orthodoxy is the third theme explored here. Black, Scholes, Merton, several of their predecessors, and most of those who in the 1970s subsequently worked on option pricing were
all (with some provisos in the case of Black, to be discussed below) recognizably ‘orthodox’
economists. As others studying different areas of economics have found, however, orthodoxy
seems not to be a single unitary doctrine, substantive or methodological (see Yonay and Breslau,
2001; Mirowski and Hands, 1998). For example, Robert C. Merton, the economist whose name
is most closely yoked to those of Black and Scholes, did not accept the original version of the
Capital Asset Pricing Model, the apparent pivot of their derivation, and Merton reached the
Black-Scholes equation by drawing on different intellectual resources. Black, in turn, never
found Merton’s derivation entirely compelling, and continued to champion the derivation based
on the Capital Asset Pricing Model. So no entirely unitary ‘constellation of beliefs, values,
techniques, and so on’ can be found. Economic ‘orthodoxy’ is a reality – attend conferences of
economists who feel excluded by it, and one is left in no doubt on that – but it is a reality that
should perhaps be construed as a cluster of family resemblances, a cluster that arises from
imaginative bricolage drawing on an only partially overlapping set of existing exemplary
solutions. ‘Orthodox’ economics is an ‘epistemic culture’ (Knorr Cetina, 1999), not a catechism.

A major aspect of Galison’s critique of the Kuhnian paradigm (conceived as all-
embracing ‘constellation’) is his argument that diversity is a source of robustness, not a weakness.
Though Galison’s topic is physics, his conclusion also appears to hold true in economics. Philip
Mirowski and Wade Hands, describing the emergence of modern economic orthodoxy in the
postwar U.S., put the point as follows:

Rather than saying it [neoclassicism] simply chased out the competition – which it
did, if by ‘competition’ one means the institutionalists, Marxists, and Austrians – and
replaced diversity with a single monolithic homogeneous neoclassical strain, we say it transformed itself into a more robust ensemble. Neoclassical demand theory gained hegemony by going from patches of monoculture in the interwar period to an interlocking competitive ecosystem after World War II. Rather than presenting itself as a single, brittle, theoretical strand, neoclassicism offered a more flexible, and thus resilient skein (Mirowski and Hands, 1998: 289; see also Sent, forthcoming).

As we shall see, that general characterization appears to hold for the particular case of option pricing theory.

The final theme explored here, and in the sister paper referred to above (MacKenzie and Millo, forthcoming), is performativity. As we shall see, there is at least qualified support here for Callon’s conjecture, albeit in a case that is favourable to the conjecture, since option pricing theory was chosen for examination in part because it seemed a plausible case of performativity. Option pricing theory seems to have been performative in a strong sense: it did not simply describe a pre-existing world, but helped create a world of which the theory was a truer reflection.

It is of course not surprising that a social science like finance theory has the potential to alter its objects of study: the more difficult issue, which fortunately does not need breached here, is to specify accurately the non-trivial ways in which natural sciences are performative (see Hacking, 1992, and from a different viewpoint, Bloor, 2003). That a social science like psychology, for example, has a ‘necessarily reflexive character’ and that psychologists influence as
well as describe ‘the psychological lives of their host societies’ has been argued by Richards (1997: xii), and Ian Hacking’s work (such as Hacking, 1992 and 1995) also demonstrates the point. As I have argued elsewhere (MacKenzie, 2001), finance is a domain of what Barnes (1983) calls ‘social-kind’ terms or what Hacking (1995b) calls ‘human kinds’, with their two-way ‘looping effects’ between knowledge and its objects.

It is clearly possible in principle, in other words, for finance theory to be performative rather than simply descriptive. However, that does not remove the need for empirical examination. That the theory can be performative does not imply that it has been performative. Indeed, as we shall see, the performativity of classic option pricing theory is incomplete and historically specific – it did not make itself wholly or permanently true – and exploring the limits and the contingency of its performativity is of some interest.

The middle sections of this paper are available only in the published version.

Conclusion: Bricolage, Exemplars, Disunity and Performativity

The importance of bricolage in the history of option pricing theory, especially in Black’s and Scholes’s work, is clear. They followed no rules, no set methodology, but worked in a creatively ad hoc fashion. Their mathematical work can indeed be seen as Lynch’s ‘particular courses of action with materials to hand’ (Lynch, 1985: 5) – in this case, conceptual materials. Consider, for example, Black and Scholes’s use of Sprenkle’s work. The latter would rate scarcely a mention in a ‘Whig’ history of option pricing: his model is, for example, dismissed in a footnote
in Sullivan and Weithers’ history as possessing ‘serious drawbacks’ (Sullivan and Weithers, 1994: 41). True, central to Sprenkle’s work was the hope that analyzing option pricing would reveal investors’ attitudes to risk, a goal that in the Black-Scholes-Merton analysis (which implies that options are priced as if all investors are entirely risk-neutral) is not achievable. Yet, as we have seen, Black and Scholes’s tinkering with Sprenkle’s equation was the key step in their finding a solution to their differential equation, and ‘tinkering’ is indeed the right word.6

It was, however, tinkering inspired by an exemplar, the Capital Asset Pricing Model. Here, the contrast with Thorp is revealing. He was far better-trained mathematically than Black and Scholes were, and had extensive experience of trading options (especially warrants), when they had next to none. He and Kassouf also conceived of a hedged portfolio of stock and options (with the same hedging ratio, $\frac{\partial 
u}{\partial x}$), and they, unlike Black and Scholes, had implemented approximations to such hedged portfolios in their investment practice. Thorp had even tinkered in essentially the same way as Black and Scholes with an equation equivalent to Sprenkle’s (equation 1 above). But while Black and Scholes were trying to solve the option pricing problem by applying the Capital Asset Pricing Model, Thorp had little interest in the latter: he was aware of it, but not ‘at the expert level’.7 Indeed, for him the proposition (central to the mathematics of Black and Scholes, and in a different way to Merton’s analysis as well) that a properly hedged portfolio could earn only the riskless rate would have stood in direct contradiction to his empirical experience. He and Kassouf were regularly earning far more than that from their hedged portfolios.
For Thorp, then, to have put forward Black and Scholes’s or Merton’s central argument would have involved overriding what he knew of empirical reality. For Scholes (trained as he was in Chicago economics), and even for Black (despite his doubts as to the precise extent to which markets were efficient), it was reasonable to postulate that markets would not allow money-making opportunities like a zero-\(\beta\) (or, in Merton’s version, zero-risk) portfolio that earned more than the riskless rate. Thorp, however, was equally convinced that such opportunities could be found in the capital markets. The ‘conventional wisdom’ had been that ‘you couldn’t beat the casino’: in the terminology of economics, that ‘the casino markets were efficient’. Thorp had showed this was not true, ‘so why should I believe these people who are saying the financial markets are efficient?’ [Thorp interview].

Theoretical commitment was thus important to the development of option pricing. It was not, however, commitment to the literal truth of economics’s models. Black and Scholes, for example, knew (indeed, they showed: see Black, Jensen and Scholes, 1972) that the Capital Asset Pricing Model’s empirical accuracy was questionable. That, however, did not stop them regarding the model as identifying an economic process of great importance. Nor, crucially, did it deter them from using the model as a resource with which to solve the option pricing problem. Similarly, neither they, nor Merton, mistook their option model for a representation of reality. Black, for example, delighted in pointing out ‘The Holes in Black-Scholes’ (Black, 1988): economically consequential ways in which the model’s assumptions were unrealistic. For Black, Scholes, and Merton – like the economists studied by Yonay and Breslau (2001) – a model had to be simple enough to be mathematically tractable, yet rich enough to capture the economically most important aspects of the situations modelled. Models were resources, not (in any simple
sense) representations: ways of understanding and reasoning about economic processes, not putative descriptions of reality. If the latter is the criterion of truth, all of the financial economists discussed here would agree with their colleague Eugene Fama that any model is ‘surely false’ (Fama, 1991: 1590).

Nor were the theoretical inspirations and commitments of option pricing theorists unitary. Black-Scholes-Merton option pricing theory is central to the ‘orthodox’ modern economic analysis of financial markets. But that does not mean that Black, Scholes and Merton adhered to the same theoretical viewpoint. They disagreed, for example, on the validity of the original form of the Capital Asset Pricing Model. As we have seen, Merton considered the original derivations of the Black-Scholes equation unrigorous; Black remained to a degree a sceptic as to the virtues of Merton’s derivation. Nor did this kind of disagreement end in 1973. For example, to Michael Harrison, an operations researcher (and essentially an applied mathematician) at Stanford University, the entire body of work in option pricing theory prior to the mid-1970s was insufficiently rigorous. Harrison and his colleague David Kreps asked themselves, ‘Is there a Black-Scholes theorem?’ From the viewpoint of the ‘theorem-proof culture ... I [Harrison] was immersed in’ [Harrison interview] there was not. So they set to work to formulate and prove such a theorem, a process that eventually brought to bear modern ‘Strasbourg’ martingale theory (an advanced and previously a rather ‘pure’ area of probability theory).8

Divergences of this kind might seem to be a source of weakness. In the case of option pricing theory, however, they are a source of strength, even more directly so than in the more
general case discussed by Mirowski and Hands (1998). If the Black-Scholes equation could be derived in only one way, it would be a fragile piece of reasoning. But it can be derived in several: not just in the variety of ways described above, but also, for example, as a limit case of the later finite-time Cox-Ross-Rubinstein model (Cox, Ross and Rubinstein, 1979). Plug the lognormal random walk and the specific features of option contracts into Harrison and Kreps’s martingale model, and Black-Scholes again emerges. Diversity indeed yields robustness. For example, as Black pointed out, defending the virtues of the original derivation from the Capital Asset Pricing Model, that derivation ‘might still go through’ even if the assumptions of the arbitrage-based derivation failed.º

This rich diversity of ways of deriving the Black-Scholes equation may prompt in the reader a profoundly unsociological thought: perhaps the equation is simply true? This is where this article’s final theme, performativity, is relevant. As an empirical description of patterns of option pricing, the equation started out as only a rough approximation, but then pricing patterns altered in a way that made it more true. In part, this was because the equation was used in arbitrage. In part, it was because the hypothetical world embedded in the equation (perhaps especially in Merton’s continuous-time derivation of it) has been becoming more real, at least in the core markets of the Euro-American world. As Robert C. Merton, in this context appropriately the son of Robert K. Merton (with his sensitivity to the dialectic of the social world and knowledge of that world), puts it, ‘reality will eventually imitate theory’ (Merton, 1992: 470; see Merton, 1936 and Merton, 1949).
Perhaps, though, the reader’s suspicion remains: that this talk of performativity is just a fancy way of saying that the Black-Scholes equation is the correct way to price options, but market practitioners only gradually learned that. Not so. The phase of increasing empirical accuracy of the Black-Scholes equation has been followed by a phase, since 1987, in which the fit of the empirical prices to the model has again deteriorated (Rubinstein, 1994). One way of expressing this partial breakdown after 1987 of the performativity of classic option theory is to note that while, as noted above, some of its assumptions have become more true (in part because of feedback loops from the theory), this has not been the case for the assumption of the log-normality of the price movements of stocks or other underlying assets. The gigantic one-day fall of the U.S. stock market on 19 October 1987 was a grotesquely unlikely event on the assumption of log-normality: for example, Jackwerth and Rubinstein (1996: 1612) calculate the probability on that assumption of the actual fall in S&P index futures as $10^{-160}$. In addition, 19 October was far more than the disembodied rejection of the null hypothesis of log-normality. The fall in stock prices came close to setting off a chain of market-maker bankruptcies that would have threatened the very existence of organized derivatives exchanges in the U.S. The subsequent systematic departure from Black-Scholes option pricing – the so-called ‘volatility skew’ – is more than a mathematical adjustment to empirical departures from log-normality: it is too large fully to be accounted for in that way (Jackwerth, 2000). It can in a sense be seen as the options market’s collective defence mechanism against systemic risk (MacKenzie and Millo, forthcoming).

More generally, market practitioners’ adoption of financial economics has not rendered fully performative economics’s pervasive, often implicit, underlying assumption of rational egoism. *Pace* Callon (1998), *homo economicus* has not in general been brought fully into being.
What has not to date been grasped in the debate over economics’s performativity (e.g. Miller, 2002) is that there exists a reasonably precise probe as to whether or not actors have been configured into *hominès œconomici*: collective action, in other words action that advances the interests of an entire group but in regard to which the rational egoist will free-ride. (A classic example of collective action is blood donation in a country such as the UK where such donation is unremunerated [Titmus, 1970]. Well-stocked blood banks are in the collective interest of the entire population of the UK, but a rational egoist would nonetheless be unlikely to donate blood because the minor inconvenience and discomfort involved would almost certainly outweigh the miniscule probability of benefiting personally from his or her own donation.) As the analysis by Olson (1980) famously shows, if all actors are *hominès œconomici* they will all free-ride in such a situation, and collective action will therefore be impossible.

However, participants in financial markets have, at least to some extent, retained the capacity for collective action. The very creation of the Chicago Board Options Exchange, which set in train the key processes that have rendered option theory performative, involved donations of unremunerated time that were structurally akin to blood donation (MacKenzie and Millo, forthcoming). The classic social network analysis of option pricing by Baker (1984) can, likewise, be read as showing the persistence, at least in CBOE’s smaller trading crowds, of collective action, and, as noted above, the volatility skew can also be interpreted, at least tentatively, as collective action.

The analysis of economics’s performativity does not point, therefore, to the smoothly performed world feared by Callon’s critics such as Miller (2002). It points to contested terrain.
When, in 1968, David Durand, a leading figure in the older form of the academic study of finance, inspected the mathematical models that were beginning to transform his field, he commented that ‘The new finance men ... have lost virtually all contact with terra firma’ (Durand, 1968: 848). As we have seen, the decades since 1968 have seen the world of finance change in such a way that the apparently ungrounded models that horrified Durand have gained verisimilitude as they have become incorporated into the structures and practices of markets. However, the financial markets remain, and I suspect will always remain, an only partially configured world. The struggles to configure that world, and the forces opposing and undermining that configuring, are, and will remain, at the heart of the history of our times.

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<table>
<thead>
<tr>
<th><strong>Arbitrage; arbitrageur</strong></th>
<th>Trading that seeks to profit from price discrepancies; a trader who seeks to do so.</th>
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<tr>
<td><strong>Call</strong></td>
<td>See option.</td>
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<tr>
<td><strong>Derivative</strong></td>
<td>An asset, such as a future or option, the value of which depends on the price of another, ‘underlying’, asset.</td>
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<tr>
<td><strong>Discount</strong></td>
<td>to calculate the amount by which future payments must be reduced to give their present value.</td>
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<td><strong>Expiration</strong></td>
<td>See option.</td>
</tr>
<tr>
<td><strong>Future</strong></td>
<td>An exchange-traded contract in which one party undertakes to buy, and the other to sell, a set quantity of an asset at a set price on a given future date.</td>
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<tr>
<td><strong>Implied volatility</strong></td>
<td>The volatility of a stock or index consistent with the price of option on the stock or index.</td>
</tr>
<tr>
<td><strong>Log-normal</strong></td>
<td>A variable is log-normally distributed if its natural logarithm is normally distributed.</td>
</tr>
<tr>
<td><strong>Market maker</strong></td>
<td>In the options market, a market participant who trades on his/her own account, is obliged continuously to quote prices at which he/she will buy and sell options, and is not permitted to execute customer orders.</td>
</tr>
<tr>
<td><strong>Option</strong></td>
<td>A contract that gives the right, but not obligation, to buy (‘call’) or sell (‘put’) an asset at a given price (the ‘strike price’) on, or up to, a given future date (the ‘expiration’).</td>
</tr>
<tr>
<td><strong>Put</strong></td>
<td>See option.</td>
</tr>
<tr>
<td><strong>Riskless rate</strong></td>
<td>The rate of interest paid by a lender who creditors are certain will default.</td>
</tr>
<tr>
<td><strong>Short selling</strong></td>
<td>Selling an asset one does not own, e.g. by borrowing it, selling it, and later repurchasing and returning it.</td>
</tr>
<tr>
<td><strong>Strike price</strong></td>
<td>See option.</td>
</tr>
<tr>
<td><strong>Swap</strong></td>
<td>A contract to exchange two income streams, e.g. fixed-rate and floating-rate interest on the same notional principal sum.</td>
</tr>
<tr>
<td><strong>Volatility</strong></td>
<td>The extent of the fluctuations of the price of an asset, conventionally measured by the annualized standard deviation of continuously-compounded returns on the asset.</td>
</tr>
<tr>
<td><strong>Warrant</strong></td>
<td>A call option issued by a corporation on its own stock. Its exercise typically leads to the creation of new shares rather than the transfer of ownership of existing stock.</td>
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Table 1. Terminology.

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Data from Bank for International Settlement, www.bis.org. These figures are adjusted for the most obvious forms of double-counting, but still arguably exaggerate the economic significance of derivatives markets. Swaps, for example, are measured by notional principal, when this is not in fact exchanged. See also note 22 below.

Aside from the recollections of Black and Scholes themselves (Black, 1989; Scholes, 1998), the main existing history is Bernstein (1992: chapter 11), which eschews detailed mathematical exposition. More mathematical, but unfortunately somewhat Whiggish (see below), is Sullivan and Weithers (1994).

Bricoleur is French for odd-job person. Lévi-Strauss (1966) introduced the Anglo-Saxon social sciences to the metaphor. Its appropriateness to describe science is argued in Barnes (1974, chapter 3).

It is used in a one-sentence summary of Black’s own history (Black, 1989: 4), but the summary is probably an editorial addition, not Black’s own.

Edward O. Thorp, email message to author, 19 October 2001.

See Harrison and Kreps (1979) and Harrison and Pliska (1981). The first derivation of the Black-Scholes formula that Harrison and Kreps would allow as reasonably rigorous is in Merton (1977). This latter paper explicitly responds to queries that had been raised about the original derivation. For example, Smith (1976: 23) had noted that the option price, \( w \), is, in the original work, assumed but not proved ‘to be twice differentiable everywhere’.


In the Black-Scholes-Merton model, the relationship of implied volatility to strike price is a flat line. Since October 1987, however, the relationship has become skewed, with options with low strike
prices having higher implied volatilities than those with higher strike prices (Rubinstein 1994). The option market has come to ‘expect’ crashes, in other words.