Foreword

To understand the relationship between economics and physics, it is important to note that economics is a science with a particularly remarkable origin story, full of many unexpected interactions with other sciences. While most preindustrial sciences began as branches of natural philosophy, economics started as a subfield of ethics. One of the oldest surviving texts on economics in the Western tradition is Aristotle's *Nicomachean Ethics*, which contains a detailed description of basic results in optimization theory and the functions of money.[1] The former is all the more striking because Aristotle not only knew nothing of calculus but he explicitly rejected the concept of infinity.

Two millennia later, economics remained a province of ethicists. The publication of Adam Smith's *Wealth of Nations* in 1776 is widely recognized as the beginning of modern economics. What most people do not know is that it was actually the sequel to his *Theory of Moral Sentiments*, an attempt to scientifically understand what determines our judgements about what is good and what is bad. A question left unanswered by the first book was how it was in a world where people are driven mostly by their own selfish desires that the distribution of "the necessities of life" is so much more equitable than the distribution of wealth.[2] Seventeen years later, Smith established that this central question of political economy could be answered in terms of the factors that determine prices or exchange value. In one of the earliest instances of cross-fertilization between physics and economics,[3] Smith argued that markets behave like a system of Newtonian bodies and have a tendency to "gravitate" towards an equilibrium where every good is priced so that all the resources used to produce the good—labor, land, and capital—are each priced according to the natural rate for that input.[4]

Aside from some arithmetic, however, the mathematical content of the *Wealth of Nations* was practically nil. Smith relied upon intuition rather than formal models to make his points. Cribbing from John Locke,[5] he observed that some goods like water have tremendous value in use but hardly any value in exchange. Conversely, some goods like diamonds have tremendous exchange value and very little use value.[6] Smith focused on prices and exchange value because he was heavily influenced by his good friend David Hume, who espoused an empirical philosophy that what we think we know about the universe is nothing more than inferences grounded upon the data

1 Books II and V.
2 Smith, *The Theory of Moral Sentiments*, pp. 184–185.
3 As an even earlier example, Nicolaus Copernicus was one of the first people to propose a quantity theory of money.
4 Smith, *The Wealth of Nations*, p. 48.
5 Locke, p. 1319.
6 Smith, *The Wealth of Nations*, p. 25.

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we collect with our senses.[7] Prices are mysterious yet observable whereas use value is both trivial to understand and difficult to quantify.

Two decades later, the mathematical sophistication of economists made a quantum jump as Thomas Malthus introduced them to the concept of a differential equation in his *Essay on Population* in 1798. However, this equation, the simple exponential growth equation, was only described in words. Malthus posited that, unobstructed, population would grow geometrically, but economic constraints would prevent this growth from continuing indefinitely. This added rigor to speculations made by Smith, and to a lesser degree Hume, about the determinants of wages and the labor supply.[8] Malthus has a poor reputation today because of his supposed failure to predict the Industrial Revolution, though what he actually failed to predict was the general decrease in sexual appetites.[9] But while Malthus was unable to forecast how the parameters of his model would change over time when applied to human beings, the model itself was perfectly valid and received the ultimate vindication from another field of science.

A common refrain of creationists is that the theory of evolution works for other species; Darwin's hubris was to extend the theory to us. In fact, what happened was just the opposite. Following the suggestions of Hume, Smith, and Malthus to zoologists, Darwin took a theory of human development and applied it to the rest of the ecosystem. Hence, modern evolutionary biology is in fact a spinoff of classical economics.

In the meantime, Malthus' predictions that the lot of workers could only get worse in the long run seemed to be confirmed as the Industrial Revolution began. He presented a very pessimistic outlook about the future that was meant to throw cold water on utopian idealism that proliferated after the American Revolution. Perhaps his most prominent critic was Karl Marx. Today, much like Malthus, Marx is remembered primarily for proposals that went disastrously wrong. Many do not realize the tremendous influence Marx had on the practice of history and the social sciences in general and on economics in particular. A lot of his ideas have become so mainstream that they are no longer recognized as being Marxist in origin.

Marx was among those economists who convinced the profession that use value was what we should focus on, not exchange value.[10] In this, he was like Moses leading his people to the Promised Land without ever visiting it himself. Instead of developing his own theory of use value, Marx fixated on the labor theory of value, a primitive version of Smith's theory of exchange value that was meant as an explicative toy model but which, taken too seriously, implies that capitalists do nothing but exploit workers.[11] How-

7 See Book I Part III of Hume's *A Treatise on Human Nature*.
8 See Book I Chapter 8 of *The Wealth of Nations* and "Of the Populousness of Ancient Nations" from Hume's essays.
9 He did state that Europe could only become as prosperous as it has with a substantial reduction in family sizes, both of which came to pass. Malthus, p. 95.
10 See Chapter 1 Section 1 of Volume I of *Capital*.
11 Smith presents the labor theory of value in Book I Chapter V of *The Wealth of Nations*.

ever, contemporaries of Marx, including Léon Walras, Alfred Marshall, Carl Menger, and William Jevons, did transform economics, which coalesced into the science of how people allocate scarce resources to extract use value. It was at this moment that economists began to view their study primarily in terms of optimization and to borrow heavily from the toolboxes already invented by physicists and engineers.

Since physics includes every component of the universe in its ambit, it has earned a reputation of being an imperialist science. Likewise, economics has earned a reputation of being the imperialist of the social sciences. Virtually every aspect of human life from the choice of where to live to the choice of a mate can be framed as a decision about how to allocate scarce resources. Physicists have, over the centuries, learned the trick to solving many difficult mathematical problems with physical implications, and Feynman's dictum that the same equation will have the same solution regardless of the context means that these tricks can often be applied to more humane questions. Econophysics took off in the 1990s when many physicists realized the social sciences offered an immense orchard of low-hanging fruit for them to harvest.

Looking forward, there are two major cultural barriers to deeper collaboration between economists and physicists, one of which may slowly be fading while the other is more systemic. The first of these is the assumption commonly made by economists that households are perfectly rational. What this means is that households have a complete and transitive preference relation over all the options they could conceivably choose from. Given a set of options that are economically feasible—for example, because they have enough money to afford these options at current prices—they will choose an option that they (weakly) prefer over all other options.

One of the reasons why this formulation of household behavior predominated was its conformity with the Principle of Least Action in physics. With additional assumptions, preferences can be represented by a utility function analogous to the Lagrangian in physics. To put this another way, economists would view the specification of a Lagrangian in a physics model as a description of the universe's preferences. Thus the same techniques used by physicists to derive the laws of motion of particles are also used by economists to derive the laws of motion of people.

Empirically, however, the assumption of perfect rationality has not fared well. Nevertheless, economics as a profession has been slow to adapt to this reality, and many econophysicists have had the experience of banging their head against the wall trying to persuade economists to consider alternative formulations of human behavior. For many economists the most convincing argument to retain the assumption of perfect rationality was put forward by Milton Friedman, who observed that natural selection is an optimization algorithm.[12] He concluded that, even if households do not

12 Friedman, pp. 21–22, actually framed this discussion in terms of why we should model firms as maximizing profits, but the argument carries over to why we should model households as maximizing utility if utility correlates with the household's survival probability or fertility.

behave rationally today, they should inevitably evolve to maximize their utility and behave more rationally.

A recently discovered flaw in Friedman's argument (Feigenbaum et al. 2011) is that natural selection does not treat economic constraints the same way that economists do. The constraint that you can only buy what you can afford depends on the prices that determine what you can afford. These are determined by supply and demand, which are aggregates of the choices of all the agents in the market. Economists define rationality so there is a pecuniary externality because households ignore the effects of their own individual choices on supply and demand and the resulting prices. We do this because then we obtain the First and Second Welfare Theorems, which are the mathematical fulfillment of the question left unanswered by Smith in *The Wealth of Nations* of why households acting independently can often achieve better outcomes than a planned economy. Rational households who take the prices determined by supply and demand as given when making their choices will generate an efficient allocation of goods that cannot be improved upon by a social planner. But Darwin presented many examples of how natural selection will act upon all the ways in which the components of an ecosystem interact,[13] which would include prices in a market economy. Contrary to the intuition engendered by the Welfare Theorems, finitely-lived households do not maximize their utility in rational competitive equilibria. They can do better following "optimally irrational" rules of thumb.

Assuming perfect rationality still provides a concise description of how people will respond to any conceivable economic situation, which is useful for projecting how they will react to a novel policy proposal. Nevertheless, such projections are extrapolations supported by no empirical data. They are also computationally expensive in models with uncertainty, which makes them increasingly difficult for economists to justify. Consequently, we can expect the fondness of economists for rationality to slowly die, although like opposition to quantum mechanics a century ago this may require the actual demise of adherents to the rational paradigm.

The second barrier to collaboration between economists and physicists is that, while the Laws of Thermodynamics are the fundamental reason why material resources are always scarce, until recently there was no need for economic models to faithfully incorporate these laws. Many economists fail to recognize that our model of goods and services is in fact a model and not a perfect representation of reality. When goods or services are produced, we do work as understood by physicists, usually to rearrange atoms. No new matter or energy is created. Likewise, when goods are consumed, atoms are again rearranged but not destroyed. The standard model of

13 See, for example, the section "Objections to the Theory of Natural Selection as Applied to Instincts: Neuter and Sterile Insects" in *On the Origin of Species by Means of Natural Selection*, which discusses how the evolution of, say, worker bees can happen through natural selection when worker bees do not reproduce.

production[14] is quite consistent with the notion that production and consumption involve rearrangements of atoms, but it does not address the concepts of energy and work. While this model accounts for the effect of wear and tear that comes from the use of created goods, it otherwise ignores the Second Law and the inexorable truth that entropy must always increase. In a closed system, we can only do a finite amount of work, yet contemporary economists generally laugh at Malthus' warning that exponential growth cannot persist indefinitely even as we observe that growth rates in both population and productivity have been declining.

Economists and physicists are going to have to join forces if we as a species are to deal with climate change and environmental degradation responsibly. There is a huge disconnect between how physicists understand the science related to climate change and environmental degradation and how economists think about these issues. In this case, however, the barrier is more psychological than scientific. No one likes to be told the party is going to end, and economists often forget how we earned the epithet of "the dismal science".

In this collection of papers we have a snapshot of the current work being done at the intersection of economics and physics. I hope studying this research will provide an impetus to continue this important collaboration as we tackle the challenges of humanity's future.

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