RESEARCH ARTICLE

AESTIMATIO, THE IEB INTERNATIONAL JOURNAL OF FINANCE, 2018. **17**: 130-147 DOI:10.5605/IEB.17.6

Truth and beauty: Finance in econophysical translation

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RECEIVED: 2 SEPTEMBER 2017 / ACCEPTED: 29 NOVEMBER 2017 / PUBLISHED ONLINE: 23 JANUARY 2017

Abstract

My recent book, *Econophysics and Capital Asset Pricing: Splitting the Atom of Systematic Risk*, splits beta, the capital asset pricing model's basic unit of systematic risk, into subatomic (or "baryonic") components, by analogy to the Standard Model of particle physics. This essay offers preliminary thoughts on the application of physics to other dimensions of finance. A more comprehensive approach would integrate *Econophysics and Capital Asset Pricing's* spatial representation of comovement between individual firms, capital markets, and the real economy, with the informational and temporal dimensions of finance. This essay also places efforts at representing finance through physics in their broader scientific and aesthetic context.

Keywords:

Econophysics, Capital asset pricing, CAPM, Physics, Efficient market hypothesis, Comovement, Procyclicality.

JEL classification:

A12, B26, G12.

Please cite this article as:

Chen, J.M. (2018). Truth and beauty: Finance in econophysical translation, *AESTIMATIO, The IEB International Journal of Finance,* **17**, pp. 130-147.
doi: 10.5605/IEB.17.6

Given the large amount of reference citations, the author has received authorization not to follow the guidelines of the journal.

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AESTIMATIO, THE IEB INTERNATIONAL JOURNAL OF FINANCE, 2018. **17**: 130-147

Verdad y belleza: **finanzas en términos econofísicos**

Chen, James Ming

Resumen

En mi reciente texto, *Econofísica y Valoración de Precios Financieros: Escindiendo el Átomo del Riesgo Sistemático*, se divide la Beta, unidad básica de riesgo sistemático en el modelo de valoración de activos financieros, en componentes subatómicos (bariónicos), por analogía con el modelo estándar de la Física de partículas. Este artículo presenta las ideas preliminares de la aplicación de la Física a otras dimensiones de las Finanzas. Un enfoque más completo abordaría la integración de la Econofísica y la representación espacial, desde la perspectiva de la valoración de activos financieros, del co-movimiento de las empresas individuales, mercados de capitales y de la economía real con las dimensiones informacional y temporal de las finanzas. Este artículo también hace un esfuerzo en la representación de las finanzas a través de la Física en un amplio contexto tanto científico como estético.

Palabras clave:

Econofísica, valoración de activos financieros, CAPM, física, hipótesis del mercado eficiente, co-moviento, prociclicalidad.

Introduction

"The detail of the pattern is movement."[1] Econophysics applies "the techniques of statistical physics and nonlinear dynamics" to complex economic problems.[2] Far from "displac[ing] economics," physics "help[s] economists find deeper understandings" of finance and related fields as "complex systems."[3] If only through "qualitative analogy," physical models "have ... helped to develop new theories to explain [existing] observations in Economics."[4] Without attempting "the complete statistical characterization of the stochastic process of price changes of a financial asset,"[5] this essay invokes physics in introducing "a theoretical model that is able to encompass all the essential features of real financial markets."[6]

This essay proceeds in three parts. Part I, "Baryonic Beta Dynamics: An Econophysical Representation of Finance," summarizes the central argument of my recent book, *Econophysics and Capital Asset Pricing: Splitting the Atom of Systematic Risk*.[7] By analogy to quantum chromodynamics and other aspects of particle physics, *Econophysics and Capital Asset Pricing* seeks to rehabilitate the capital asset pricing model (CAPM) by splitting beta, the model's basic unit of systematic risk, into subatomic (or "baryonic") components.

Part II of this essay, "Finance in Econophysical Spacetime," offers preliminary thoughts on the application of physics to other dimensions of finance. Although *Econophysics and Capital Asset Pricing* addressed the diffusion of financial information and intertemporal asset pricing, it did not incorporate those subjects into a consciously physical framework. A more comprehensive approach would integrate *Econophysics and Capital Asset Pricing*'s spatial representation of comovement between individual firms, capital markets, and the real economy, with the informational and temporal dimensions of finance.

Part III, "Econophysics as the Music of Strings and Spheres," places these efforts at representing finance through physics in their broader scientific and aesthetic context.

[1] T.S. Eliot, *Burnt Norton*, in Four Quartets 13-22, 19 (Harcourt, Brace & Co. 1971; 1st ed. 1943). *See generally* Helen Gardner, The Composition of "Four Quartets" (1978).
[2] Sitabhra Sinha, Arnab Chatterjee, Anirban Chakraborti & Bikas K. Chakrabarti, Econophysics: An Introduction 1 (2011).
[3] Peter Richmond, Jürgen Mimkes & Stefan Hutzler, Econophysics and Physical Economics § 1.5, at 17 (2013).
[4] Anibran Chakraborti, Ioane Muni Toke, Marco Patriarca & Frédéric Abergel, *Econophysics Review: I. Empirical Facts,* 11 Quant. Fin. 991-1012, 992 (2011).
[5] Rosario N. Mantegna & H. Eugene Stanley, An Introduction to Econophysics: Correlations and Complexity in Finance 6-7 (2000).
[6] *Id.* at 7. *See generally* Bertrand M. Roehner, Patterns of Speculation: A Study in Observational Econophysics (2005).
[7] James Ming Chen, Econophysics and Capital Asset Pricing: Splitting the Atom of Systematic Risk (2017).

1. Baryonic beta dynamics: An econophysical representation of finance

The conventional capital asset pricing model quantifies the risk-based premium for any asset relative to a risk-free benchmark:

$$r_a = r_f + \beta_a (r_m - r_f) \tag{1}$$

where r_a, r_m, and r_f represent returns on the asset, the broader market, and a risk-free investment, and β_a represents the asset's beta vis-à-vis the market portfolio.[8]

Throughout the 1970s and 1980s, financial scholarship identified significant departures from beta-driven asset pricing models. Small firms[9] and firms with a high book-to-market ratio[10] offered returns exceeding those predicted by beta. In 1992 Eugene Fama and Kenneth French declared that "the relation between β and average return ... is weak, perhaps nonexistent."[11] Mark Carhart later identified momentum in short-run stock prices[12] as a distinct factor within the comprehensive Fama-French-Carhart four-factor model.[13]

The CAPM nevertheless remains the dominant paradigm in financial risk management.[14] "It takes a better theory to kill an existing theory," and the financial profession has "yet to see [a] better theory."[15] The CAPM endures "because (a) the empirical support for other asset-pricing models is no better, (b) the theory behind the CAPM has an intuitive appeal that other models lack, and (c) the economic importance of the empirical evidence against the CAPM ... is ambiguous."[16] The "concept of beta risk" remains "the single most important contribution of academic researchers to the financial community."[17]

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8 *See* Robert A. Korajczyk, *Introduction*, *in* Asset Pricing and Portfolio Performance: Models, Strategy and Performance Metrics, at viii, xv (Robert A. Korajczyk ed., 1999).

9 *See, e.g.*, Rolf W. Banz, *The Relationship Between Return and Market Valuation of Common Stocks*, 9 J. Fin. Econ. 3-18 (1981).

10 *See, e.g.*, S. Basu, *Investment Performance of Common Stocks in Relation to Their Price-Earning Ratios: A Test of the Efficient Market Hypothesis*, 32 J. Fin. 663-682 (1977); Marc R. Reinganum, *Misspecification of Capital Asset Pricing: Empirical Anomalies Based on Earnings'Yield and Market Values*, 9 J. Fin. Econ. 19-46 (1981) (identifying both the size and the value anomalies).

11 Eugene F. Fama & Kenneth R. French, *The Cross-Section of Expected Stock Returns*, 47 J. Fin. 427-465, 464 (1992); *see also*, e.g., Kent D. Daniel & Sheridan Titman, *Evidence on the Characteristics of Cross-Sectional Variation in Stock Returns*, 52 J. Fin. 1-33 (1997); Eugene F. Fama & Kenneth R. French, *Size and Book-to-Market Factors in Earnings and Returns*, 50 J. Fin. 131-155 (1995); John M. Griffin, *Are the Fama and French Factors Global or Country Specific?*, 15 Rev. Fin. Stud. 783-803 (2002).

12 See Mark M. Carhart, *On Persistence in Mutual Fund Performance*, 52 J. Fin. 57-82 (1997); Mark Grinblatt, Sheridan Titman & Russ Wermers, *Momentum Investment Strategies, Portfolio Performance, and Herding: A Study of Mutual Fund Behavior*, 85 Am. Econ. Rev. 1088-1105 (1995); Narasimhan Jegadeesh & Sheridan Titman, *Returns to Buying Winners and Selling Losers: Implications for Market Efficiency*, 48 J. Fin. 65-91 (1993).

13 *See, e.g.*, Louis K.C. Chan, Narasimhan Jegadeesh & Josef Lakonishok, *Momentum Strategies*, 51 J. Fin. 1681-1713 (1996); Eugene F. Fama & Kenneth R. French, *Dissecting Anomalies*, 63 J. Fin. 1653-1678 (2008); Eugene F. Fama & Kenneth R. French, *Multifactor Explanation of Asset Pricing Anomalies*, 51 J. Fin. 55-85 (1996); Eugene F. Fama & Kenneth R. French, *Size, Value, and Momentum in International Stock Returns*, 105 J. Fin. Econ. 457-472 (2012); Subhrendu Rath & Robert B. Durand, *Decomposing the Size, Value and Momentum Premia of the Fama–French–Carhart Four-Factor Model*, 132 Econ. Letters 139–141 (2015); *see also* Doron Avramov & Tarun Chordia, *Pricing Stock Returns*, 82 J. Fin. Econ. 387-415 (2006) (favoring size, value, and momentum as primary drivers of excess return, over alternative factors such as dividend yield, the term spread, the default spread, and the yield on Treasury bills); *cf.* Jimmy Liew & Maria Vassalou, *Can Book-to-Market, Size and Momentum Be Risk Factors That Predict Economic Growth?*, 57 J. Fin. Econ. 221-245 (2000).

14 *See* Haim Levy, The Capital Asset Pricing Model in the 21st Century: Analytical, Empirical, and Behavioral Perspectives 4-5 (2012).

15 Tim Koller, Marc Goedhart & David Wessels, Valuaiton: Measuring and Managing the Value of Companies 261 (5th ed. 2010).

16 Ravi Jagannathan & Zhenyu Wang, *The Conditional CAPM and the Cross-Section of Expected Returns*, 51 J. Fin. 3-53, 4 (1996) (footnote omitted).

17 Louis K.C. Chan & Josef Lakonishok, *Are Reports of Beta's Death Premature?*, 19:4 J. Portfolio Mgmt. 51-62, 51 (Summer 1993); *see also* Jagannathan & Wang, *supra* note 16, at 4 ("The CAPM is widely viewed as one of the two or three major contributions of academic research to financial

Econophysics and Capital Asset Pricing sought to rehabilitate beta through an extended analogy to the "particle zoo" of contemporary physics.[18] Even models purporting to dismiss beta as "insignificant" retain beta as "an important explanatory variable," despite deprecating its traditional status as "the *main* explanatory variable."[19]

"In physics and in other natural sciences, it is often a successful strategy to analyze the behavior of a system by studying the smallest components of that system."[20] If examined "on steadily decreasing time and length scales," that system may exhibit complex properties and behaviors that cannot be explained by its smallest components, but rather by their interactions.[21]

The Standard Model of particle physics provides a fruitful analogy for the subcomponents of financial risk.[22] Quantum chromodynamics focuses on six quarks in three matched pairs of quark families:[23]

Table 1. Generations of quarks in the standard model of particle physics

Quarks	First generation	Second generation	Third generation
Up-type quarks with a $+\frac{2}{3}e$ charge	Up	Charm	Top (truth)
Down-type quarks with a $-\frac{1}{3}e$ charge	Down	Strange	Bottom (beauty)

Baryons are subatomic particles consisting of three quarks. The most familiar baryons, protons and neutrons, are comprised of different combinations of up and down quarks:[24]

$$\begin{array}{ll} proton & 2u + 1d = +1e \\ neutron & 1u + 2d = 0e \end{array}$$

Since the up quark has a charge of $+\frac{2}{3}$ and the down quark has a charge of $-\frac{1}{3}$, these combinations account for proton's +1 and the neutron's neutral charge.[25]

managers during the postwar era.").

18 The "particle zoo" is the playful name originally assigned to the particles now classified within the Standard Model. *See* Cindy Schwartz, A Tour of the Subatomic Zoo: A Guide to Particle Physics (1997).

19 Levy, CAPM in the 21st Century, *supra* note 14, at 4 (emphasis in original); *cf.* Robert C. Merton, *On Estimating the Expected Return on the Market: An Exploratory Investigation*, 8 J. Fin. Econ. 323-361, 324 (1980) ("[I]n all … models, the market risk of a security will affect its equilibrium expected return, and indeed, for most common stocks, market risk will be the dominant factor.").

20 Tobias Preis & H. Eugene Stanley, *Switching Phenomena in a System with No Switches*, 138 J. Stat. Phys. 431-446, 432 (2010).

21 *Id.*

22 *See generally* Robert Mann, An Introduction to Particle Physics and the Standard Model (2010); Robert Oerter, The Theory of Almost Everything: The Standard Model, the Unsung Triumph of Modern Physics (2006).

23 *See* Murray Gell-Mann, The Quark and the Jaguar: Adventures in the Simple and the Complex 191 (1994); Murray Gell-Mann, *A Schematic Model of Baryons and Mesons*, 8 Phys. Letters 214-215 (1964); George Zweig, *An SU(3) Model for Strong Interaction Symmetry and Its Breaking*, *in* 1 Developments in the Quark Theory of Hadrons 22-101 (Don Bernett Lichtenberg & S.P. Rosen eds., 1980). *See generally* Particle Physics: One Hundred Years of Discoveries (V.V. Ezhela *et al.* eds., 1996); M. Aguilar-Benitez *et al.* (Particle Data Group), *Review of Particle Physics*, 170 Phys. Letters B 2-344, 11-35 (1986) (summarizing particle names and properties).

24 *See* Michael Munowitz, Knowing The Nature of Physical Law 35 (2005).

25 *See* Gell-Mann, *supra* note 23, at 181.

Color SU(3) is the gauge symmetry that governs color change and interaction among quarks under quantum chromodynamics.[26] Absent violations of Color SU(3),[27] baryons consist of exactly three quarks satisfying the chromodynamic requirement of one red, one blue, and one green quark. Analgous to the Standard Model's classification of quarks within three generations of matter and to quantum chromodynamics' description of three-way interaction among red, blue, and green colors of quarks, *Econophysics and Capital Asset Pricing* divided beta into three distinct "generations":

1. Up and down on either side of mean returns[28]
2. Relative volatility ( ) and correlation ( ) between asset-specific and market-wide returns[29]
3. "Bad" cash-flow beta versus "good" discount-rate beta[30]

These generations of "baryonic" beta correspond to the Standard Model's generations of quarks:[31]

Table 2. Three generations of quarks alongside three generations of "baryonic" beta

Generation	Quark	Beta	Mathematical relationship to conventional beta
First	Up	Upside	$\beta_+ = \frac{\text{cov}_+(a,m)}{\text{cov}_+(m,m)}$; $\beta_- = \frac{\text{cov}_-(a,m)}{\text{cov}_-(m,m)}$
	Down	Downside	$\beta = \frac{\text{cov}_+(a,m) + \text{cov}_-(a,m)}{\text{cov}_+(m,m) + \text{cov}_-(m,m)} = \frac{\text{cov}(a,m)}{\text{cov}(m,m)}$
Second	Charm	Correlation tightening	$\beta = \frac{\sigma_a}{\sigma_m}\rho(a,m) = \frac{\sigma_a}{\sigma_m} \cdot \frac{\text{cov}(a,m)}{\sigma_a \sigma_m}$
	Strange	Relative volatility	
Third	Top (truth)	Discount-rate (good)	$\beta = \beta_{CF} + \beta_{DR}$
	Bottom (beauty)	Cash-flow (bad)	

The Standard Model isolates six distinct "flavors" of up- and down-type quarks within three generations of matter. Quarks interact according to the three-way Color SU(3)

[26] See, e.g., Vincent Icke, The Force of Symmetry 216 (1995); Richard C. Brower, Samir D. Mathur & Chung-I Tan, *Glueball Spectrum for QCD from AdS Supergravity Duality*, 587 Nuclear Phys. B 249–276 (2000); Joseph Polchinski & Matthew J. Strassler, *Hard Scattering and Gauge/String Duality*, 88 Phys. Rev. Letters 31601 (2002).

[27] *Compare* C. Amsler *et al.* (Particle Data Group), *Review of Particle Physics*, 667 Phys. Letters B 1-1340, 1019-1022 (2008) (documenting failed attempts to detect particles consisting of five quarks) *with* R Aaij *et al.* (LHCb Collaboration), *Observation of J/ψp Resonances Consistent with Pentaquark States in $\Lambda^0_b \rightarrow J/\psi K^- p$ Decays*, 115 Phys. Rev. Letters 072001 (Aug. 12, 2015) (finding evidence of pentaquark states with a confidence of 15σ).

[28] See, e.g., Andrew Ang, Joseph Chen & Yuhang Xing, *Downside Risk*, 19 Rev. Fin. Stud. 1191-1239, 1199-1200 (2006); Javier Estrada, *Mean-Semivariance Behavior: Downside Risk and Capital Asset Pricing*, 16 Int'l Rev. Econ. & Fin. 169-185, 171, 174 (2007); Javier Estrada, *Systematic Risk in Emerging Markets: The D-CAPM*, 3 Emerging Mkts. Rev. 365-377, 368 (2002); Hsin-Jung Tsai, Ming-Chi Chen & Chih-Yuang Yang, *A Time-Varying Perspective on the CAPM and Downside Betas*, 29 Int'l Rev. Econ.. & Fin. 440-454, 441 (2014).

[29] See, e.g., Martin L. Leibowitz, Anthony Bova & P. Brett Hammond, The Endowment Model of Investing: Return, Risk, and Diversification 14 (2010); Michael B. Miller, Mathematics and Statistics for Financial Risk Management 198, 213, 292 (2d ed. 2014); Shannon P. Pratt & Roger J. Grabowski, Cost of Capital: Applications and Examples 305-206 (4th ed. 2010).

[30] See John Y. Campbell & Tuomo Vuolteenaho, *Bad Beta, Good Beta*, 94 Am. Econ. Rev. 1249-1275 (2004).

[31] *See generally* Haim Harari & Stanford Linear Accelerator Center, *Three Generations of Quarks and Leptons*, *in* Proceedings of the XII Rencontre de Moriond 170-184 (1997).

gauge symmetry of quantum chromodynamics. In like fashion, *Econophysics and Capital Asset Pricing* bifurcated beta three ways: upside and downside beta on either side of mean returns, the relative volatility and correlation tightening components of beta, and the intertemporally dynamic distinction between "bad" cash-flow beta and "good" discount-rate beta. Systematic risk consists of coherent "subatomic" components that interact in quantifiable and perhaps even predictable ways.

2. Finance in econophysical spacetime

2.1. Beyond baryonic beta dynamics

The Standard Model, as a manifestation of the science of the very small, might not explain phenomena at all scales. In particular, the Standard Model fails to account for gravity, a critical component of general relativity. "It is remarkable that two of the greatest successes of 20th century physics, general relativity and the standard model, appear to be fundamentally incompatible."[32]

More precisely, physics needs to revitalize the "usual marriage of general relativity and quantum mechanics" beyond coherence "at ordinary energies" and to ensure these theories' compatibility under "more extreme conditions."[33] "Rather than a fundamental incompatibility of quantum mechanics and gravity, we are in the more familiar situation of needing a more complete theory beyond the range of their combined applicability."[34] The detection of gravitational waves — an accomplishment warranting the 2017 Nobel Prize in physics — brings physics one step closer to unity.[35]

As the application of physics to economics, econophysics confronts comparable problems of compatibility and scale. Economists have explained phenomena from macroeconomic fluctuations to financial returns "by constructing a *model* in the most literal sense: a fully articulated artificial economy which behaves through time so as to imitate closely the time series behavior of actual economies."[36] This essay seeks to identify limitations on "baryonic beta dynamics" and to sketch the outlines of a more comprehensive, accurate econophysical representation of mathematical finance.

[32] A.O. Sushkov, W.J. Kim, D.A.R. Dalvit & S.K. Lamoreaux, *New Experimental Limits on Non-Newtonian Forces in the Micrometer Range*, 107 Phys. Rev. Letters 171101 (2011).
[33] John F. Donoghue, *The Effective Field Theory Treatment of Quantum Gravity*, 1483 AIP Conference Proceedings 73 (2012).
[34] *Id.*
[35] *See* B.P. Abbott *et al.*, (LIGO Scientific Collaboration & Virgo Collaboration), *Observation of Gravitational Waves from a Binary Black Hole Merger*, 116 Phys. Rev. Letters 061102 (2016); B.P. Abbott *et al.* (LIGO Scientific Collaboration & Virgo Collaboration), *GW170814: A Three-Detector Observation of Gravitational Waves from a Binary Black Hole Coalescence at Redshift 0.2*, 118 Phys. Rev. Letters 221101 (2017); B.P. Abbott *et al.* (LIGO Scientific Collaboration & Virgo Collaboration), *GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral*, 119 Phys. Rev. Letters (forthcoming 2017). On the history of the search for gravitational waves, see Harry Collins, Gravity's Shadow: The Search for Gravitational Waves (2004).
[36] Robert E. Lucas, Jr., *Understanding Business Cycles*, *in* Stabilization of the Domestic and International Economy 7-29, 11 (Karl Brunner & Allan H. Meltzer eds., 1977) (Carnegie-Rochester Conference Series on Public Policy, volume 5); *accord* Stanley E. Zin, *Are Behavioral Asset-Pricing Models Structural?*, 49 J. Monetary Econ. 215-228 (2002).

Three mysteries elude the provisional, perhaps primitive model sketched in *Econophysics and Capital Asset Pricing*. First, a more comprehensive model should account for departures from the perfectly efficient diffusion of information. Second, "baryonic beta" as a spatial model of finance may mischaracterize correlation within capital markets and the relationship between cash-flow and discount-rate effects as separate phenomena. Instead, these forces are arguably special cases of a more general form of economic comovement. Finally, econophysics demands an explicit account of time, in its serial, cyclical, and stochastic incarnations.

2.2. Information and its diffusion

Imperfections in the diffusion of information may account for departures from rationality and symmetry in the temporal and spatial dimensions of finance. Prices as tools for discovering and disseminating economic knowledge[37] inform a collective "wisdom of prices."[38] Trading within capital markets, like all other forms of business activity, conveys information.[39] This aspect of finance is often salient by its absence: A slowdown reduces the rate at which trading and other business activity transmit economic information.[40] A more complete econophysical model should address all plausible accounts of informational diffusion, from the efficient market hypothesis[41] to "rational learning."[42]

The "strong" form of the efficient market hypothesis posits that the prices of securities reflect all information, public and private. "[I]n an efficient market," the prevalence of this knowledge prevents "most investors [from] achiev[ing] consistently superior rates of return."[43] Even less stringent forms of efficiency bode ill for excess returns.[44] The weak version of the hypothesis posits that markets assimilate all public

[37] *See, e.g.*, Sanford J. Grossman, *Dynamic Asset Allocation and the Informational Efficiency of Markets*, 50 J. Fin. 773-787 (1995); Sanford J. Grossman, *On the Efficiency of Competitive Stock Markets Where Traders Have Diverse Information*, 31 J. Fin. 573-585 (1977); Sanford J. Grossman & Robert J. Shiller, *The Determinants of the Variability of Stock Market Prices*, 71 Am. Econ. Rev. 222-227 (1981); Sanford J. Grossman & Joseph Stiglitz, *On the Impossibility of Informationally Efficient Markets*, 70 Am. Econ. Rev. 393-408 (1980); Leonid Hurwicz, *Optimality and Informational Efficiency in Resource Allocation Processes*, *in* Mathematical Models in the Social Sciences, 1959: Proceedings of the First Stanford Symposium 27-47 (Kenneth J. Arrow, Samuel Karlin & Patrick Suppes eds., 1960); Thomas Marschak, *Price Versus Direct Revelation: Informational Judgments for Finite Mechanisms*, *in* Information, Incentives, and Economic Mechanisms: Essays in Honor of Leonid Hurwicz 132-180 (Theodore Groves, Roy Radner & Stanley Reiter eds., 1980); Thomas Marschak & Stefan Reichelstein, *Network Mechanisms, Informational Efficiency, and Hierarchies*, 79 J. Econ. Theory 106-141 (1998).

[38] *See* F.A. Hayek, *Economics and Knowledge*, 4 Economica 33-54 (1937); F.A. Hayek, *The Use of Knowledge in Society*, 35 Am. Econ. Rev. 519-530 (1945); Richard Bronk, *Hayek on the Wisdom of Prices: A Reassessment*, 6 Erasmus J. Phil. & Econ. 82-107 (2013).

[39] *See, e.g.*, Michael J. Brennan & Patricia J. Hughes, *Stock Prices and the Supply of Information*, 46 J. Fin. 1665–1691 (1991); Joel Hasbrouck, *Measuring the Information Content of Stock Trades*, 46 J. Fin. 179-207 (1991); Joel Hasbrouck, *The Summary Informativeness of Stock Trades: An Econometric Analysis*, 4 Rev. Fin. Stud. 571-595 (1991).

[40] *See* Nicholas Bloom, *Fluctuations in Uncertainty*, 28 J. Econ. Persp. 153-176, 162 (2014). *See generally* Pablo Fajgelbaum, Eduardo Schaal & Mathieu Taschereau-Dumouchel, Uncertainty Traps (2014); Stijn Van Nieuwerburgh & Laura Veldkamp, *Learning Asymmetries in Real Business Cycles*, 53 J. Monetary Econ. 753-772 (2006).

[41] *See generally, e.g.*, Paul H. Cootner, The Random Character of Stock Market Prices (1964); Eugene F. Fama, *Efficient Capital Markets: A Review of Theory and Empirical Work*, 25 J. Fin. 383-417 (1970); Eugene F. Fama, *Efficient Capital Markets II*, 46 J. Fin. 1575-1617 (1991); Eugene F. Fama, *The Behavior of Stock Market Prices*, 38 J. Bus. 34-105 (1965); Lawrence H. Summers, *Does the Stock Market Rationally Reflect Fundamental Values?*, 41 J. Fin. 591-601 (1986); Fama & French, *The Cross-Section of Expected Stock Returns*, *supra* note 11, at 427-429.

[42] *See generally*, *e.g.*, Lawrence E. Blume & David Easley, *Learning to Be Rational*, 26 J. Econ. Theory 340-351 (1982); Lawrence E. Blume & David Easley, *Rational Expectations and Rational Learning*, *in* Organizations with Incomplete Information: Essays in Economic Analysis: A Tribute to Roy Radner 61-109 (Mukul Majumdar ed., 1998); Margaret Bray & David M. Kreps, *Rational Learning and Rational Expectations*, *in* Arrow and the Ascent of Modern Economic Theory 597-625 (George R. Feiwel ed., 1987); Francis, Lafond, Olsson & Schipper, *supra* note 89.

[43] Richard A. Brealey, Stewart C. Myers & Franklin Allen, Principles of Corporate Finance 330 (10th ed. 2011); *accord* Amgen Inc. v. Connecticut Retirement Plans & Trust Funds, 133 S. Ct. 1184, 1192 (2013).

[44] *See generally* Frederick C. Dunbar & Dana Heller, *Fraud on the Market Meets Behavioral Finance,* 31 Del. J. Corp. L. 455-531, 463-464 (2006).

information.[45] Disproving the presence of serial dependencies in security prices would confirm at least the weak form of the efficient market hypothesis.[46]

The "fraud on the market" theory of federal securities law "relie[s] upon the 'semi-strong' version" of the efficient market hypothesis.[47] Semi-strong efficiency assumes that the diffusion of publicly available information into security prices takes place immediately.[48] If "the market price of shares traded on well-developed markets reflects all publicly available information and, hence, any material misrepresentations," then the typical "investor who buys or sells stock at the price set by the market does so in reliance on the integrity of that price."[49] Despite scholarly criticism that this presumption naively accepts market efficiency,[50] the Supreme Court of the United States continues to assume "that most investors ... will rely on the security's market price."[51]

Theories of information diffusion should also address anomalies involving "short-term stock price continuation."[52] These anomalies include "post-analyst forecast revision price drift" in the wake of new information on corporate earnings.[53] Short-term price continuation also includes momentum, especially in the sense of positive serial correlation at three- to twelve-month horizons.[54]

Perhaps the striking form of short-term stock price continuation is post-earnings announcement drift (PEAD). In principle, "fundamental news" about individual firms' cash flow should "command[] a much higher price of risk than other market risk factors," including discount rates.[55] A rational, efficient market should quickly and accurately incorporate such news into stock prices.[56] In actual markets,

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[45] *See* Paul A. Samuelson, *Proof That Properly Anticipated Prices Fluctuate Randomly*, 6 Indus. Mgmt. Rev. 41-49 (1965)

[46] *See* Eugene F. Fama, *The Behavior of Stock-Market Prices*, 38 J. Bus. 34-105, 34 (1965); Eugene F. Fama, *Random Walks in Stock Market Prices*, 21:5 Fin. Analysts J. 55-59, 56-57 (Sept./Oct. 1965).

[47] Halliburton Co. v. Erica P. John Fund Inc., 134 S. Ct. 2398, 2420 (2014) (Thomas, J., concurring in the judgment) (citing, *inter alia*, Lynn A. Stout, *The Mechanisms of Market Inefficiency: An Introduction to the New Finance*, 28 J. Corp. L. 635-669, 640 & n.24 (2003)).

[48] Fama, *Efficient Capital Markets: A Review of Theory and Empirical Work*, *supra* note 41, at 388.

[49] Basic, Inc. v. Levinson, 485 U.S. 224, 246-247 (1988). Violations of section 10(b) of the Securities and Exchange Act of 1934, 15 U.S.C. § 78j(b), and Securities and Exchange Commission Rule 10b-5, 17 C.F.R. § 240.10b-5, give rise to an implied private cause of action. *See, e.g.*, Blue Chip Stamps v. Manor Drug Stores, 421 U.S. 723, 730 (1975); Amgen Inc. v. Connecticut Retirement Plans & Trust Funds, 133 S. Ct. 1184, 1192 (2013).

[50] *See, e.g.*, Edward S. Adams & David E. Runkle, *Solving a Profound Flaw in Fraud-on-the-Market Theory: Utilizing a Derivative of Arbitrage Pricing Theory to Measure Rule 10b-5 Damages*, 145 U. Pa. L. Rev. 1097-1145, 1110-1113 (1997); James D. Cox, *Understanding Causation in Private Securities Lawsuits: Building on* Amgen, 66 Vand. L. Rev. 1719-1753, 1732 (2013) (arguing that "friction in accessing public information" and nontrivial "processing costs" prevent markets from incorporating "all public information … in a security's price with the same alacrity, or perhaps with any quickness at all"); Donald C. Langevoort, Basic *at Twenty: Rethinking Fraud on the Market*, 2009 Wis. L. Rev. 151-198, 175 ("Doubts about the strength and pervasiveness of market efficiency are much greater today than they were in the mid-1980s"); Baruch Lev & Meiring de Villiers, *Stock Price Crashes and 10b-5 Damages: A Legal, Economic and Policy Analysis*, 47 Stan. L. Rev. 7-37, 20-21 (1994).

[51] *Amgen*, 133 S. Ct. at 1192; *accord* Halliburton Co. v. Erica P. John Fund, Inc., 134 S. Ct. 2398, 2411 (2014); *see also* Schleicher v. Wendt, 618 F.3d 679, 685 (7th Cir. 2010) (recognizing the fact that "the … price [of a stock] may be inaccurate does not detract from the fact that false statements affect it, and cause loss").

[52] X. Frank Zhang, *Information Uncertainty and Stock Returns,* 61 J. Fin. 105-137, 105 (2006).

[53] *Id.* at 106. *See generally*, *e.g.,* Jeffrey S. Abarbanell & Victor L. Bernard, *Tests of Analysts' Overreaction/Underreaction to Earnings Information as an Explanation for Anomalous Stock Price Behavior*, 47 J. Fin. 1181-1207 (1992); Zhi Da & Mitch Craig Warachka, *Cashflow Risk, Systematic Earnings Revisions, and the Cross-Section of Stock Returns*, 94 J. Fin. Econ. 48-468 (2009).

[54] *See* Zhang, *supra* note 52, at 105. *See generally*, e.g., Louis K.C. Chan, Narasimhan Jegadeesh & Josef Lakonishok, *Momentum Strategies*, 51 J. Fin. 1681-1713 (1996); Kent D. Daniel, David A. Hirshleifer & Avanidhar Subrahmanyam, *Investor Psychology and Security Market Under- and Overreaction*, 53 J. Fin. 1839-1886 (1998); Kent D. Daniel, David A. Hirshleifer & Avanidhar Subrahmanyam, *Overconfidence, Arbitrage, and Equilibrium Asset Pricing*, 56 J. Fin. 921-965 (2001); Guohua Jiang, Charles M.C. Lee & Yi Zhang, *Information Uncertainty and Expected Returns*, 10 Rev. Accounting Stud. 185-221 (2005).

[55] Paul Savor & Mungo Wilson, *Earnings Announcements and Systematic Risk,* 71 J. Fin. 83-138, 128 (2016).

[56] *See generally* John Y. Campbell, *Intertemporal Asset Pricing without Consumption Data,* 83 Am. Econ. Rev. 487-512 (1993).

however, abnormal returns from positive and negative earnings surprises drift, in the direction of the earnings surprise, for days or even weeks. After its initial recognition in 1968,[57] PEAD has become one of the most exhaustively examined anomalies in asset pricing.[58]

2.3. Comovement in financial space

Comovement (whether between assets and benchmarks or between capital markets and the broader economy) is perhaps the greatest force in financial space. A more comprehensive spatial understanding of finance would treat comovement among agents, asset classes, and macroeconomic forces as a general, overriding principle. Indeed, the appropriate measure of comovement should be regarded as the decisive force in financial space. As we move outward from individual agents to capital markets and eventually to the real economy, we see with increasingly clarity that relative volatility defines idiosyncratic risk, while correlation controls much of the contribution of systematic risk to asset pricing. A more complete econophysical model should therefore subsume relationships between relative volatility and correlation and between cash-flow and discount-rate beta as special cases of comovement.

Econophysics and Capital Asset Pricing relied on single-sided measures of risk to distinguish between beta on the upside and downside of mean returns.[59] This distinction has a profound effect on all types of comovement. Downside risk dominates upside risk in its impact on asset pricing. So too does the more economically complex component in all forms of comovement — correlation relative to volatility, discount-rate effects relative to cash flow — dominate its simpler counterpart.

More than any other variable, downside correlation explains abnormal returns on value and small-cap stocks in the Fama-French three-factor model.[60] Downside correlation accounts for much of the low-volatility anomaly.[61] As an artifact of strategic management, Bowman's paradox explains the idiosyncratic, firm-specific

[57] *See* Ray J. Ball & Philip Brown, *An Empirical Evaluation of Accounting Income*, 6 J. Accounting Research 159-178 (1968); William H. Beaver, *The Information Content of Annual Earnings Announcements*, 6 J. Accounting Research 67-92 (1968).

[58] *See, e.g.*, Victor L. Bernard & Jacob K. Thomas, *Post-Earnings Announcement Drift: Delayed Price Response or Risk Premium?*, 27 J. Accounting Research 1-36 (1989); Victor L. Bernard & Jacob K. Thomas, *Evidence That Stock Prices Do Not Fully Reflect the Implications of Current Earnings for Future Earnings*, 13 J. Accounting & Econ. 305-340 (1990); Charles P. Jones & Robert H. Litzenberger, *Quarterly Earnings Reports and Intermediate Stock Price Trends*, 25 J. Fin. 143-148 (1968); O. Maurice Joy, Robert H. Lizenberger & Richard W. McEnally, *The Adjustment of Stock Prices to Announcements of Unanticipated Changes in Quarterly Earnings*, 15 J. Accounting Research 207-225 (1977); Richard J. Rendleman Jr., Charles P. Jones & Henry A. Latané, *Empirical Anomalies Based on Unexpected Earnings and the Importance of Risk Adjustments*, 10 J. Fin. Econ. 269-287 (1982). *See generally* Victor L. Bernard, *Stock Price Reactions to Earnings Announcements: A Summary of Recent Anomalous Evidence and Possible Explanations*, *in* Advances in Behavioral Finance 303-340 (Richard H. Thaler ed., 1992).

[59] *See Chen,* Econophysics and Capital Asset Pricing, supra note 7, §§ 2.1-2.4, at 31-45.

[60] *See, e.g.,* David Morelli, *Beta, Size, Book-to-Market Equity and Returns: A Study Based on UK Data,* 17 J. Multinat'l Fin. Mgmt. 257-272, 263 (2007); Peter Xu & Rich Pettit, *No-Arbitrage Conditions and Expected Returns When Assets have Different β's in Up and Down Markets*, 15 J. Asset Mgmt. 62-71, 69 (2014) (small-caps); Zhang, *supra* note 95, at 67 (value).

[61] *See, e.g.*, Martin L. Leibowitz, Anthony Bova & P. Brett Hammond, The Endowment Model of Investing: Return, Risk, and Diversification 235, 265 (2010); Ang, Chen & Xing, *Downside Risk*, supra note 28, at 1228; Malcolm Baker, Brendan Bradley & Jeffrey Wurgler, *Benchmarks as Limits to Arbitrage: Understanding the Low-Volatility Anomaly*, 67:1 Fin. Analysts J. 40-54, 43 (Jan./Feb. 2011).

factors that contribute to high alpha on low-beta stocks.[62] Temporal convergence between financial capital, human capital, and the broader economy explains the equity premium puzzle.[63] Careful parsing of cash-flow and discount-rate effects opens the door to understanding capital market interactions with the macroeconomy.[64]

Macroeconomic ignorance is even more dire. Comovement in "asset prices suggest[s] the presence of underlying exogenous influences," even if it does not "determine[] which economic variables, if any, are responsible."[65] But both halves of the equity premium puzzle indicate "large gaps in our understanding of the macroeconomy."[66] The risk-free rate puzzle "indicates that we do not know why people save even when returns our low."[67] Conversely, "[t]he equity premium puzzle demonstrates that we do not know why individuals are so averse to the highly procyclical risk" associated with stocks.[68]

Rising ambiguity in signals affecting idiosyncratic, systematic, and macroeconomic risk ultimately unites asset pricing with human capital in a comprehensive solution to the equity risk premium. The ratio of consumption to aggregate wealth, including human capital, elevates asset pricing into a broader expression of life-cycle economics.[69]

"Most of the puzzles and anomalies" in finance "amount to discount-rate variation"[70] that financial professionals "almost completely ignore in practice."[71] Much of the literature of finance "explain[s] an asset's expected return by its covariance with other assets' returns, rather than covariance with macroeconomic risks."[72] The capital asset pricing model, which stresses beta and returns on the market-wide portfolio, epitomizes this emphasis. Though conventional models of covariance among assets "may successfully *describe* variation in expected returns, they will never *explain* it."[73]

[62] *See* Edward H. Bowman, *A Risk/Return Paradox for Strategic Management*, 21 Sloan Mgmt. Rev. 17-33 (1980); Edward H. Bowman, *Risk Seeking by Troubled Firms*, 23 Sloan Mgmt. Rev. 33-42 (1982); Edward H. Bowman, *Content Analysis of Annual Reports for Corporate Strategy and Risk*, 14 Interfaces 61-71 (1984). *See generally* Manuel Núñez Nickel & Manuel Cano Rodriguez, *A Review of Research on the Negative Accounting Relationship Between Risk and Return: Bowman's Paradox*, 30 Omega 1-18, 1 (2002).

[63] *See, e.g.*, John Y. Campbell & John H. Cochrane, *By Force of Habit: A Consumption Based Explanation of Aggregate Stock Market Behavior*, 107 J. Pol. Econ. 205-251, 240, 248 (1999); Rajnish Mehra, *The Equity Premium: Why Is It a Puzzle?*, 59:1 Fin. Analysts J. 54-69, 61 (Jan./Feb. 2003); Rajnish Mehra & Edward C. Prescott, *The Equity Premium Puzzle in Retrospect*, *in* Handbook of the Economics of Finance 889-938, 917 (George M. Constantinides, Milton Harris & René M. Stulz eds., 2003).

[64] *See, e.g.*, Campbell & Vuolteenaho, *supra* note 30; Mark J. Flannery & Aris A. Protopapadakis, *Macroeconomic Factors* Do *Influence Aggregate Stock Returns*, 15 Rev. Fin. Stud. 751-782 (2002); Grant McQueen & V. Vance Roley, *Stock Prices, News, and Business Conditions*, 6 Rev. Fin. Stud. 683-707, 693-697 (1993).

[65] Nai-Fu Chen, Richard Roll & Stephen A. Ross, *Economic Forces and the Stock Market*, 59 J. Bus. 383-403, 384 (1986).

[66] Narayana R. Kocherlakota, *The Equity Premium: It's Still a Puzzle*, 34 J. Econ. Lit. 42-71, 44 (1996).

[67] *Id.*

[68] *Id.*

[69] *See generally* Angus Deaton, *Francisco Modigliani and the Life-Cycle Theory of Consumption*, 58 Banco Nazionale del Lavoro Q. Rev. 91-107 (2005); Franco Modigliani, *The Life Cycle Hypothesis of Saving, the Demand for Wealth and the Supply of Capital*, 33 Social Research 160-217 (1966).

[70] John H. Cochrane, *Discount Rates*, 66 J. Fin. 1047-1108, 1091 (2011).

[71] *Id.* at 1082.

[72] John H. Cochrane, *A Cross-Sectional Test of an Investment-Based Asset Pricing Model*, 104 J. Pol. Econ. 572, 573 (1996).

[73] *Id.* (emphases in original).

2.4. Economic fluctuations and procyclicality

The significance of comovement, as we have seen, often hinges on economic conditions — namely, whether the relevant market or the broader economy is in recession, on the upswing, or in transition between one extreme or the other. Many studies tend to treat the basic condition of the economy as a state variable.[74] Econophysics promises a more quantitatively sophisticated treatment of this critical factor.

Whether capital markets and/or the broader economy are on the upside or downside warrants subtler treatment than classification according to a binary state variable. Historically, economics has spoken of "cycles" of boom and bust.[75] Contemporary economic literature prefers to speak of economic "fluctuations,"[76] consigning the notion of "cycles" to little more than shorthand.[77] Without necessarily endorsing the imperfectly supported and possibly misleading hypothesis that economic fluctuations come in waves and can be expressed as periodic functions or Fourier series,[78] we may conjecture that one or more sinusoid functions of unknown (or at best stochastic) frequency, phase, and amplitude represent fluctuations in the real economy or any of its constituent parts.

On this understanding, a state variable indicating the upside or downside condition of the economy is merely the sign function of such sinusoid functions, the binary expression of a more elaborate (and granular) function taking essentially periodic form. Even the term "procyclicality," often used to describe temporal alignment between bank assets and the broader economy,[79] implies some sort of periodicity. Downside correlation and discount-rate effects are different manifestations of negative comovement involving a single asset or market and a broader swath of the economy.

To speak of downside correlation or discount-rate effects therefore indicates that the broader phenomenon (correlation or discount-rate changes) dominate the more localized phenomenon (volatility or cash-flow surprises). Consistent with loss aversion

[74] *See* William J. Palm III, System Dynamics 225 (2d ed. 2010); *cf.* Cochrane, *Discount Rates*, *supra* note 70, at 1082 (lamenting financial professionals' failure to implement "state-variable hedging").

[75] *See, e.g.*, Arthur F. Burns & Wesley C. Mitchell, Measuring Business Cycles (1946); Rabah Benkemoune, *Charles Dunoyer and the Emergence of the Idea of an Economic Cycle*, 41 Hist. Pol. Econ. 271-295 (2009); Joseph Kitchin, *Cycles and Trends in Economic Factors*, 5 Rev. Econ. & Stat. 10-16 (1923).

[76] *See, e.g.*, Anna J. Schwartz, Money in Historical Perspective 24-77 (1987).

[77] *See, e.g.*, Gregory Mankiw, *Real Business Cycles: A New Keynesian Perspective*, 3 J. Econ. Persp. 79-90 (1989).

[78] *See generally* Andrey V. Korotayev & Sergey V. Tsiret, *A Spectral Analysis of World GDP Dynamcs: Kondratieff Waves, Kuznets Swings, Juglar and Kitchin Cycles in Global Economic Development and the 2008-2009 Economic Crisis*, 4 Structure & Dynamics 3-57 (2010).

[79] *See, e.g.*, Charles Goodhart, *Financial Regulation, Credit Risk, and Financial Stability*, 192 Nat'l Inst. Econ. Rev. 118-127 (2005) (proposing that regulatory capital adequacy requirements be set on a *procyclical* basis relative to inflation and other macroeconomic indicators); Rafael Repullo & Javier Suarez, *The Procyclical Effects of Bank Regulation*, 26 Rev. Fin. Stud. 452-490 (2013). *See generally* Markus Brunnermeier, Andrew Crocket, Charles Goodhart, Avinash D. Persaud & Hyun Shin, The Fundamental Principles of Financial Regulation 8 (2009) (Geneva Reports on the World Economy, No. 11); Malcolm P. Baker & Jeffrey Wurgler, *Do Strict Capital Requirements Raise the Cost of Capital? Bank Regulation, Capital Structure and the Low Risk Anomaly*, 105 Am. Econ. Rev. 315-320 (2015); Samuel G. Hanson, Anil K. Kashyap & Jeremy C. Stein, *A Macroprudential Approach to Financial Regulation*, 25:1 J. Econ. Persp. 3-28 (Winter 2011); Zeyu Zheng, Boris Podobnik, Ling Feng & Baowen Li, *Changes in Cross-Correlations as an Indicator for Systemic Risk*, 2 Sci. Rpts. 888 (2012).

in prospect theory,[80] the asymmetric nature of procyclical effects reflects pronounced human sensitivity to economic states in which "[l]osing hurts worse than wining feels good."[81] Econophysics thus invites (and supports) more explicitly behavioral accounts of abnormal markets and irrational investors, such as SP/A theory[82] and behavioral portfolio theory.[83]

Differences between objectively quantifiable data and subjective perception give rise to theories of behavioral finance.[84] A "market composed solely of information traders" is a market "where price efficiency and the CAPM hold," where "[r]isk premia are determined solely by beta and distribution of returns on the market portfolio," and where option prices[85] obey deliver rational, mathematically beautiful rules.[86]

The incorporation of behavioral elements into econophysics places an affirmative premium on mathematical rigor. Despite diametrically opposite assumptions, behavioral accounts of irrational decisionmaking and informational accounts stressing rationally structured responses to financial uncertainty "bear considerable mathematical resemblance to each other."[87] They are equally able "to explain similar evidence."[88] Bluntly stated, "it is impossible to empirically distinguish between many irrational behavior theories and rational Bayesian models because their predictions are too similar."[89]

As competing theories, neither behavioral finance nor constrained rationality unequivocally prevails. "[A]sset pricing tests can find patterns in returns that are neither part of the subjective distribution (as assumed by market efficiency) nor caused by irrationality (as assumed by behavioral finance)."[90] Econophysics therefore counsels skepticism of purely behavioral approaches that are "relatively detached from economic fundamentals."[91] Instead, "linking risk and expected return" to economic fundamentals "provides a unified framework to rationalize many empirical regularities in the cross-section of returns."[92]

[80] *See, e.g.*, Daniel Kahneman & Amos Tversky, *Prospect Theory: An Analysis of Decision under Risk*, 47 Econometrica 263-292 (1979); Paul Slovic, *Psychological Study of Human Judgment: Implications for Investment Decision Making*, 27 J. Fin. 779-799 (1972).

[81] Lewis Grizzard, Gettin' It On: A Down-Home Treasury 72 (1990); *accord* Joe Garagiola, It's Anyone's Ballgame 109 (1988).

[82] *See* Lola L. Lopes, *Between Hope and Fear: The Psychology of Risk*, 20 Advances in Experimental Soc. Psych. 255-295, 283 (1987).

[83] *See* Hersh Shefrin & Meir Statman, *Behavioral Portfolio Theory*, 35 J. Fin. & Quant. Analysis 127-151 (2000).

[84] *See* Hersh Shefrin & Meir Statman, *Behavioral Capital Asset Pricing Theory*, 29 J. Fin. & Quant. Analysis 323-349, 323 (1994). *See generally* Fischer Black, *Noise*, 41 J. Fin. 529-543 (1986).

[85] *See generally* Fischer Black & Myron S. Scholes, *The Pricing of Options and Corporate Liabilities,* 81 J. Pol. Econ. 637-654 (1973); Robert C. Merton, *The Theory of Rational Option Pricing*, 4 Bell J. Econ. 141-183 (1973).

[86] Shefrin & Statman, *Behavioral Capital Asset Pricing Theory*, *supra* note 84, at 323.

[87] Alon Brav & John B. Heaton, *Competing Theories of Financial Anomalies*, 15 Rev. Fin. Stud. 576-606, 589 (2002).

[88] *Id.*

[89] Jennifer Francis, Ryan Lafond, Per Olsson & Katherine Schipper, *Information Uncertainty and Post-Earnings-Announcement Drift*, 34 J. Bus. Fin. & Accounting 403-433, 406 (2007).

[90] Jonathan Lewellen & Jay Shanken, *Learning, Asset-Pricing Tests, and Market Efficiency*, 57 J. Fin. 1113-1145, 1114 (2002).

[91] Zhang, *supra* note 95, at 69.

[92] *Id.*

3. Econophysics as the music of strings and spheres

Econophysics aspires to deliver the "coherent story" that Eugene Fama has challenged finance to tell.[93] A persuasive account of finance not only "relates the cross-section properties of expected returns to the variation of expected returns through time," but also "relates the behavior of expected returns to the real economy in a rather detailed way."[94] The introduction of physical concepts into finance represents "a growing strand of applied theoretical literature."[95]

Depicting economic phenomena in physical terms offers deep aesthetic and philosophical satisfaction. Through scientific ages, "[f]rom the ancient Pythagorean 'music of the spheres' to the 'harmonies of nature,'" physicists "have collectively sought the song of nature in the gentle wanderings of celestial bodies and the riotous fulmination of subatomic particles."[96] In science as in poetry, "metaphors challenge us to see connections and make associations that are not otherwise apparent."[97] Even where the "inspiration ... is metaphorical, not mechanical," connections between sensory perception and finance should "be spelled out via ... mathematics."[98]

When fields as disparate as economics, physics, and biology collide,[99] the most "useful and fertile combinations" are those "which seem the results of a first impression," as if they "present themselves ... after an unconscious working somewhat prolonged."[100] Mathematics boasts a "beauty cold and austere, ... without any appeal to any part of our weaker nature, without the gorgeous trappings of painting or music, yet sublimely pure, and capable of a stern perfection such as only the greatest art can show."[101] As Edna St. Vincent Millay rhapsodized: "Euclid alone has looked on Beauty bare."[102] Or as John Keats wrote: "'Beauty is truth, truth beauty,' — that is all / Ye know ... and all ye need to know."[103] When pressed to choose between truth and beauty, physicist Hermann Weyl "usually chose the beautiful."[104]

93 Eugene F. Fama, *Efficient Capital Markets: II*, 46 J. Fin. 1575-1617, 1610 (1991).
94 *Id.*
95 Lu Zhang, *The Value Premium*, 60 J. Fin. 67-103, 94 (2005). *See generally* Jonathan B. Berk, Richard C. Green & Vasant Naik, *Optimal Investment, Growth Options and Security Returns*, 54 J. Fin. 1553-1607 (1999).
96 Brian Greene, The Elegant Universe: Superstrings, Hidden Dimensions, and the Quest for the Ultimate Theory 135 (1999). *See generally* Peter Pesić, Music and the Making of Modern Science (2014).
97 Lev Ginzburg & Mark Colyvan, Ecological Orbits: How Planets Move and Populations Grow 8 (2004).
98 *See id.* at ix.
99 *See* Gian-Carlo Rota, The Phenomenology of Mathematical Beauty 173 (1997); *cf.* Donald N. McCloskey, *History, Differential Equations, and the Problem of Narration*, 30 Hist. & Theory 21-36 (1991) (describing how economics blends rhetoric and quantitative reasoning).
100 Henri Poincaré, *Mathematical Creation*, *in* The Foundations of Science: Science and Hypothesis, the Value of Science, Science and Method 383-394, 391 (George Bruce Halstead trans., 1913); *cf.* G.H. Hardy, A Mathematician's Apology 29 (1940) (praising beautiful mathematical results with "a very high degree of unexpectedness, combined with inevitability and economy").
101 Bertrand Russell, *The Study of Mathematics*, *in* Mysticism and Logic, and Other Essays 58-73, 60 (1988).
102 Edna St. Vincent Millay, *Euclid Alone Has Looked on Beauty Bare*, *in* Selected Poems 52 (J.D. McClatchy ed., 2003).
103 John Keats, *Ode on a Grecian Urn*, *in* The Complete Poems 345-346, 346 (John Barnard ed., 3d ed. 1988).
104 Freeman J. Dyson, *Obituary: Hermann Weyl,* 177 Nature 457-458, 458 (1956); *accord* Edward O. Wilson, Biophilia 61 (1984); cf. Richard Feynman, The Character of Physical Law 165 (Modern Library 1994) (1st ed. 1965) ("You can recognize truth by its beauty and simplicity. … [T]he truth always turns out to be simpler than you thought.").

Like color vision[105] or musical pitch,[106] the perception of financial information is a psychophysical phenomenon. All "aesthetics ... must appeal to what human beings, situated as they are, can find significant, enhancing, a joy for the senses, or a spur to the imagination and intellect."[107] The confluence of physics with physiology enables economists to embed explicitly behavioral elements within mathematical models. From the "hedonimetry" of cardinal utility[108] to the "psychophysics of chances,"[109] econophysics promises to quantify the sensory aspects of finance, at least to the extent that economic behavior can be "contained [by] the axioms and corollaries of a book of mathematics."[110]

In a "world ... lit by lightning," the application of physics to economics seeks to "find in motion what was lost in space."[111] Closer examination of comovement across economics, from labor markets to unemployment, inflation, and discount rates, provides a more complete and convincing account of asset prices and their movement. Econophysics spans "the macroeconomic level ... of the market equilibrium models" as well as "the individual agent level ... of the market microstructure theory."[112] This panoramic perspective illuminates "stock market movements" within "a world of complex spatial patterns and structures such as coastlines and river networks."[113]

In econophysics as in physics itself, perceived differences in the operation of rules arise from the scale at which we observe the universe. String theory, which describes the fundamental operation of physical systems through the propagation and interaction of one-dimensional objects called strings, proceeds at a characteristic scale defined by the Planck length:[114]

$$\ell_P = \sqrt{\frac{\hbar G}{c^3}} \approx 1.616\ 229\ (38)\ \text{x}10^{-35}\ m \qquad (2)$$

[105] *See, e.g.*, Allan Hanbury, *Constructing Cylindrical Coordinate Colour Spaces*, 29 Pattern Recognition Letters 494-500 (2008); Jay Neitz & Gerald H. Jacobs, *Polymorphism of the Long-Wavelength Cone in Normal Human Colour Vision*, 323 Nature 623-625 (1986); Brian C. Verrelli & Sara Tishkoff, *Signatures of Selection and Gene Conversion Associated with Human Color Vision Variation*, 75 Am. J. Human Genetics 363-375 (2004).

[106] *See, e.g.*, Roy D. Patterson, Etienne Gaudrain & Thomas C. Walters, *The Perception of Family and Register in Musical Tones*, *in* Music Perception 13-50, 37-38 (Mari Riess Jones, Richard R. Fay & Arthur N. Popper eds., 2010).

[107] Janna Thompson, *Aesthetics and the Value of Nature*, 17 Envtl. Ethics 291-305, 305 (1995).

[108] *See, e.g.*, Tore Ellingsen, *Cardinal Utility: A History of Hedonimetry*, *in* Cardinalism: A Fundamental Approach 105-165 (Maurice Allais & Ole Hagen eds., 1994); Ole Hagen, *Separation of Cardinal Utility and Specific Utility of Risk in Theory of Choices Under Uncertainty*, 3 Saertrykk av Statsøkonomisk Tidsskrift 81-107, 92-99 (1969); Ole Hagen, *Neo-Cardinalism*, *in* Progress in Utility and Risk Theory 145-164 (Ole Hagen & Fred Wenstøp eds., 1984).

[109] Daniel Kahneman & Amos Tversky, *Choices, Values, and Frames*, 39 Am. Psychologist 344-350, 344 (1984); *cf.* Lola L. Lopes, *Between Hope and Fear: The Psychology of Risk*, 20 Advances Experimental Soc. Psych. 255-295, 283 (1987) (describing "[p]sychophysical theories" and "moment theories" as "theories of Everyman because they are based mechanistically on principles" that presumably bind all of humanity).

[110] Oliver Wendell Holmes, Jr., The Common Law 1 (Sheldon M. Novick intro., 1991) (1st ed. 1881).

[111] Tennessee Williams, The Glass Menagerie 97 (Robert Bray introd., 1999) (1st ed. 1945).

[112] J-P. Bouchaud & R. Cont, *A Langevin Approach to Stock Market Fluctuations and Crashes*, 6 Eur. Phys. J. B 543-550, 544 (1998). On macroeconomic equilibrium models, see generally William A. Brock, David A. Hsieh & Black LeBaron, Nonlinear Dynamics, Chaos and Instability (1991); W.A. Brock & C.F. Hommes, *A Rational Route to Randomness*, 65 Econometrica 1059-1095 (1997); Jean-Michel Grandmont, *Temporary General Equilibrium Theory*, 2 Handbook of Mathematical Economics 879-922 (Kenneth J. Arrow ed., 1992). On market microstructure theory, see generally Maureen O'Hara, Market Microstructure Theory (1995); Lawrence Harris, Trading and Exchanges: Market Microstructure for Practitioners (2003); Joel Hasbrouch, Empirical Market Microstructure (2007); Ananth Madhavan, *Market Microstructure: A Survey*, 3 J. Fin. Mkts. 205-258 (2000).

[113] Terence Hwa & Mehran Kardar, *Avanlances, Hydrodynamics, and Discharge Events in Models of Sandpiles*, 45 Phys. Rev. A 7002-7023 (1992). *See generally* P. Bak, C. Tang & K. Wiesenfeld, *Self Organized Criticality: An Explanation of 1/f Noise*, 59 Phys. Rev. Letters 381-384 (1987); P. Bak, C. Tang & K. Wiesenfeld, *Self Organized Criticality*, 38 Phys. Rev. A 364-374 (1988); Juan L. Valderrábano López & Miguel Ángel Alonso Neira, *The Taylor Rule and the Sandpile: A Former Paper's Review*, 3 Open J. Modelling & Simulation 191-195 (2015).

[114] *See* Katrin Becker, Melanie Becker & John Schwarz, String Theory and M-Theory: A Modern Introduction 6 (2007).

where c is the speed of light in a vacuum, G is the gravitational constant, is the reduced Planck constant, and (38) reports the estimated standard error associated with the reported numerical value.[115]

This is a profoundly small scale. On scales larger than the characteristic length of string theory, a string will resemble an ordinary particle, whose mass, charge, and other properties will be determined by the string's vibrational state.[116] But Planck length characterizes the region in which the Standard Model and general relativity can no longer be mathematically reconciled,[117] and the quantum effects of gravity — the lone force that eludes the Standard Model — are expected to dominate.[118]

The discovery of mathematical dualities connecting different versions of string theory has inspired an even more general framework called M-theory.[119] Insofar as string theory and M-theory can accommodate not only the Standard Model's elementary particles, but also fundamental interactions such as gravity (which the Standard Model cannot explain), these comprehensive efforts at describing the universe may constitute a theory of everything.[120]

String theory and M-theory have continued "the surprising synergy" that began no later than the "convergence of results from astrophysics and elementary particles."[121] As the bridge to a Grand Unified Theory,[122] if not quite a theory of everything, the "Standard Model brings us full circle, to a point where particle physics and astrophysics" — the fundamental sciences of the very small and the very large — "are no longer separate disciplines."[123]

Let us take note of two other Planck units alongside Planck length.[124] Planck temperature takes the following form:

$$T_P = \sqrt{\frac{\hbar c^5}{Gk^2}} \approx 1.416\,808\ (35)\ \text{x}10^{32}\ K \qquad (3)$$

[115] *See generally*, *e.g.*, Luis J. Garay, *Quantum Gravity and Minimum Length*, 10 Int'l J. Mod. Physics A 145-166 (1995); Carlo Rovelli, *What is Observable in Classical and Quantum Gravity?*, 8 Classical Quantum Gravity 297-316 (1991). This is the value of the reduced Planck constant: $\hbar = 1.054\ 571800\ (13)\text{x}10^{34}\ J \cdot s = 6.582119\ 514\ (40)\text{x}10^{-16}\ eV \cdot s$

[116] *See* Becker, Becker & Schwarz, *supra* note 114, at 2-3.

[117] *See* T. Padmanabhan, *Planck Length as the Lower Bound to All Physical Length Scales*, 17 General Relativity & Gravitation 215-221 (1985).

[118] *See* John D. Barrow & Douglas J. Shaw, *The Value of the Cosmological Constant*, 43 General Relativity & Gravitation 2555-2560 (2011); Young-Wan Kim & Young-Jai Park, *Entropy of the Schwarzschild Black Hole to All Orders in the Planck Length*, 655 Phys. Letters B 172-177 (2007).

[119] *See* Becker, Becker & Schwarz, *supra* note 114, at 9-12.

[120] *See id.* at 15-16; Barton Zwiebach, A First Course in String Theory 6-9 (2d ed. 2009).

[121] Robert Oerter, The Theory of Almost Everything: The Standard Model, the Unsung Triumph of Modern Physics 213 (2006).

[122] *See*, *e.g.*, Robert P. Crease & Charles C. Mann, The Second Creation: Makers of the Revolution in Twentieth-Century Physics 393-404 (1996); A.J. Buras, J. Ellis, M.K. Gaillard & D.V. Nanopoulos, *Aspects of the Grand Unification of Strong, Weak and Electromagnetic Interactions* 135 Nuclear Physics B 66-92 (1978).

[123] Oerter, *supra* note 121, at 213. On the birth, growth, and death of galaxies, see James Binney & Scott Tremaine, Galactic Dynamics 716-769 (2d ed. 2008); Houjun Mo, Frank van den Bosch & Simon White, Galaxy Formation and Evolution § 1.4, at 15-24 (2010); Joshua E. Barnes, *Evolution of Compact Groups and the Formation of Elliptical Galaxies*, 338 Nature 123-126 (1989); T.J. Cox & Abraham Loeb, *The Collision Between the Milky Way and Andromeda*, 386 Monthly Notices Royal Astronom. Soc'y 461-471 (2008).

[124] *See generally* John D. Barrow, The Constants of Nature: From Alpha to Omega — The Numbers That Encode the Deepest Secrets of the Universe (2002); John D. Barrow & Frank J. Tipler, The Anthropic Cosmological Principle (1986).

For its part, Planck energy is defined thus:

$$E_P = \sqrt{\frac{\hbar c^5}{G}} \approx 1.956 \text{ x} 10^9 J \approx 1.2209\text{x}10^{19}\, GeV \approx 0.54336\, MWh \tag{4}$$

Although there is no reason to assume that universal constants, base Planck units, and derived Planck units should carry anthropocentric significance, the contrast between Planck length, temperature, and energy is at least entertaining. Planck length is fantastically small. It is hypothesized to represent the scale at which string theory, M-theory, or some other would-be theory of everything must bridge hitherto irreconcilable contradictions between general relativity and the Standard Model. Planck temperature expresses a fantastically large quantity, so much so that it is considered the conceptual opposite of absolute zero, or zero degrees Kelvin.

Between these extreme stands Planck energy. At roughly half a megawatt-hour, Planck energy approximates a tank of gasoline. Economics at its most solipsistic imagines wide gulfs separating the household from the firm, the firm from capital markets, and the private economy from domestic money supply and foreign exchange. Traditional finance omits key elements of the household portfolio.[125] In his celebrated “second critique,” Richard Roll excoriated the CAPM’s failure to reflect the full portfolio of assets held by investors.[126] Standard “market portfolio measures” typically exclude “human capital, real estate, and consumer durables.”[127]

Economics operates at the quotidian scale of Planck energy. Intellectual housekeeping counsels a return to etymological as well as epistemic roots. Economics and ecology stem from οἶκος , the ancient Greek word uniting families and their property within an idea we now embrace within our concept of a *household*.[128] This is domain of economists and other social scientists, who represent a “third culture” transcending both science and literature and addressing the conditions under which “human beings are living or have lived.”[129]

Among the gifts that physics has conferred upon economics, new ways of framing financial inquiries may be the greatest. Philosophers of science have long understood that “[t]he way a question is asked limits and disposes the ways in which any answer to it — right or wrong — may be given.”[130] Risk measures with clear physical

125 *See* John Y. Campbell, *Household Finance*, 61 J. Fin. 1553-1604, 1564-1565 (2006); Alessandro Bucciol & Raffaele Mianiaci, *Household Portfolio Risk*, 19 Rev. Fin. 739-783 (2015); Luigi Guiso & Paolo Sodini, *Household Finance: An Emerging Field*, 2 Handbook of the Economics of Finance 1397-1532, 1406-1417 (George M. Constantinides, Milton Harris & René M. Stulz eds., 2013).

126 *See* Richard Roll, *A Critique of the Asset Pricing Theory's Tests*, 4 J. Fin. Econ. 129-176, 155 (1977).

127 Douglas T. Breeden, *An Intertemporal Asset Pricing Model with Stochastic Consumpiton and Investment Opportunities*, 7 J. Fin. Econ. 265-296, 292 (1979).

128 Ernst Haeckel is credited with deriving the word *ecology* from ancient Greek. *See* Stephen Jay Gould, Ontogeny and Phylogeny 76 n.* (1977). *Economics* as housekeeping figures prominently in the literature of environmental and ecological economics. *See, e.g.*, Jeremy L. Caradonna, Sustainability: A History 112-113 (2014).

129 C.P. Snow, The Two Cultures: And a Second Look 70 (2d ed. 1964).

130 Susanne K Langer, Philosophy in a New Key: A Study in the Symbolism of Reason, Rite, and Art 3 (3d ed. 1957).

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interpretations provide readily understandable, easily quantifiable, and statistically verifiable support or contradiction for intuitions about risk management. The representation of risk according to physical and sensory models unveils merely one of many new insights from physics, hitherto "Not known, because not looked for / But heard, half-heard, in the stillness / Between two waves of the sea."[131]

Acknowledgements

I appreciate comments by Lee J. Alston, José-María Montero, Jagoda Anna Kaszowska, Kamil Mojsa, and Mobeen Ur Rehman. Special thanks to Heather Elaine Worland Chen.

[131] Eliot, *Little Gidding*, *in* Four Quartets, *supra* note 1, at 49-59, 59.