Biological Economics
Volume I

The International Library of Critical Writings in Economics

Founding Editor: Mark Blaug

Late Professor Emeritus, University of London, UK
Late Professor Emeritus, University of Buckingham, UK

This series is an essential reference source for students, researchers and lecturers in economics. It presents by theme a selection of the most important articles across the entire spectrum of economics. Each volume has been prepared by a leading specialist who has written an authoritative introduction to the literature included.

Wherever possible, the articles in these volumes have been reproduced as originally published using facsimile reproduction, inclusive of footnotes and pagination to facilitate ease of reference.

For a list of all Edward Elgar published titles visit our website at
www.e-elgar.com

Biological Economics
Volume I

Edited by

Andrew W. Lo

Charles E. and Susan T. Harris Professor
MIT Sloan School of Management
and Director, MIT Laboratory for Financial Engineering
Cambridge, Massachusetts, USA

and

Ruixun Zhang

Research Affiliate
MIT Laboratory for Financial Engineering
Cambridge, Massachusetts, USA

THE INTERNATIONAL LIBRARY OF CRITICAL WRITINGS IN ECONOMICS

An Elgar Research Collection
Cheltenham, UK • Northampton, MA, USA

Published by
Edward Elgar Publishing Limited
The Lypiatts
15 Lansdown Road
Cheltenham
Glos GL50 2JA
UK

Edward Elgar Publishing, Inc.
William Pratt House
9 Dewey Court
Northampton
Massachusetts 01060
USA

A catalogue record for this book
is available from the British Library

Library of Congress Control Number: 2017955160

ISBN 978 1 78254 853 9 (2 volume set)

Contents

Acknowledgements ix
Introduction Andrew W. Lo and Ruixun Zhang xiii

PART I FOUNDATIONS

1. Rev. T.R. Malthus (1830), 'On Population', in *A Summary View of the Principle of Population*, London, UK: John Murray, i, 1–77 3
2. Joseph A. Schumpeter (1947), 'The Creative Response in Economic History', *Journal of Economic History*, **VII** (2), November, 149–59 81
3. Armen A. Alchian (1950), 'Uncertainty, Evolution, and Economic Theory', *Journal of Political Economy*, **58** (3), June, 211–21 92
4. J. Hirshleifer (1977), 'Economics from a Biological Viewpoint', *Journal of Law and Economics*, **20** (1), April, 1–52 103
5. Richard R. Nelson (1995), 'Recent Evolutionary Theorizing About Economic Change', *Journal of Economic Literature*, **XXXIII** (1), March, 48–90 155

PART II SOCIOBIOLOGY

6. W.D. Hamilton (1964), 'The Genetical Evolution of Social Behaviour I and II', *Journal of Theoretical Biology*, **7** (1), July, 1–16, 17–52 201
7. Robert L. Trivers (1971), 'The Evolution of Reciprocal Altruism', *Quarterly Review of Biology*, **46** (1), March, 35–57 253
8. Richard D. Alexander (1974), 'The Evolution of Social Behavior', *Annual Review of Ecology and Systematics*, **5**, November, 325–83 276
9. David Sloan Wilson and Elliott Sober (1994), 'Reintroducing Group Selection to the Human Behavioral Sciences', *Behavioral and Brain Sciences*, **17** (4), December, 585–608, references 335
10. Herbert Gintis, Samuel Bowles, Robert Boyd and Ernst Fehr (2003), 'Explaining Altruistic Behavior in Humans', *Evolution and Human Behavior*, **24** (3), May, 153–72 364
11. Joseph Henrich (2004), 'Cultural Group Selection, Coevolutionary Processes and Large-Scale Cooperation', *Journal of Economic Behavior and Organization: Evolution and Altruism*, **53** (1), January, 3–35 384
12. Martin A. Nowak (2006), 'Five Rules for the Evolution of Cooperation', *Science*, **314** (5805), December, 1560–63 417

13. David Sloan Wilson and Edward O. Wilson (2007), 'Rethinking the Theoretical Foundation of Sociobiology', *Quarterly Review of Biology*, **82** (4), December, 327–48 421

PART III EVOLUTIONARY PSYCHOLOGY AND BEHAVIORAL E COLOGY

14. Erika R. Behrend and M.E. Bitterman (1961), 'Probability-Matching in the Fish', *American Journal of Psychology*, **74** (4), December, 542–51 445
15. R.J. Herrnstein (1961), 'Relative and Absolute Strength of Response as a Function of Frequency of Reinforcement', *Journal of the Experimental Analysis of Behavior*, **4** (3), July, 267–72 455
16. Colin W. Clark (1973), 'The Economics of Overexploitation', *Science*, **181** (4100), August, 630–34 461
17. Colin W. Clark and Marc Mangel (1986), 'The Evolutionary Advantages of Group Foraging', *Theoretical Population Biology*, **30** (1), August, 45–75 466
18. Lawrence D. Harder and Leslie A. Real (1987), 'Why Are Bumble Bees Risk Averse?', *Ecology*, **68** (4), August, 1104–8 497
19. Leda Cosmides and John Tooby (1994), 'Better than Rational: Evolutionary Psychology and the Invisible Hand', *American Economic Review: Papers and Proceedings*, **84** (2), May, 327–32 502
20. Herbert Gintis (2007), 'Review of *Adapting Minds: Evolutionary Psychology and the Persistent Quest for Human Nature*', *Journal of Bioeconomics*, **9** (2), August, 191–9 508
21. Avraham Be'er, H.P. Zhang, E.-L. Florin, Shelley M. Payne, Eshel Ben-Jacob and Harry L. Swinney (2009), 'Deadly Competition between Sibling Bacterial Colonies', *Proceedings of the National Academy of Sciences*, **106** (2), January, 428–33 517
22. Kenneth J. Arrow and Simon A. Levin (2009), 'Intergenerational Resource Transfers with Random Offspring Numbers', *Proceedings of the National Academy of Sciences*, **106** (33), August, 13702–6 523
23. Thomas J. Brennan and Andrew W. Lo (2011), 'The Origin of Behavior', *Quarterly Journal of Finance*, **1** (1), March, 55–108 528

PART IV THE BIOLOGICAL FOUNDATIONS OF UTILITY

24. Ingemar Hansson and Charles Stuart (1990), 'Malthusian Selection of Preferences', *American Economic Review*, **80** (3), June, 529–44 585
25. Alan R. Rogers (1994), 'Evolution of Time Preference by Natural Selection', *American Economic Review*, **84** (3), June, 460–81 601
26. Arthur J. Robson (1996), 'A Biological Basis for Expected and Non-expected Utility', *Journal of Economic Theory*, **68** (2), February, 397–424 623

27. Arthur J. Robson (2001), 'The Biological Basis of Economic Behavior', *Journal of Economic Literature*, **XXXIX** (1), March, 11–33 651
28. Rose McDermott, James H. Fowler and Oleg Smirnov (2008), 'On the Evolutionary Origin of Prospect Theory Preferences', *Journal of Politics*, **70** (2), April, 335–50 674
29. Arthur J. Robson and Larry Samuelson (2009), 'The Evolution of Time Preference with Aggregate Uncertainty', *American Economic Review*, **99** (5), December, 1925–53 690
30. Ruixun Zhang, Thomas J. Brennan and Andrew W. Lo (2014), 'The Origin of Risk Aversion', *Proceedings of the National Academy of Sciences*, **111** (50), December, 17777–82 719

PART V RATIONALITY AND INTELLIGENCE

31. Herbert A. Simon (1955), 'A Behavioral Model of Rational Choice', *Quarterly Journal of Economics*, **69** (1), February, 99–118 727
32. J. Maynard Smith (1984), 'Game Theory and the Evolution of Behaviour', *Behavioral and Brain Sciences*, **7** (1), March, 95–101, references 747
33. Alan Kirman (1993), 'Ants, Rationality, and Recruitment', *Quarterly Journal of Economics*, **108** (1), February, 137–56 755
34. Michael Waldman (1994), 'Systematic Errors and the Theory of Natural Selection', *American Economic Review*, **84** (3), June, 482–97 775
35. Theodore C. Bergstrom (2002), 'Evolution of Social Behavior: Individual and Group Selection', *Journal of Economic Perspectives*, **16** (2), Spring, 67–88 791
36. Larry Samuelson (2002), 'Evolution and Game Theory', *Journal of Economic Perspectives*, **16** (2), Spring, 47–66 813
37. Thomas J. Brennan and Andrew W. Lo (2012), 'An Evolutionary Model of Bounded Rationality and Intelligence', *PLOS ONE*, **7** (11), November, 1–8 833
38. Andrew W. Lo (2013), 'The Origin of Bounded Rationality and Intelligence', *Proceedings of the American Philosophical Society*, **157** (3), September, 269–80 841
39. Terence C. Burnham (2013), 'Toward a Neo-Darwinian Synthesis of Neoclassical and Behavioral Economics', *Journal of Economic Behavior and Organization*, **90** (Supplement), June, S113–S127 853

Acknowledgements

The editors and publishers wish to thank the authors and the following publishers who have kindly given permission for the use of copyright material.

American Association for the Advancement of Science via the Copyright Clearance Center's RightsLink service for articles: Colin W. Clark (1973), 'The Economics of Overexploitation', *Science*, **181** (4100), August, 630–34; Martin A. Nowak (2006), 'Five Rules for the Evolution of Cooperation', *Science*, **314** (5805), December, 1560–63.

American Economic Association for articles: Ingemar Hansson and Charles Stuart (1990), 'Malthusian Selection of Preferences', *American Economic Review*, **80** (3), June, 529–44; Leda Cosmides and John Tooby (1994), 'Better than Rational: Evolutionary Psychology and the Invisible Hand', *American Economic Review: Papers and Proceedings*, **84** (2), May, 327–32; Alan R. Rogers (1994), 'Evolution of Time Preference by Natural Selection', *American Economic Review*, **84** (3), June, 460–81; Michael Waldman (1994), 'Systematic Errors and the Theory of Natural Selection', *American Economic Review*, **84** (3), June, 482–97; Richard R. Nelson (1995), 'Recent Evolutionary Theorizing About Economic Change', *Journal of Economic Literature*, **XXXIII** (1), March, 48–90; Arthur J. Robson (2001), 'The Biological Basis of Economic Behavior', *Journal of Economic Literature*, **XXXIX** (1), March, 11–33; Larry Samuelson (2002), 'Evolution and Game Theory', *Journal of Economic Perspectives*, **16** (2), Spring, 47–66; Theodore C. Bergstrom (2002), 'Evolution of Social Behavior: Individual and Group Selection', *Journal of Economic Perspectives*, **16** (2), Spring, 67–88; Arthur J. Robson and Larry Samuelson (2009), 'The Evolution of Time Preference with Aggregate Uncertainty', *American Economic Review*, **99** (5), December, 1925–53.

American Philosophical Society for article: Andrew W. Lo (2013), 'The Origin of Bounded Rationality and Intelligence', *Proceedings of the American Philosophical Society*, **157** (3), September, 269–80.

Annual Reviews via the Copyright Clearance Center's RightsLink service for article: Richard D. Alexander (1974), 'The Evolution of Social Behavior', *Annual Review of Ecology and Systematics*, **5**, November, 325–83.

Thomas J. Brennan and Andrew W. Lo for their own work: (2012), 'An Evolutionary Model of Bounded Rationality and Intelligence', *PLOS ONE*, **7** (11), November, 1–8.

Cambridge University Press for articles: Joseph A. Schumpeter (1947), 'The Creative Response in Economic History', *Journal of Economic History*, **VII** (2), November, 149–59; J. Maynard Smith (1984), 'Game Theory and the Evolution of Behaviour', *Behavioral and Brain Sciences*,

7 (1), March, 95–101, references; David Sloan Wilson and Elliott Sober (1994), ‘Reintroducing Group Selection to the Human Behavioral Sciences’, *Behavioral and Brain Sciences*, **17** (4), December, 585–608, references.

Ecological Society of America via the Copyright Clearance Center’s RightsLink service for article: Lawrence D. Harder and Leslie A. Real (1987), ‘Why Are Bumble Bees Risk Averse?’, *Ecology*, **68** (4), August, 1104–8.

Elsevier Ltd for articles: W.D. Hamilton (1964), ‘The Genetical Evolution of Social Behaviour I and II’, *Journal of Theoretical Biology*, **7** (1), July, 1–16, 17–52; Colin W. Clark and Marc Mangel (1986), ‘The Evolutionary Advantages of Group Foraging’, *Theoretical Population Biology*, **30** (1), August, 45–75; Arthur J. Robson (1996), ‘A Biological Basis for Expected and Non-expected Utility’, *Journal of Economic Theory*, **68** (2), February, 397–424; Herbert Gintis, Samuel Bowles, Robert Boyd and Ernst Fehr (2003), ‘Explaining Altruistic Behavior in Humans’, *Evolution and Human Behavior*, **24** (3), May, 153–72; Joseph Henrich (2004), ‘Cultural Group Selection, Coevolutionary Processes and Large-Scale Cooperation’, *Journal of Economic Behavior and Organization: Evolution and Altruism*, **53** (1), January, 3–35; Terence C. Burnham (2013), ‘Toward a Neo-Darwinian Synthesis of Neoclassical and Behavioral Economics’, *Journal of Economic Behavior and Organization*, **90** (Supplement), June, S113–S127.

National Academy of Sciences, USA for articles: Avraham Be’er, H.P. Zhang, E.-L. Florin, Shelley M. Payne, Eshel Ben-Jacob and Harry L. Swinney (2009), ‘Deadly Competition between Sibling Bacterial Colonies’, *Proceedings of the National Academy of Sciences*, **106** (2), January, 428–33; Kenneth J. Arrow and Simon A. Levin (2009), ‘Intergenerational Resource Transfers with Random Offspring Numbers’, *Proceedings of the National Academy of Sciences*, **106** (33), August, 13702–6; Ruixun Zhang, Thomas J. Brennan and Andrew W. Lo (2014), ‘The Origin of Risk Aversion’, *Proceedings of the National Academy of Sciences*, **111** (50), December, 17777–82.

Oxford University Press via the Copyright Clearance Center’s RightsLink service for articles: Herbert A. Simon (1955), ‘A Behavioral Model of Rational Choice’, *Quarterly Journal of Economics*, **69** (1), February, 99–118; Alan Kirman (1993), ‘Ants, Rationality, and Recruitment’, *Quarterly Journal of Economics*, **108** (1), February, 137–56.

Society for the Experimental Analysis of Behavior, with permission of John Wiley and Sons Ltd, for article: R.J. Herrnstein (1961), ‘Relative and Absolute Strength of Response as a Function of Frequency of Reinforcement’, *Journal of the Experimental Analysis of Behavior*, **4** (3), July, 267–72 (http://onlinelibrary.wiley.com/doi/10.1901/jeab.1961.4-267/full).

Springer Science and Media B.V. for article: Herbert Gintis (2007), ‘Review of *Adapting Minds: Evolutionary Psychology and the Persistent Quest for Human Nature*’, *Journal of Bioeconomics*, **9** (2), August, 191–9.

University of Chicago Press for articles: Armen A. Alchian (1950), ‘Uncertainty, Evolution, and Economic Theory’, *Journal of Political Economy*, **58** (3), June, 211–21; Robert L. Trivers

(1971), ‘The Evolution of Reciprocal Altruism’, *Quarterly Review of Biology*, **46** (1), March, 35–57; J. Hirshleifer (1977), ‘Economics from a Biological Viewpoint’, *Journal of Law and Economics*, **20** (1), April, 1–52; David Sloan Wilson and Edward O. Wilson (2007), ‘Rethinking the Theoretical Foundation of Sociobiology’, *Quarterly Review of Biology*, **82** (4), December, 327–48; Rose McDermott, James H. Fowler and Oleg Smirnov (2008), ‘On the Evolutionary Origin of Prospect Theory Preferences’, *Journal of Politics*, **70** (2), April, 335–50.

University of Illinois Press for article: Erika R. Behrend and M.E. Bitterman (1961), ‘Probability-Matching in the Fish’, *American Journal of Psychology*, **74** (4), December, 542–51.

World Scientific Publishing via the Copyright Clearance Center’s RightsLink service for article: Thomas J. Brennan and Andrew W. Lo (2011), ‘The Origin of Behavior’, *Quarterly Journal of Finance*, **1** (1), March, 55–108.

Every effort has been made to trace all the copyright holders but if any have been inadvertently overlooked the publishers will be pleased to make the necessary arrangement at the first opportunity.

In addition the publishers wish to thank the Library of Indiana University at Bloomington, USA for their assistance in obtaining these articles.

Introduction

Andrew W. Lo and Ruixun Zhang

1 Foundations

This volume brings together a collection of articles that reflect the influence of biological ideas in economics. Such an undertaking was considerably more challenging than we first thought – we discovered much to our surprise that this literature is vast, spanning the disciplines of evolutionary biology, ecology, evolutionary and social psychology, economics, finance neuroscience, and even genomics. A comprehensive survey is well beyond the scope of this book (and would require several volumes); our more modest goal is to provide a representative sampling of the many strands of research that are most relevant to this exciting and dynamic field of study.

Early connections between biologists and economists can be traced back to the 19th century. Malthus (1830, Part I Chapter 1) used a simple biological argument – the fact that populations increase at geometric rates, whereas natural resources increase at only arithmetic rates (at least in the 19th century) – to arrive at the dire economic consequences that earned the field the moniker "dismal science." Charles R. Darwin was clearly influenced by this idea and published his famous *On the Origin of Species* (Darwin 1859) subsequently, which launched the discipline of evolutionary biology.

Joseph A. Schumpeter and Armen A. Alchian were among the first economists to formally bring evolutionary ideas into the study of economic systems. Schumpeter (1947, Part I Chapter 2) argued that capitalism should be understood as an evolutionary process of continuous innovation and "creative destruction," a concept that has taken on much greater relevance as driverless cars are poised to upend the trucking, taxi, and livery industries. Alchian (1950, Part I Chapter 3) interpreted the economic system as an adaptive process that chooses among exploratory actions generated by the pursuit of "success" or "profits." This was completely revolutionary at the time, and eliminated the unrealistic assumption of accurate anticipations and fixed states of knowledge.

Since then, biological ideas have been brought into the study of economic behavior and systems in many ways. Sociobiology and evolutionary psychology sparked early studies of social behavior from an evolutionary perspective. Similar ideas were adopted by economists in the late 20th century in a wide range of topics including utility theory, rationality, intelligence, firms, and financial markets. These developments, in turn, inspired a new and growing literature in neuroscience and genomics attempting to trace the origins of economic behavior to their biological roots. For example, Hirshleifer (1977, Part I Chapter 4) studied the connections between economics and sociobiology comprehensively and noted their mutual influences, and Nelson (1995, Part I Chapter 5) promoted the evolutionary theorizing of economics by studying the mechanisms and implications of economic change.

2 Sociobiology, Evolutionary Psychology, and Behavioral Ecology

The first concerted attempts to apply evolutionary principles to the study of human behavior span the disciplines of sociobiology, evolutionary and social psychology, and behavioral ecology, with many interrelated connections within each of these fields.

Sociobiology

The sociobiology literature began with the notion that evolution could be applied to social behaviors such as group selection, cooperation, and altruism. Hamilton (1964, Part I Chapter 6) was the first to put forward the great insight that individual fitness is not maximized by social evolution; inclusive fitness is. Trivers (1971, Part I Chapter 7) showed how "reciprocally altruistic" behavior can be favored by natural selection even when the recipient is only distantly related to the organism performing the altruistic act. The idea that something other than the individual organism could be the fitness-maximizing unit was completely revolutionary at the time and opened new research areas that are still being explored and debated today.

In particular, multilevel selection theory (including group selection) (Wilson and Sober 1994, Part I Chapter 9) and reciprocity (Trivers 1971, Part I Chapter 7) have been used to explain a wide range of social behaviors including altruism (Alexander 1974, Part I Chapter 8; Wilson and Wilson 2007, Part I Chapter 13) and cooperation (Henrich 2004, Part I Chapter 11; Nowak 2006, Part I Chapter 12). Gintis et al. (2003, Part I Chapter 10) showed that strong reciprocity is an "evolutionarily stable strategy" (see below) under certain conditions, and they present empirical evidence supporting strong reciprocity as a schema for predicting and understanding altruism in humans.

Evolutionary Psychology and Behavioral Ecology

These ideas from sociobiology were subsequently subsumed by the fields of behavioral ecology and evolutionary psychology. Examples in the behavioral ecology literature include the study of probability matching in fish (Behrend and Bitterman 1961, Part I Chapter 14) and pigeons (Herrnstein 1961, Part I Chapter 15), risk-sensitive foraging behavior in bumble bees (Harder and Real 1987, Part I Chapter 18), the evolution of group foraging behavior (Clark and Mangel 1986, Part I Chapter 17), and the deadly competition between sibling bacterial colonies (Be'er et al. 2009, Part I Chapter 21).

Evolutionary psychology has provided many key insights into human behavior by understanding the brain's particular capacities and limitations (Gintis 2007, Part I Chapter 20), including the economics of overexploitation of biological resources (Clark 1973, Part I Chapter 16), and intergenerational resource transfers and wealth accumulation (Arrow and Levin 2009, Part I Chapter 22). Brennan and Lo (2011, Part I Chapter 23) proposed a single evolutionary explanation for the origin of several "irrational" behaviors that have been observed in organisms ranging from ants to human subjects. This framework suggests that these derived behaviors are primitive and nearly universal within and across species. Natural selection's invisible hand created the structure of the human mind, and the interaction of these minds is what generates, in turn, the invisible hand of economics (Cosmides and Tooby 1994, Part I Chapter 19).

3 Economic Sciences

Applications of evolution to the economic sciences cover a wide spectrum of topics, including the biological foundation of utility functions, rationality and intelligence, the dynamics of financial markets, and the theory of firms and institutions.

The Biological Foundations of Utility

Preferences are central to economic theory, yet most economists treat them as exogenous and determined by "deep parameters" that are taken as given. In contrast to this neoclassical economic pre-determinism, evolutionary arguments can explain or "endogenize" the specific forms of utility functions. Studying the biological basis of economic behavior can help determine the leading candidates from the entire slate of standard and nonstandard models of utility (Robson 2001, Part I Chapter 27).

For example, Robson's (1996, Part I Chapter 26) seminal paper on the evolutionary origins of utility functions derived the expected utility from fixed environments and non-expected utility from random environments. Furthermore, it can be shown that evolutionarily selected agents are less averse to idiosyncratic reproductive risks than systematic reproductive risks (Zhang et al. 2014, Part I Chapter 30). The evolutionary origin of prospect theory preferences has also been considered in a model of risk-sensitive optimal foraging theory (McDermott et al. 2008, Part I Chapter 28).

Hansson and Stuart (1990, Part I Chapter 24) focused on intergenerational saving and consumption-leisure choice and concluded that preferences with maximum biological fitness given resource constraints are selected. Following this approach, Rogers (1994, Part I Chapter 25) concluded that the long-term real interest rate should equal ln(2) per generation, and that young adults should discount the future more rapidly than their elders (which is supported by casual observation of typical teenage behavior). Robson and Samuelson (2009, Part I Chapter 29) argued that aggregate uncertainty leads to higher discount rates and can push agents away from exponential discounting in an evolutionary framework.

Rationality and Intelligence

Traditional economic models almost always assume perfect knowledge of the relevant environment and a well-defined and stable system of preferences. Simon (1955, Part I Chapter 31) was the first to propose the notion of "bounded rationality," which was meant to replace the hyper-rationality of *Homo economicus* by a more realistic *Homo sapiens* constrained by limited access to information and finite computational capacity. From an evolutionary perspective, Brennan and Lo (2012, Part I Chapter 37) and Lo (2013, Part I Chapter 38) argued that bounds on rationality and intelligence are determined by physiological and environmental constraints, and provided a simple binary choice model that illustrates how such bounds can arise.

Evolutionary arguments have also been used to explain a wide range of systematic deviations from rationality, including foraging in ants and herding in financial markets (Kirman 1993, Part I Chapter 33), overestimation by males (Waldman 1994, Part I Chapter 34), and cooperation and group selection (Bergstrom 2002, Part I Chapter 35). Burnham (2013, Part I Chapter 39) proposed a biological foundation for several anomalies of behavioral economics by separating proximate and ultimate causation.

Maynard Smith (1984, Part I Chapter 32) summarizes important work on evolutionary game theory that was developed in the 1970s, including the concept of an "evolutionarily stable strategy" (ESS). An ESS is an equilibrium refinement of the Nash equilibrium that is stable from an evolutionary perspective: once adopted by a population, it cannot be invaded by any alternative strategy that is initially rare. Evolutionary game theory complements general equilibrium theory and, in cases of multiple equilibria, provides support for which equilibrium we might expect to see (Samuelson 2002, Part I Chapter 36).

Financial Markets

Biological ideas have also played an important role in the study of financial markets. As an alternative to the Efficient Markets Hypothesis, financial markets can be viewed within an evolutionary framework in which instruments, institutions, and investors interact and evolve dynamically according to the "law" of economic selection (Farmer and Lo 1999 Part II Chapter 2). Under this view, financial agents are highly interconnected and engaged in complex behaviors, and can therefore pose systemic risks (May et al. 2008). They compete and adapt, but do not necessarily do so in an optimal fashion. The Adaptive Markets Hypothesis (Lo 2004, Part II Chapter 6; 2012, Part II Chapter 11; 2017) reconciles economic theories based on the Efficient Markets Hypothesis with behavioral economics: the neoclassical models of rational behavior can coexist with behavioral models, and what are often cited as counterexamples to rationality – loss aversion, overconfidence, overreaction, and other behavioral biases – are, in fact, consistent with natural selection shaping human behavior over many generations and across a variety of environments.

More specifically, evolutionary principles have been used to explain the survival of the "fittest" investment strategies and traders, and their impact on market dynamics. Blume and Easley (1992, Part II Chapter 1) studied wealth flows between investors and found that fit rules need not be rational and rational rules need not be fit. In the context of trading with market orders, Farmer (2002, Part II Chapter 3) found that value investing and trend following can generate boom–bust cycles, excess and temporally correlated volatility, and fat tails in price fluctuations all of which slows the progression to efficiency. He went so far as to argue that the timescale for efficiency is years to decades. Brock et al. (2005, Part II Chapter 8) modeled the dynamical behavior of heterogeneous markets with many trader types. Kogan et al. (2006, Part II Chapter 7) showed that survival and price impact are two independent concepts, and irrational traders can have a significant impact on asset prices even when their wealth becomes negligible. Hommes and Wagener (2009) calibrated a model of complex evolutionary systems to real financial market data and laboratory experiments with human subjects. Sugihara et al. (2012, Part II Chapter 10) studied causal networks in complex ecosystems including financial markets.

Psychological and physiological effects in financial traders and stock markets have also been documented. Through links between seasonal affective disorder and depression and between depression and risk aversion, seasonal variation in length of day can translate into seasonal variation in equity returns (Kamstra et al. 2003, Part II Chapter 4). By examining daily market index returns across 26 countries, Hirshleifer and Shumway (2003, Part II Chapter 5) found that sunshine is significantly positively correlated with stock returns, which is difficult to reconcile with fully rational price setting. In live trading sessions, fear, greed, and other emotional responses to price fluctuations cause financially ruinous biases, and it has been documented that even the most seasoned trader exhibits significant emotional response, and that successful trading behavior and emotional reactivity are negatively correlated (Lo et al. 2005, Part II Chapter 9).

Evolution of Firms and Institutions

Biological analogies in the theory of the firm can be traced back to Alchian (1950, Part I Chapter 3). Winter (1964, Part II Chapter 12) examined systematically the implications of the natural selection mechanism in firms and argued that it only supports the profit-maximization assumption under special circumstances and for a restricted range of applications. Luo (1995, Part II Chapter 14) showed that the industry converges to the same perfectly competitive equilibrium as profit maximization, even if firms behave irrationally. More recently, Darwinian ideas such as group selection have also been used to understand institutional change in history (Herrmann-Pillath 1991, Part II Chapter 13), and the selection of organizational routines and structures, social norms, and public policy (van den Bergh and Gowdy 2009, Part II Chapter 15).

4 Neuroscience, Hormones, and Genomics

Human genomics determines the structure of our brain, and the brain controls human behavior, which includes economic behavior; hence, the emerging field of behavioral genomics. In the past two decades, an enormous amount of research in biology, neuroscience, and human genomics has, in turn, been stimulated by developments in the study of economic behavior.

Neuroscience and Neuroeconomics

Progress in functional magnetic resonance imaging (fMRI) technology has made possible a series of studies on the neural basis of decision making, giving rise to the new field of "neuroeconomics." Examples of this burgeoning literature include the anticipation and experience of monetary gains and losses (Breiter et al. 2001, Part II Chapter 16), deviations from rationality including risk-seeking and risk-aversion mistakes (Kuhnen and Knutson 2005, Part II Chapter 18), framing effects (De Martino et al. 2006, Part II Chapter 19), loss aversion (Tom et al. 2007, Part II Chapter 21), and altruistic, fair, and trusting behaviors (Fehr and Camerer 2007, Part II Chapter 20). These studies suggest that distinct neural circuits promote specific types of financial choices (Kuhnen and Knutson 2005, Part II Chapter 18), and highlight the importance of incorporating emotional processes within models of human choice (Lo and Repin 2002, Part II Chapter 17; De Martino et al. 2006, Part II Chapter 19).

These rapid developments in neuroscience provide an understanding of human decision making from a completely new perspective. Gold and Shadlen (2007) reviewed the formal, mathematical prescriptions for how to make a decision, and then identified neural substrates of decision making from experimental results. Fehr and Rangel (2011, Part II Chapter 23) described computational models of two choice problems as well as the neuroeconomic experiments that distinguish among the different components of the model. Neural activity causally determines economic choices (Fehr and Rangel 2011, Part II Chapter 23), and emotions play a crucial supporting role even if they may not always be balanced appropriately (Bossaerts 2009, Part II Chapter 22). This view is shared by Lo (2013, Part II Chapter 24), who pointed out that by exploring the neuroscientific basis of cognition and behavior, including fear and greed, we may be able to identify more fundamental drivers of financial crises and improve our methods of dealing with them.

Hormones

In addition to brain activity, a variety of hormones have also been associated with economic behaviors. Testosterone is known to be involved in males seeking dominance in a wide range of species, and a series of studies found that testosterone is also related to human decision making. In the context of the "ultimatum game," men who rejected low offers had significantly higher testosterone levels than those who accepted (Burnham 2007, Part II Chapter 26), which is difficult to reconcile with the standard view of economic rationality where any positive offer should be preferred over the prospect of receiving nothing. In an investment game with potential for real monetary payoffs, risk-taking behavior correlated positively with salivary testosterone levels (Apicella et al. 2008, Part II Chapter 27). Under real working conditions on a London trading floor, a trader's morning testosterone level predicted his day's profitability, and his cortisol level rose with both the variance of his trading results and the volatility of the market (Coates and Herbert 2008, Part II Chapter 28). In a study of 98 young subjects on the Harvard campus, salivary testosterone levels were significantly correlated with Zuckerman's sensation-seeking scale (Campbell et al. 2010, Part II Chapter 29).

Other hormones that correlate with economic behavior include oxytocin and dopamine. In the context of a "trust game," higher oxytocin levels were associated with trustworthy behavior, and perceptions of intentions of trust affected levels of circulating oxytocin (Zak et al. 2005, Part II Chapter 25). Among serious tournament bridge players, the dopamine system played an important role in both advantageous and disadvantageous risk-taking behavior among men, in the context of both bridge and financial gambles (Dreber et al. 2011, Part II Chapter 30). However, no relationship was found among their female subjects.

Genomics

Nature versus nurture: it has long been a hotly debated topic as to which determines behavior, including economic behavior. Benjamin et al. (2012, Part II Chapter 35) provided an excellent review of the existing research at the intersection of genetics and economics. Twin studies suggest that economic outcomes and preferences, once corrected for measurement error, appear to be about as heritable as many medical conditions and personality traits (Benjamin et al. 2012, Part II Chapter 35). This view is supported by Barnea et al. (2010, Part II Chapter 32) and Cesarini et al. (2010, Part II Chapter 33), who found that genetic variation explains between a fifth and a third of the variance in stock market participation and asset allocation among identical and fraternal twins. Furthermore, in a game with real monetary payoffs, men with the 7-repeat allele (7*R*+) in the dopamine receptor *D*4 gene were significantly more risk loving than 7*R*− men. This is consistent with previous evolutionary explanations that selection for this allele was linked to behaviors associated with migration and male competition, both of which entail an element of risk (Dreber et al. 2009, Part II Chapter 31).

Genetic variation has also been used to explain behavioral anomalies and biases. Survey-based evidence from more than 11,000 Swedish twins demonstrated that a number of anomalies such as the conjunction fallacy, the default bias, and loss aversion are moderately heritable (Cesarini et al. 2012, Part II Chapter 34). Up to 45 percent of the variation in several investment biases including the lack of diversification, excessive trading, and the disposition effect can be explained by genetic differences after controlling for individual characteristics (Cronqvist and Siegel 2014, Part II Chapter 36). These studies suggest that the heritable variation in behavioral anomalies is partly mediated by genetic variation in cognitive ability (Cesarini et al. 2012, Part II Chapter 34), and that investment behaviors are manifestations of innate and evolutionarily ancient features of human behavior (Cronqvist and Siegel 2014, Part II Chapter 36).

5 Conclusion

Upon deeper reflection and introspection, the close connections between biology and economics should come as no surprise to anyone. After all, economics is simply the study of how one particular animal species has adapted to its environment. The opposable thumb is no more a product of natural selection than fiat money, property rights, and derivative securities. Moreover, economies are populated with people, not automatons, hence biology is inextricably linked to economic activity.

In fact, the biggest barrier between the fields of biology and economics is the "physics envy" that still pervades the economics profession (Lo and Mueller 2010). The elegant axiomatic derivations of expected utility theory, general equilibrium theory, and rational expectations models are irresistible to economists who aspire to explain 99 percent of all observable phenomenon with three laws, as physicists do. Unfortunately, biology is more complex than physics, especially human biology. As the great physicist Richard Feynman explained succinctly, "imagine how much harder physics would be if electrons had feelings."

Our hope in putting together this volume is to stimulate greater collaboration between biology and economics – both fields will be the richer from such engagement. Biology is messier and not nearly as mathematically precise as physics, but it is a much closer cousin of economics and has a logic and aesthetic of its own. To paraphrase Dobzhansky, nothing in economics makes sense except in the light of human biology.

Acknowledgments

We thank Tom Brennan, Terry Burnham, Doyne Farmer, David Hirshleifer, Simon Levin, and Allen Orr for many helpful discussions about the role of biology in economics, and are grateful to Jayna Cummings for editorial assistance and the MIT Laboratory for Financial Engineering for research support. The views and opinions expressed in this introduction are those of the editors only, and do not necessarily represent the views and opinions of any institution or agency, any of their affiliates or employees, any of the contributors to this volume, or any of the individuals acknowledged above.

References

Darwin, C.R., 1859, *On the Origin of Species*. John Murray, London.
Gold, J.I., and M.N. Shadlen, 2007, "The neural basis of decision making," *Annual Review of Neuroscience*, 30, 535–574.
Hommes, C.H., and F.O. Wagener, 2009, "Complex evolutionary systems in behavioral finance," in *Handbook of Financial Markets*, ed. by T. Hens, and K. Schenk-Hoppe. New York: Elsevier North Holland, pp. 217–276.
Lo, A, W., 2017, *Adaptive Markets: Financial Evolution at the Speed of Thought*. Princeton, NJ: Princeton University Press.
Lo, A.W., and M. Mueller, 2010, "Warning: physics envy may be hazardous to your wealth," *Journal of Investment Management*, 8, 13–63.
May, R.M., S.A. Levin, and G. Sugihara, 2008, "Complex systems: ecology for bankers," *Nature*, 451(7181), 893–895.

Biological Economics
Volume II

The International Library of Critical Writings in Economics

Founding Editor: Mark Blaug

Late Professor Emeritus, University of London, UK
Late Professor Emeritus, University of Buckingham, UK

This series is an essential reference source for students, researchers and lecturers in economics. It presents by theme a selection of the most important articles across the entire spectrum of economics. Each volume has been prepared by a leading specialist who has written an authoritative introduction to the literature included.

Wherever possible, the articles in these volumes have been reproduced as originally published using facsimile reproduction, inclusive of footnotes and pagination to facilitate ease of reference.

Biological Economics Volume II

Edited by

Andrew W. Lo

Charles E. and Susan T. Harris Professor
MIT Sloan School of Management
and Director, MIT Laboratory for Financial Engineering
Cambridge, Massachusetts, USA

and

Ruixun Zhang

Research Affiliate
MIT Laboratory for Financial Engineering
Cambridge, Massachusetts, USA

THE INTERNATIONAL LIBRARY OF CRITICAL WRITINGS IN ECONOMICS

An Elgar Research Collection
Cheltenham, UK • Northampton, MA, USA

Published by
Edward Elgar Publishing Limited
The Lypiatts
15 Lansdown Road
Cheltenham
Glos GL50 2JA
UK

Edward Elgar Publishing, Inc.
William Pratt House
9 Dewey Court
Northampton
Massachusetts 01060
USA

A catalogue record for this book
is available from the British Library

Library of Congress Control Number: 2017955160

ISBN 978 1 78254 853 9 (2 volume set)

Contents

Acknowledgements ix
Introduction An introduction to both volumes by the editors appears in Volume I

PART I FINANCIAL MARKETS

1. Lawrence Blume and David Easley (1992), 'Evolution and Market Behavior', *Journal of Economic Theory*, **58** (1), October, 9–40 3
2. J. Doyne Farmer and Andrew W. Lo (1999), 'Frontiers of Finance: Evolution and Efficient Markets', *Proceedings of the National Academy of Sciences*, **96** (18), August, 9991–2 35
3. J. Doyne Farmer (2002), 'Market Force, Ecology and Evolution', *Industrial and Corporate Change*, **11** (5), November, 895–953 37
4. Mark J. Kamstra, Lisa A. Kramer and Maurice D. Levi (2003), 'Winter Blues: A SAD Stock Market Cycle', *American Economic Review*, **93** (1), March, 324–43 96
5. David Hirshleifer and Tyler Shumway (2003), 'Good Day Sunshine: Stock Returns and the Weather', *Journal of Finance*, **LVIII** (3), June, 1009–32 116
6. Andrew W. Lo (2004), 'The Adaptive Markets Hypothesis: Market Efficiency from an Evolutionary Perspective', *Journal of Portfolio Management: 30th Anniversary Issue*, **30** (5), 15–29 140
7. Leonid Kogan, Stephen A. Ross, Jiang Wang and Mark M. Westerfield (2006), 'The Price Impact and Survival of Irrational Traders', *Journal of Finance*, **LXI** (1), February, 195–229 155
8. William A. Brock, Cars H. Hommes and Florian O.O. Wagener (2005), 'Evolutionary Dynamics in Markets with Many Trader Types', *Journal of Mathematical Economics: Special Issue on Evolutionary Finance*, **41** (1–2), February, 7–42 190
9. Andrew W. Lo, Dmitry V. Repin and Brett N. Steenbarger (2005), 'Fear and Greed in Financial Markets: A Clinical Study of Day-Traders', *American Economic Review: Papers and Proceedings*, **95** (2), May, 352–9 226
10. George Sugihara, Robert May, Hao Ye, Chih-hao Hsieh, Ethan Deyle, Michael Fogarty and Stephan Munch (2012), 'Detecting Causality in Complex Ecosystems', *Science*, **338** (6106), October, 496–500 234
11. Andrew W. Lo (2012), 'Adaptive Markets and the New World Order', *Financial Analysts Journal*, **68** (2), March–April, 18–29, Errata 239

PART II EVOLUTION OF FIRMS AND INSTITUTIONS

12. Sidney G. Winter, Jr. (1964), 'Economic "Natural Selection" and the Theory of the Firm', *Yale Economic Essays*, **4** (1), Spring, 225–72 255
13. Carsten Herrmann-Pillath (1991), 'A Darwinian Framework for the Economic Analysis of Institutional Change in History', *Journal of Social and Biological Structures*, **14** (2), 127–48 303
14. Guo Ying Luo (1995), 'Evolution and Market Competition', *Journal of Economic Theory*, **67** (1), October, 223–50 325
15. Jeroen C.J.M. van den Bergh and John M. Gowdy (2009), 'A Group Selection Perspective on Economic Behavior, Institutions and Organizations', *Journal of Economic Behavior and Organization*, **72** (1), October, 1–20 353

PART III NEUROSCIENCE

16. Hans C. Breiter, Itzhak Aharon, Daniel Kahneman, Anders Dale and Peter Shizgal (2001), 'Functional Imaging of Neural Responses to Expectancy and Experience of Monetary Gains and Losses', *Neuron*, **30** (2), May, 619–39 375
17. Andrew W. Lo and Dmitry V. Repin (2002), 'The Psychophysiology of Real-Time Financial Risk Processing', *Journal of Cognitive Neuroscience*, **14** (3), April, 323–39 396
18. Camelia M. Kuhnen and Brian Knutson (2005), 'The Neural Basis of Financial Risk Taking', *Neuron*, **47** (5), September, 763–70 413
19. Benedetto De Martino, Dharshan Kumaran, Ben Seymour and Raymond J. Dolan (2006), 'Frames, Biases, and Rational Decision-Making in the Human Brain', *Science*, **313**, (5787), August, 684–7 421
20. Ernst Fehr and Colin F. Camerer (2007), 'Social Neuroeconomics: The Neural Circuitry of Social Preferences', *TRENDS in Cognitive Sciences*, **11** (10), October, 419–27 425
21. Sabrina M. Tom, Craig R. Fox, Christopher Trepel and Russell A. Poldrack (2007), 'The Neural Basis of Loss Aversion in Decision-Making Under Risk', *Science*, **315** (5811), January, 515–18 434
22. Peter Bossaerts (2009), 'What Decision Neuroscience Teaches Us About Financial Decision Making', *Annual Review of Financial Economics*, **1**, 383–88, C1–C3, 389–404 438
23. Ernst Fehr and Antonio Rangel (2011), 'Neuroeconomic Foundations of Economic Choice – Recent Advances', *Journal of Economic Perspectives*, **25** (4), Fall, 3–30 463
24. Andrew W. Lo (2013), 'Fear, Greed, and Financial Crises: A Cognitive Neurosciences Perspective', in Jean-Pierre Fouque and Joseph A. Langsam (eds), *Handbook on Systemic Risk*, Part VIII, Chapter 23, New York, NY, USA: Cambridge University Press, 622–62 491

PART IV HORMONES

25. Paul J. Zak, Robert Kurzban and William T. Matzner (2005), ‘Oxytocin is Associated with Human Trustworthiness’, *Hormones and Behavior*, **48** (5), December, 522–7 535
26. Terence C. Burnham (2007), ‘High-Testosterone Men Reject Low Ultimatum Game Offers’, *Proceedings of the Royal Society B: Biological Sciences*, **274** (1623), September, 2327–30 541
27. Coren L. Apicella, Anna Dreber, Benjamin Campbell, Peter B. Gray, Moshe Hoffman and Anthony C. Little (2008), ‘Testosterone and Financial Risk Preferences’, *Evolution and Human Behavior*, **29** (6), November, 384–90 545
28. J.M. Coates and J. Herbert (2008), ‘Endogenous Steroids and Financial Risk Taking on a London Trading Floor’, *Proceedings of the National Academy of Sciences*, **105** (16), April, 6167–72 552
29. Benjamin C. Campbell, Anna Dreber, Coren L. Apicella, Dan T.A. Eisenberg, Peter B. Gray, Anthony C. Little, Justin R. Garcia, Richard S. Zamore and J. Koji Lum (2010), ‘Testosterone Exposure, Dopaminergic Reward, and Sensation-Seeking in Young Men’, *Physiology and Behavior*, **99** (4), March, 451–6 558
30. Anna Dreber, David G. Rand, Nils Wernerfelt, Justin R. Garcia, Miguel G. Vilar, J. Koji Lum and Richard Zeckhauser (2011), ‘Dopamine and Risk Choices in Different Domains: Findings among Serious Tournament Bridge Players’, *Journal of Risk and Uncertainty*, **43** (1), August, 19–38 564

PART V GENOMICS

31. Anna Dreber, Coren L. Apicella, Dan T.A. Eisenberg, Justin R. Garcia, Richard S. Zamore, J. Koji Lum and Benjamin Campbell (2009), ‘The 7R Polymorphism in the Dopamine Receptor D_4 Gene (*DRD4*) is Associated with Financial Risk-Taking in Men’, *Evolution and Human Behavior*, **30** (2), March, 85–92 587
32. Amir Barnea, Henrik Cronqvist and Stephan Siegel (2010), ‘Nature or Nurture: What Determines Investor Behavior?’, *Journal of Financial Economics*, **98** (3), December, 583–604 595
33. David Cesarini, Magnus Johannesson, Paul Lichtenstein, Örjan Sandewall and Björn Wallace (2010), ‘Genetic Variation in Financial Decision-Making’, *Journal of Finance*, **LXV** (5), October, 1725–54 617
34. David Cesarini, Magnus Johannesson, Patrik K.E. Magnusson and Björn Wallace (2012), ‘The Behavioral Genetics of Behavioral Anomalies’, *Management Science*, **58** (1), January, 21–34 647

35. Daniel J. Benjamin, David Cesarini, Christopher F. Chabris, Edward L. Glaeser, David I. Laibson, Vilmundur Guđnason, Tamara B. Harris, Lenore J. Launer, Shaun Purcell, Albert Vernon Smith, Magnus Johannesson, Patrik K.E. Magnusson, Jonathan P. Beauchamp, Nicholas A. Christakis, Craig S. Atwood, Benjamin Hebert, Jeremy Freese, Robert M. Hauser, Taissa S. Hauser, Alexander Grankvist, Christina M. Hultman and Paul Lichtenstein (2012), 'The Promises and Pitfalls of Genoeconomics', *Annual Review of Economics*, **4**, 627–62, C1 661
36. Henrik Cronqvist and Stephan Siegel (2014), 'The Genetics of Investment Biases', *Journal of Financial Economics*, **113** (2), August, 215–34 698

Acknowledgements

The editors and publishers wish to thank the authors and the following publishers who have kindly given permission for the use of copyright material.

American Association for the Advancement of Science via the Copyright Clearance Center's RightsLink service for articles: Benedetto De Martino, Dharshan Kumaran, Ben Seymour and Raymond J. Dolan (2006), 'Frames, Biases, and Rational Decision-Making in the Human Brain', *Science*, **313**, (5787), August, 684–7; Sabrina M. Tom, Craig R. Fox, Christopher Trepel and Russell A. Poldrack (2007), 'The Neural Basis of Loss Aversion in Decision-Making Under Risk', *Science*, **315** (5811), January, 515–18; George Sugihara, Robert May, Hao Ye, Chih-hao Hsieh, Ethan Deyle, Michael Fogarty and Stephan Munch (2012), 'Detecting Causality in Complex Ecosystems', *Science*, **338** (6106), October, 496–500.

American Economic Association for articles: Mark J. Kamstra, Lisa A. Kramer and Maurice D. Levi (2003), 'Winter Blues: A SAD Stock Market Cycle', *American Economic Review*, **93** (1), March, 324–43; Andrew W. Lo, Dmitry V. Repin and Brett N. Steenbarger (2005), 'Fear and Greed in Financial Markets: A Clinical Study of Day-Traders', *American Economic Review: Papers and Proceedings*, **95** (2), May, 352–9; Ernst Fehr and Antonio Rangel (2011), 'Neuroeconomic Foundations of Economic Choice – Recent Advances', *Journal of Economic Perspectives*, **25** (4), Fall, 3–30.

American Finance Association, with permission of John Wiley and Sons Ltd, for articles: David Hirshleifer and Tyler Shumway (2003), 'Good Day Sunshine: Stock Returns and the Weather', *Journal of Finance*, **LVIII** (3), June, 1009–32 (http://onlinelibrary.wiley.com/doi/10.1111/1540-6261.00556/full); Leonid Kogan, Stephen A. Ross, Jiang Wang and Mark M. Westerfield (2006), 'The Price Impact and Survival of Irrational Traders', *Journal of Finance*, **LXI** (1), February, 195–229 (http://onlinelibrary.wiley.com/doi/10.1111/j.1540-6261.2006.00834.x/full); David Cesarini, Magnus Johannesson, Paul Lichtenstein, Örjan Sandewall and Björn Wallace (2010), 'Genetic Variation in Financial Decision-Making', *Journal of Finance*, **LXV** (5), October, 1725–54 (http://onlinelibrary.wiley.com/doi/10.1111/j.1540-6261.2010.01592.x/full).

Annual Reviews via the Copyright Clearance Center's RightsLink service for articles: Peter Bossaerts (2009), 'What Decision Neuroscience Teaches Us About Financial Decision Making', *Annual Review of Financial Economics*, **1**, 383–88, C1–C3, 389–404; Daniel J. Benjamin, David Cesarini, Christopher F. Chabris, Edward L. Glaeser, David I. Laibson, Vilmundur Guđnason, Tamara B. Harris, Lenore J. Launer, Shaun Purcell, Albert Vernon Smith, Magnus Johannesson, Patrik K.E. Magnusson, Jonathan P. Beauchamp, Nicholas A. Christakis, Craig S. Atwood, Benjamin Hebert, Jeremy Freese, Robert M. Hauser, Taissa S. Hauser, Alexander

Grankvist, Christina M. Hultman and Paul Lichtenstein (2012), ‘The Promises and Pitfalls of Genoeconomics’, *Annual Review of Economics*, **4**, 627–62, C1.

Cambridge University Press for excerpt: Andrew W. Lo (2013), ‘Fear, Greed, and Financial Crises: A Cognitive Neurosciences Perspective’, in Jean-Pierre Fouque and Joseph A. Langsam (eds), *Handbook on Systemic Risk*, Part VIII, Chapter 23, 622–62.

CFA Institute for article: Andrew W. Lo (2012), ‘Adaptive Markets and the New World Order’, *Financial Analysts Journal*, **68** (2), March–April, 18–29, Errata.

Elsevier Ltd for articles: Carsten Herrmann-Pillath (1991), ‘A Darwinian Framework for the Economic Analysis of Institutional Change in History’, *Journal of Social and Biological Structures*, **14** (2), 127–48; Lawrence Blume and David Easley (1992), ‘Evolution and Market Behavior’, *Journal of Economic Theory*, **58** (1), October, 9–40; Guo Ying Luo (1995), ‘Evolution and Market Competition’, *Journal of Economic Theory*, **67** (1), October, 223–50; Hans C. Breiter, Itzhak Aharon, Daniel Kahneman, Anders Dale and Peter Shizgal (2001), ‘Functional Imaging of Neural Responses to Expectancy and Experience of Monetary Gains and Losses’, *Neuron*, **30** (2), May, 619–39; William A. Brock, Cars H. Hommes and Florian O.O. Wagener (2005), ‘Evolutionary Dynamics in Markets with Many Trader Types’, *Journal of Mathematical Economics: Special Issue on Evolutionary Finance*, **41** (1–2), February, 7–42; Camelia M. Kuhnen and Brian Knutson (2005), ‘The Neural Basis of Financial Risk Taking’, *Neuron*, **47** (5), September, 763–70; Paul J. Zak, Robert Kurzban and William T. Matzner (2005), ‘Oxytocin is Associated with Human Trustworthiness’, *Hormones and Behavior*, **48** (5), December, 522–7; Ernst Fehr and Colin F. Camerer (2007), ‘Social Neuroeconomics: The Neural Circuitry of Social Preferences’, *TRENDS in Cognitive Sciences*, **11** (10), October, 419–27; Coren L. Apicella, Anna Dreber, Benjamin Campbell, Peter B. Gray, Moshe Hoffman and Anthony C. Little (2008), ‘Testosterone and Financial Risk Preferences’, *Evolution and Human Behavior*, **29** (6), November, 384–90; Anna Dreber, Coren L. Apicella, Dan T.A. Eisenberg, Justin R. Garcia, Richard S. Zamore, J. Koji Lum and Benjamin Campbell (2009), ‘The 7R Polymorphism in the Dopamine Receptor D_4 Gene (*DRD4*) is Associated with Financial Risk-Taking in Men’, *Evolution and Human Behavior*, **30** (2), March, 85–92; Jeroen C.J.M. van den Bergh and John M. Gowdy (2009), ‘A Group Selection Perspective on Economic Behavior, Institutions and Organizations’, *Journal of Economic Behavior and Organization*, **72** (1), October, 1–20; Amir Barnea, Henrik Cronqvist and Stephan Siegel (2010), ‘Nature or Nurture: What Determines Investor Behavior?’, *Journal of Financial Economics*, **98** (3), December, 583–604; Benjamin C. Campbell, Anna Dreber, Coren L. Apicella, Dan T.A. Eisenberg, Peter B. Gray, Anthony C. Little, Justin R. Garcia, Richard S. Zamore and J. Koji Lum (2010), ‘Testosterone Exposure, Dopaminergic Reward, and Sensation-Seeking in Young Men’, *Physiology and Behavior*, **99** (4), March, 451–6; Henrik Cronqvist and Stephan Siegel (2014), ‘The Genetics of Investment Biases’, *Journal of Financial Economics*, **113** (2), August, 215–34.

Institute for Operations Research and the Management Sciences (INFORMS) via the Copyright Clearance Center’s RightsLink service for article: David Cesarini, Magnus Johannesson, Patrik K.E. Magnusson and Björn Wallace (2012), ‘The Behavioral Genetics of Behavioral Anomalies’, *Management Science*, **58** (1), January, 21–34.

Institutional Investor for article: Andrew W. Lo (2004), 'The Adaptive Markets Hypothesis: Market Efficiency from an Evolutionary Perspective', *Journal of Portfolio Management: 30th Anniversary Issue*, **30** (5), 15–29.

MIT Press for article: Andrew W. Lo and Dmitry V. Repin (2002), 'The Psychophysiology of Real-Time Financial Risk Processing', *Journal of Cognitive Neuroscience*, **14** (3), April, 323–39.

National Academy of Sciences, USA for articles: J. Doyne Farmer and Andrew W. Lo (1999), 'Frontiers of Finance: Evolution and Efficient Markets', *Proceedings of the National Academy of Sciences*, **96** (18), August, 9991–2; J.M. Coates and J. Herbert (2008), 'Endogenous Steroids and Financial Risk Taking on a London Trading Floor', *Proceedings of the National Academy of Sciences*, **105** (16), April, 6167–72.

Oxford University Press via the Copyright Clearance Center's RightsLink service for article: J. Doyne Farmer (2002), 'Market Force, Ecology and Evolution', *Industrial and Corporate Change*, **11** (5), November, 895–953.

The Royal Society for article: Terence C. Burnham (2007), 'High-Testosterone Men Reject Low Ultimatum Game Offers', *Proceedings of the Royal Society B: Biological Sciences*, **274** (1623), September, 2327–30.

Springer Science and Business Media B.V. for article: Anna Dreber, David G. Rand, Nils Wernerfelt, Justin R. Garcia, Miguel G. Vilar, J. Koji Lum and Richard Zeckhauser (2011), 'Dopamine and Risk Choices in Different Domains: Findings among Serious Tournament Bridge Players', *Journal of Risk and Uncertainty*, **43** (1), August, 19–38.

Sidney G. Winter, Jr. for his own work: (1964), 'Economic "Natural Selection" and the Theory of the Firm', *Yale Economic Essays*, **4** (1), Spring, 225–72.

Every effort has been made to trace all the copyright holders but if any have been inadvertently overlooked the publishers will be pleased to make the necessary arrangement at the first opportunity.