ARTICLE IN PRESS
REVFIN-00340; No of Pages 9
Review of Financial Economics xxx (2015) xxx–xxx
Contents lists available at ScienceDirect
Review of Financial Economics
journal homepage: www.elsevier.com/locate/rfe

Economics as energy framework: Complexity, turbulence, financial crises, and protectionism

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ARTICLE INFO

Available online xxxx

JEL classification:
B52
F60
G11
G15

Keywords:
Non-equilibrium
Turbulence
Financial crisis
Thermodynamics
Complexity

ABSTRACT

This paper presents a framework for thinking about economic growth, trade, and capital flows viewed as transformations of current and vintage solar energy, stored in the form of natural resources, human capital, physical capital and technology described by the laws of thermodynamics. Recent developments in nonequilibrium thermodynamics (NET) show how efficient global capital markets and high-speed communications networks accelerate energy flow and growth but also create turbulence, financial crisis, protectionism and conflict. The paper discusses the role that NET can play in helping us understand stock market bubbles and financial crises.

1. Introduction

Advances in information technology and communications networks affect global growth through three primary channels. First, they allow people to view each other's lives in real time for the first time in history, exposing gaping income and wealth differentials within and across nations to public view. This instantaneous transparency motivates people in low-income countries to demand pro-growth policy reforms from their governments. And it motivates people in high-income countries to demand protection from cheap foreign labor.

Second, communications technology makes it faster, cheaper and easier to move resources around the globe to take advantage of price and return differentials. Labor, capital, and technology move at the speed of light through fiber-optic networks at practically no cost, accelerating growth in emerging market countries.

Third, cheap, fast communications make global capital markets more efficient, reducing the cost of moving capital and, therefore, the minimum return-differential threshold for triggering capital redeployment.[1] Policy reforms make capital still easier to move. These changes facilitate higher growth but they increase volatility and can trigger financial crises. Both intensify economic and political conflicts within and among nations.

This paper outlines a framework for economic activity based on the laws of thermodynamics. In this framework, economic agents respond to energy gradients—price and return differentials—to transform *current* and *stored* energy—natural resources, human capital, physical capital, and technology—to create *work*, or economic activity according to the

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[1] In economics, speed of adjustment toward equilibrium is driven by price and return differentials subject to transactions or transportation costs that limit arbitrage. In thermodynamics, speed of adjustment toward (thermal) equilibrium depends on temperature and activation energy. According to Atkins (1991), Arrhenius Behavior—proposed by Dutch Chemist Jacobus van't Hoff in 1884, interpreted by Svante Arrhenius in 1889—states that reaction rate is an exponential function of temperature, or Rate $= k_0 e^{-T_a/T}$. In this expression, T_a represents the reaction-specific *activation temperature*—the minimum temperature at which a reaction will occur. Boltzmann (1886/1974) derived a related expression for the proportion of collisions between molecules in a reaction that occur with at least the *activation energy* E_a, the threshold below which no reaction will occur, as $e^{-E_a/KT}$, where k, known as Boltzmann's constant, is a fundamental constant of nature. In economics E_a would play the role of transportation or transactions costs in determining the minimum price or return on capital differential needed to trigger a profitable arbitrage transaction. In either case, reducing E_a would increase adjustment speed for a given price gradient.

http://dx.doi.org/10.1016/j.rfe.2015.02.003
1058-3300/

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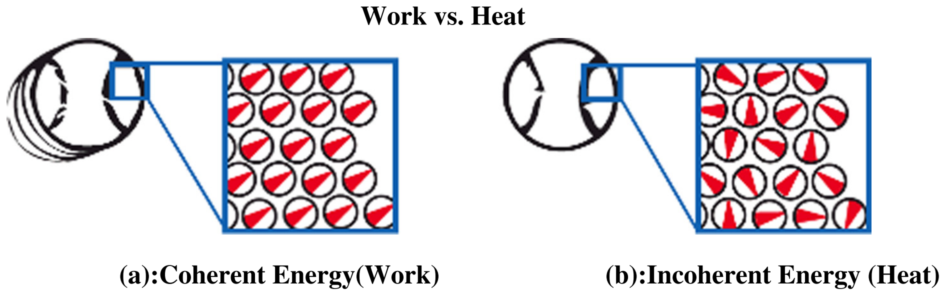

Fig. 1. Work vs. heat. (a) Coherent energy (work). (b) Incoherent energy (heat).

second law of thermodynamics.[2] Policies impact resource flows by steepening or flattening price and return gradients, providing incentives, or signals, for entrepreneurs to change behavior.[3]

This framework allows us to draw on recent advances in non-equilibrium thermodynamics (NET) pioneered by Prigogine (1996), Bak (1996), and others. NET sheds light on situations of sudden, discontinuous change, such as asset market bubbles and financial crises. The next section summarizes this framework.

2. The laws of thermodynamics are immutable

Einstein (1905) showed in his famous equation, $E = mc^2$, that mass and energy are interchangeable. In this view, all activity can be viewed as energy transformations driven by the flow of energy from the sun. Mining energy to produce goods and services, the domain of economics, must obey the laws of thermodynamics. As Feynman (1989, 4-1 to 4-8) explains:

> There is a fact, or if you wish, a law, governing all natural phenomena that are known to date. There is no known exception to this law—it is exact as far as we know. The law is called the conservation of energy…Although we know for a fact that energy is conserved, the energy available for human utility is not conserved so easily. The laws that govern how much energy is available are called the laws of thermodynamics…

3. Work, coherent energy, and economic activity

Macroeconomics, developed after the Great Depression, focuses on aggregate demand, or spending. More recently, supply-side economics, pioneered by Mundell (2000), focused attention on resources and the incentives for their productive use.

Work is the source of income, production, profit, and wealth. The purpose of macroeconomics is to explain variations in economic activity—how much work the people in an economy perform during a given time period.

Physicists have been measuring work since Galileo rolled a ball down an incline 500 years ago. Energy transformations produce work and heat. Physicists refer to work as *coherent motion*, and refer to heat as *incoherent motion*.

To illustrate, in Fig. 1(a) every particle in the baseball is moving at the same speed, and in the same direction. This is an example of *work*, also known as *kinetic energy*, *coherent energy*, *or order*.

In Fig. 1(b), a stationary baseball has been heated to a high temperature; its particles are moving in random directions, colliding with each other. Every particle in the baseball is moving but the baseball, viewed as a macro object, or system of particles, appears to be at rest. This is an example of *heat*, also known as *thermal energy*, *incoherent energy*, *or chaos*.

In economics, the picture on the left represents economic activity, where people are engaging in work—organized, purposeful activity—to produce goods and services. The picture on the right represents cost, wasted effort, inefficiency, or conflict. Policies that encourage people to produce work, or coherent energy, increase output and living standards, suggesting a simple litmus test for policy: does it increase work?

The law of conservation of energy states that energy can be transformed but never created or destroyed. Unfortunately, there is no law of conservation of work. Work can be destroyed by policies that blunt incentives or make it more difficult for people to access and transform energy. Subsidies, tariffs, quotas, price controls, excise taxes, burdensome or unpredictable regulations and taxes reduce work. This suggests a simple principle of taxation: governments should collect revenues in the manner that destroys the least possible work.

Markets facilitate the energy transformations that result in work by distributing information on relative scarcity using symbols we call prices. People respond to price, wage and return differences, or gradients, that signal profitable opportunities to redeploy resources. In flow markets, we call the result supply and demand. In asset markets, we call it portfolio balance. Both represent arbitrage fed by price and return differentials, driven by the second law of thermodynamics.

Economists since the time of David Ricardo have agreed that trade—whether within or between nations—increases aggregate incomes, a measure of total work. But changes in trade also force changes in resource allocation and have important impacts on people's lives. These changes can lead to turbulence, social instability and protectionism.

4. Solar energy drives work

Energy can neither be created nor destroyed but it can be transformed from one form to another. All activity on earth, including economic activity, is the result of transformations of energy from the sun, "that orbed continent, the fire that severs day from night" (Shakespeare, 2008). The second law of thermodynamics states that heat flows in only one direction, from warm to cold bodies. The difference between the 5800 K surface temperature of the sun, and the 280 K temperature of the earth causes energy to flow from the sun to the earth in the form of radiation, the source of work and heat on earth (Fig. 2).

The sun is a thermonuclear reactor that has been converting 5 million tons of hydrogen into helium each second for 5 billion years. Its temperatures vary from 15 million K at its core, to as low as 4000 K in sunspots. The rate of energy delivered to earth by the sun, 1.36 kilowatts (kW) per square meter, is known as the solar constant, although recent measurements show it varies by as much as .2%, four times all human energy

[2] The second law states that energy has a tendency to disperse to a less orderly form, in Clausius's words, "heat cannot by itself pass from a colder to a warmer body" (Kondepude & Prigogine, 1998, 84). The second law was established by Carnot in 1824, Clausius in 1850 and Lord Kelvin in 1851, and applied to chemical reactions by Gibbs in the 1870s. Josiah Gibbs's most famous student was Irving Fisher.

[3] See the work of Georgescu-Roegen (1999), Sornette (2014), and Roehner (2010) as examples of earlier work done linking economics and thermodynamics.

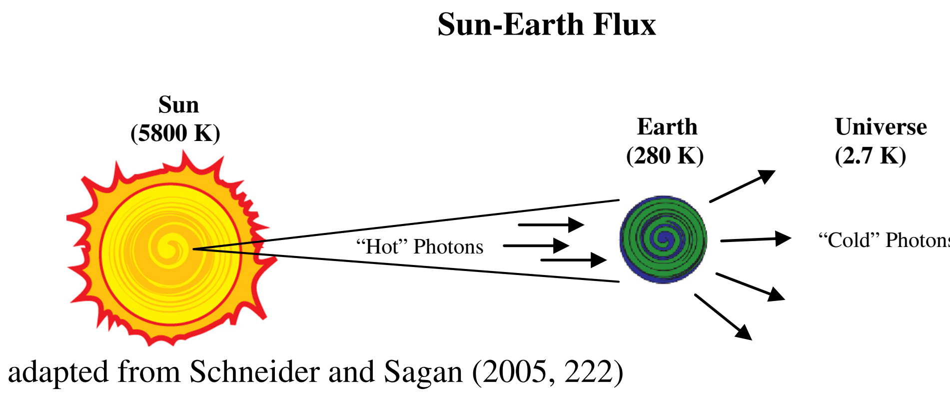

Fig. 2. Sun–Earth flux.
Adapted from Schneider and Sagan (2005, 222).

consumed on earth today.[4] In all, only one billionth of total solar energy falls on the earth, roughly 5 million horsepower per square mile.

About two-thirds of the radiation that enters the earth's atmosphere hits the surface; the remaining third is absorbed by clouds as heat or reflected back into space. In all, only about 1% of the energy that hits the surface is converted through photosynthesis into energy stored in the form of organic molecules. According to Atkins (1994, p. 210) about 10^{18} kJ of solar energy are stored in this way each year, 30 times current global energy consumption.

Through this seemingly wasteful collection process, stored sunlight makes the earth habitable. Sunlight trapped by photosynthesis produces carbohydrates in plants, which provide food for plant-eaters and animal-eaters, including humans (Fig. 3).

We can think of stored solar energy as having a *vintage*, or time subscript, like the year on a wine label, that shows when the solar energy stored in its organic molecules first reached the earth.

Economic activity is the directed transformation and distribution of solar energy to satisfy man's wants. For most of history, hunter-gatherers eked out a subsistence living by harvesting only the most recent vintages of solar energy stored in the form of plants and animals. For hunter-gatherers, the oldest solar vintage available was the wood they used for fuel.

Wood—solar vintage measured in decades—has been man's primary fuel source for almost all of recorded history, only surpassed by coal in the closing decades of the nineteenth century, as shown in Fig. 4. Modern man has learned to reach deep into the wine cellar of vintage sunlight to mine energy stored in the distant past. Sunlight stored in the form of coal reached the earth 350 Ma ago during the Carboniferous Period of the Later Paleozoic Era when vast forests flourished in river deltas (Maiklem, 1998). Coal was succeeded by oil, then by gas, after 1950. Today, fossil fuels provide about 85% of the energy we use.

But fossil fuels are too narrow a definition of energy to account for today's living standards. Their consumption accounts for only a small percentage of GDP in most nations. The bulk of energy used to produce work is stored as human capital (stored food, knowledge, and experience), as technology (stored knowledge), and as tools (stored technology and knowledge), depicted in Fig. 5. All are mechanisms for storing solar energy for a later time when it can be used to produce work.

Wealth represents command over stored energy in all its forms. People use stored energy to produce work valued in markets at prices that reflect relative scarcities. National income is a price-weighted sum of work.

[4] According to Friedman (1986, p. 87), the largest variation on record, a drop of .23%, occurred in July 1981 during a period of intense sunspot activity.

5. Arbitrage and the second law

Stores of energy are not evenly distributed around the globe. Oil and gas are concentrated in the Arabian Gulf; coal in North America, Russia, parts of Europe, and Australia; technology and physical capital in North America, Western Europe, and Japan; human capital in Asia.

If national economies were closed with no trade, then national endowments of stored energy would determine relative prices, which would vary significantly from nation to nation. International trade theory refers to this closed system as *autarky*, illustrated in Fig. 6 as two compartments of a washtub—two closed systems—separated by a solid barrier.

When two *closed systems* are brought into communication to form a single *open system* the second law of thermodynamics forces energy to disperse. In Fig. 7, the pressure differential forces water to flow from the full tank into the empty tank. In economics, we would call this arbitrage. Both represent an open system moving toward its low energy equilibrium state.

In the absence of continuing energy flow into the system, the end result will be *thermal equilibrium* where no further *net* energy flow takes place, as illustrated in Fig. 8. Similarly, in economics, a *market* is defined as an area in which prices tend to converge to a single level. This *law of one price* in economics corresponds to thermal equilibrium.

In today's connected global economy, stored energy imbalances are reflected in price and return differentials that trigger arbitrage where

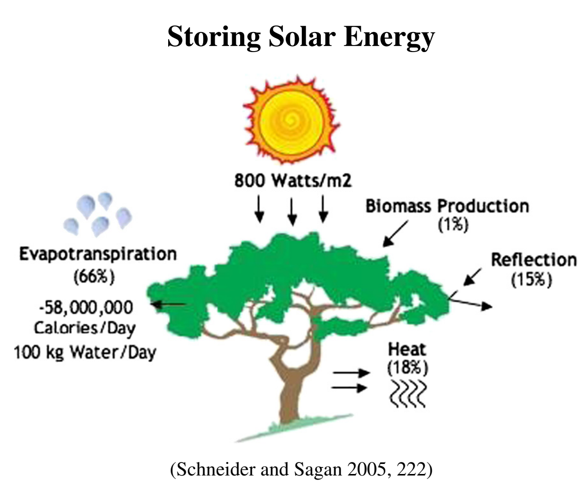

Fig. 3. Storing solar energy.
Adapted from Schneider & Sagan (2005, 222).

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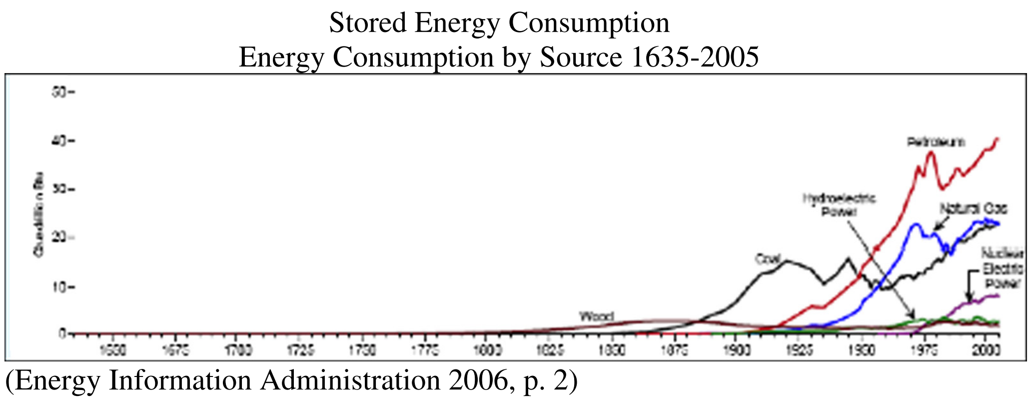

Fig. 4. Stored energy consumption energy consumption by source 1635–2005.
Source: (Information Administration, 2006, p. 2).

people redeploy resources toward areas of greater relative scarcity. This can be viewed in two equivalent ways.

From the point of view of physical capital, capital is relatively abundant in the U.S. and scarce in China and India, as shown in Fig. 9. Returns on capital will be lower in the U.S. than in China and India; the relative price of capital will be higher in China and India than in the U.S. Opening trade—creating holes in the barriers—will communicate incentives for owners of capital to redeploy capital out of the U.S. and into China and India through Foreign Direct Investment (FDI) and Portfolio Investment. Capital redeployment reduces the return differential, forcing returns to converge over time.[5]

From the point of view of human capital people are abundant in China and India relative to the U.S., as in Fig. 10. Opening trade will result in a net flow of human capital from Asia to the U.S. via immigration, outsourcing, and import of goods and services, which will raise wages in China and India relative to wages in the United States.

Economists typically describe trade-driven adjustments of this sort as smooth and gradual. That may have made sense when trade meant loading physical goods and people on ships. It takes weeks to load a ship in Shanghai, sail it to Long Beach, unload the cargo and transport it to warehouses and retail stores; and the largest ships today carry less than 14,000 standard 20-foot containers. Traditional trade adjustment is slow, with price and wage changes and resource redeployments taking place gradually over many years. When countries trade capital and services over optical fiber, however, as they do today change can be sudden and discontinuous, the realm of nonequilibrium thermodynamics.

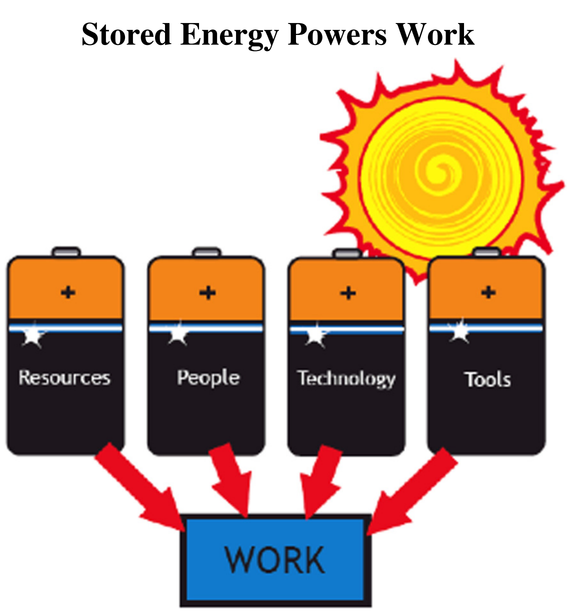

Fig. 5. Stored energy powers work.

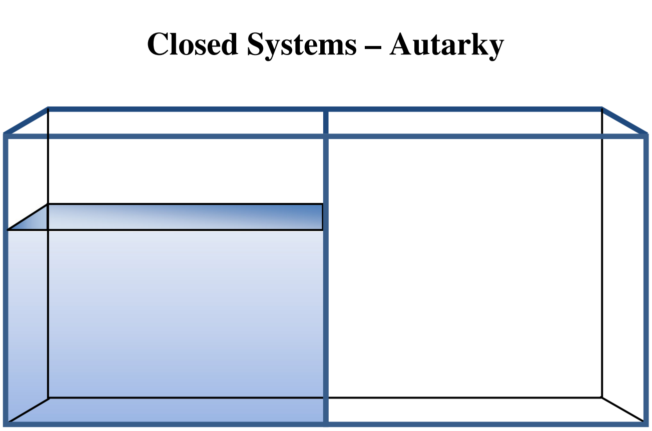

Fig. 6. Closed systems—autarky.

6. Nonequilibrium thermodynamics (NET)

Through most of its history, thermodynamics has focused on studying the properties of systems in. or near equilibrium where adjustments are smooth and gradual. These gradual adjustments are known as *reversible* thermodynamic change. Reversible change takes place when the distance from equilibrium is small—the gradient is relatively flat—and adjustment takes place at slow speeds.

According to Prigogine (1996), researchers who sought to examine the behavior of systems far from equilibrium were shunned in physics and chemistry during the early 20th century, including both Ludwig von Boltzmann and Prigogine's professor at the Free University of Brussels, Theophile de Donder. This is unfortunate, because far from equilibrium is where the interesting thermodynamic behavior takes place.

Prigogine later was awarded the Nobel Prize in chemistry in 1977 for showing that distance from equilibrium is an important and fundamental parameter of nature. As the distance from equilibrium and the corresponding temperature, pressure, or energy gradient increases beyond a

[5] American investors may not see this. Financial statements of U.S. public companies report the profits and returns of companies *listed* in America, not the returns on capital *deployed* in America. A company that redeploys capital from the US to China will see an increase in overall returns. Capital redeployment is one of the major reasons why U.S. companies have been reporting record profits as a percentage of GDP in recent years.

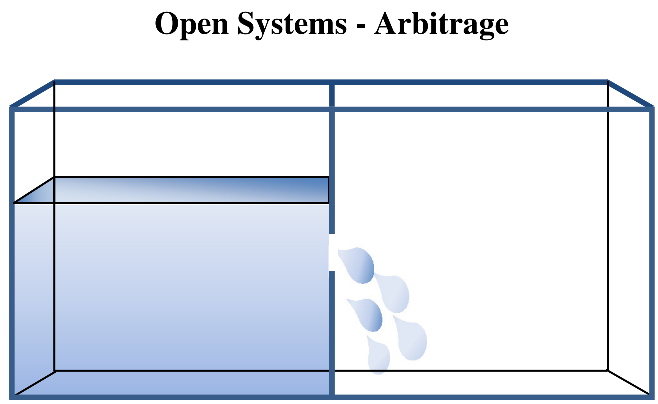

Fig. 7. Open systems—arbitrage.

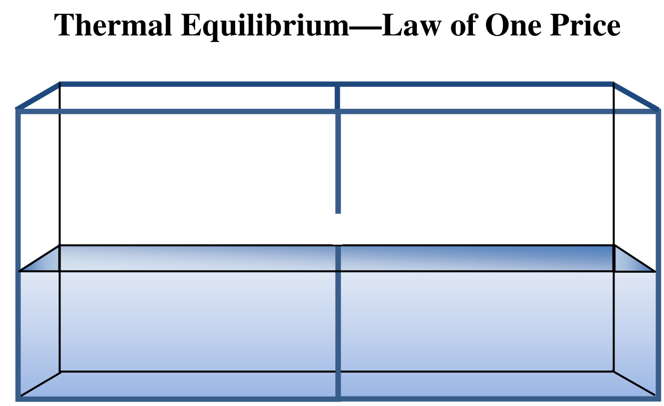

Fig. 8. Thermal equilibrium—law of one price.

certain point, known as the *bifurcation point*, qualitative changes in structure appear leading to abrupt, unpredictable, and discontinuous change. These changes produce new coherent structures that Prigogine called *dissipative systems*[6] These open non-equilibrium thermodynamic systems, also known as complex adaptive systems, maintain their structure by feeding on energy gradients to produce a flow of work and entropy. When distance from equilibrium increases still further beyond a second critical point, randomness forcefully reappears in a regime characterized by erratic behavior in time; the same chaotic, unpredictable behavior that engineers—and airplane pilots—refer to as *turbulence*.

There is a long and storied history linking thermodynamics and modern economics, in part documented in an insightful recent paper by Backhouse (2014). Samuelson (1998) credited E.W. Wilson as his mentor and most important influence in writing *Foundations of Economic Analysis* (1948), arguably the birthplace of modern economics. Wilson, in turn, was one of the two major protégées of Yale's Josiah Gibbs, America's leading thermo-dynamicist. The other was Irving Fisher (1933), whose *The Debt-Deflation Theory of Great Depressions* may represent the earliest description of the dynamics of a complex economic system as it experiences a phase transition into a state of self-reinforcing depression. Joseph Schumpeter, America's other great dynamicist, was the mentor of both Samuelson and Georgescu-Roegen, whose classic work *The Entropy Law and the Economic Process* (1999) helped spark both Ecological Economics and Evolutionary Economics. Samuelson (1999) described Georgescu-Roegen as "…a great mind…one of those who is so far ahead of his time that he fails to get the recognition he deserves".

Much of this early work used the tools of near-equilibrium thermodynamics to describe the dynamics of a system as it approaches equilibrium. This may be because academic economists were discouraged from studying non-equilibrium states, as was the case with Boltzmann and de Dondé in physics and chemistry. More recent work by Prigogine (1996), Bak (1996), Arthur (2013), Foster and Metcalfe (2009), Schweitzer, Fagiolo, Sornette, Vega-Redondo, and White (2009), and others uses the tools of far-from-equilibrium physics to analyze situations of abrupt, discontinuous change. These are the financial crises and depressions in economics that correspond to *phase transitions* in science.

Today's networked global economy is certainly far from equilibrium, as measured by price, income, wage, or return differentials, making nonequilibrium thermodynamics extremely relevant. Nations today are connected by optical fiber that transports vast amounts of resources at the speed of light, as depicted in Fig. 11. This has dramatically increased the ability of economic agents to redeploy resources in response to price and return differentials. The resulting capital flows, outsourcing, cross-border M&A, supply-chain, and restructuring activities have important effects on people's lives in both capital exporting and importing countries, raising important questions of economic and political stability.

7. Turbulence, cascading network failures, and financial crises

Leonhard Euler, the Swiss mathematician and physicist, revolutionized the analysis of fluid dynamics in 1753 when he derived the set of partial differential equations that describe the motion of a zero viscosity fluid (Johnson, 1998), the smooth, *laminar flow* illustrated in Fig. 12(a) (Acheson, 1990 p. 123). Real fluids, however, behave differently. Fig. 12(b) shows the motion of a real fluid with positive but small viscosity past a cylinder. The area immediately downstream from (to the right of) the cylinder is characterized by turbulence.

Osborne Reynolds presented experiments to the Royal Society in 1883 showing that turbulence arises when the rate of flow of a viscous fluid exceeds a critical level. Reynolds marked water flowing through a tube with a streak of visible dye. At very low velocity the flow was smooth, or *laminar*, as shown in Fig. 13(a).

As Reynolds gradually increased the velocity of the flow of fluid through the tube, however, he identified a point where an arbitrarily small further increase in velocity would cause the flow to experience a phase transition from laminar flow to turbulence, the dark mass shown in Fig. 13(b). When lit from behind by a spark, as shown in Fig. 13(c), the dark mass was revealed to be a path of more or less distinct curls. According to Acheson (1990, p. 134), "this sudden transition from laminar flow to turbulence as speed is gradually increased is still one of the deepest problems in classical physics".

The transition from laminar flow to turbulence is well known to engineers. Increases in velocity, sharp changes of direction and obstacles to flow create turbulence, as in Fig. 14.

Just as increasing velocity and sharp changes in direction can produce turbulence in flow of physical fluids, increases in the velocity of trade and capital flows and sharp changes in employment and income can create turbulence in human societies, creating whole new industries and destroying others. Those who have been displaced and those who are simply afraid of change will appeal to the political process for relief. This can lead to global trade war as country after country erects non-market barriers to the smooth flow of trade. Ultimately, these mounting frictions can produce system failure, akin to the blackout of an electricity network.

As Hayek (1945) argued, markets are extraordinarily efficient information networks that use prices to transmit signals on relative wants and scarcities to people who need to make decisions. When markets

[6] This new field of study is variously called chaos theory, complexity, complex adaptive systems, network theory, self-organizing systems, emergence, nonequilibrium thermodynamics, or NET. See the work of Barábasi (2002), Buchanan (2002), Gleick (1987), Holland (1995), Kauffman (1993), Nicolis and Prigogine (1989), Prigogine (1996), Schneider and Sagan (2005), Strogatz (2003), Bak (1996), and Mitchell (2011). The root of them all is Irwin Schrodinger's (1946) *What is Life*? based on three lectures delivered at Trinity College, Dublin in 1943. This book spawned both the discovery of DNA and NET.

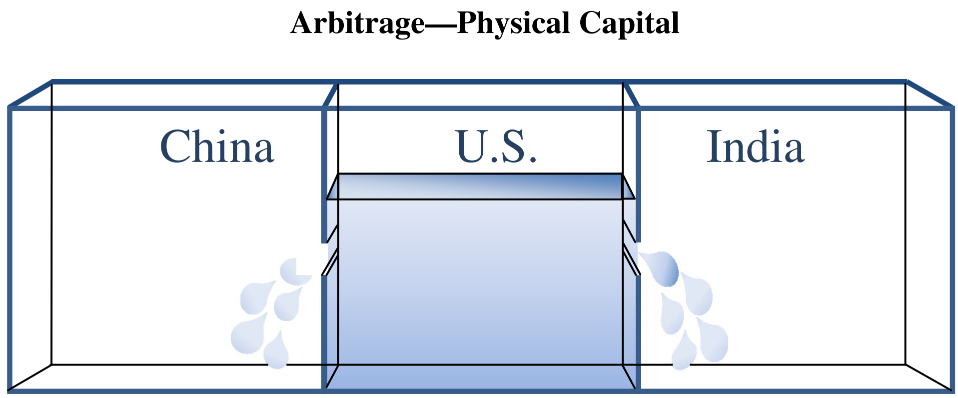

Fig. 9. Arbitrage—physical capital.

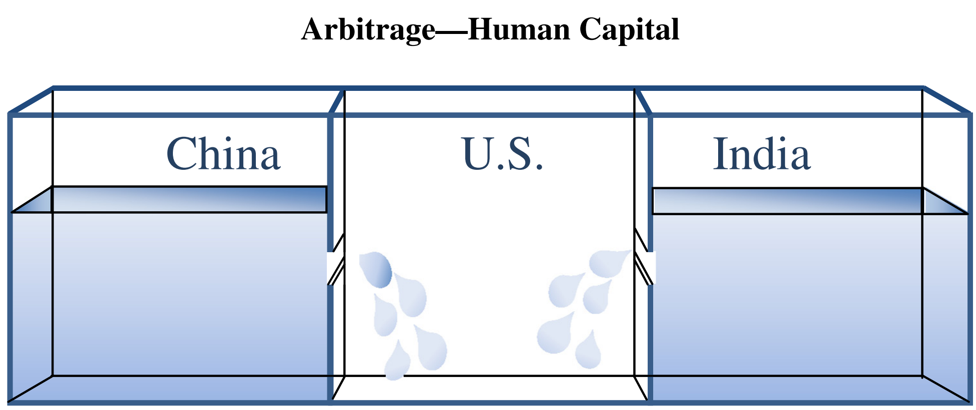

Fig. 10. Arbitrage—human capital.

break down, as they do in financial crises, and prices no longer allocate resources, incomes and net worth suffer. Schneider and Sagan (2005) argue that complex nonequilibrium thermodynamic systems—societies, political systems, ecosystems, and economies—share a universal feature; they regress to earlier, more hierarchical, less complex and less open forms of organization under conditions of environmental stress such as plagues, wars and depressions. This property is known as the *Savonarola Effect*, after the Dominican priest whose sermons against the corrupt Catholic Church incited Florence mobs to burn books and works of art (Bloom, 1997). But turbulence works both ways. Savonarola was, in turn, burned by the church in 1498.

NET has important implications for recessions, asset price bubbles and other temporary market failures. All are system, or network-wide events that, in general, cannot be understood by reductionist analysis of the behavior of representative agents or even sub-groups of market participants. In network theory, financial crises can best be understood as temporary network blackouts, known as cascading network failures.

In the complexity literature, two related approaches are making progress in understanding financial crises. The *network theory* literature views financial crises as cascading network failures where an initial disturbance, say, a bankruptcy, propagates through the economy along the links that connect nodes—financial institutions and their customers—like a forest fire jumping from tree to tree to burn an entire forest.

Network theory views systemic risk of financial crisis and contagion as issues of network architecture and focuses policy discussions on managing system architecture and increasing the fitness of highly-connected nodes. Barábasi (2002) showed that scale-free networks with few highly-connected nodes and many sparsely-connected nodes are highly vulnerable to failure of highly connected nodes. Barabasi (2009) and others showed that many real-world networks display scale-free architecture. Gabaix (2008) showed evidence that scale-free networks, and their distinctive power law statistical signatures, are pervasive in economics and finance. Haldane and May (2011) described financial crises as collapse of the banking ecosystem. Caballero (2010) likened the onset of financial crisis to cardiac arrest.

The closely related *criticality* literature extends the work of Per Bak (1996) who argued that complex systems have a natural tendency to self-organize to a critical state that is highly efficient but prone to unavoidable catastrophic events he refers to as *avalanches*. Examples include avalanches, earthquakes, volcanic eruptions, hurricanes and financial crises. Statistically, avalanche scale, or intensity, is distributed according to a power law with many small events and a few large events. Much research has gone into identifying statistical markers showing that a system is approaching a point of criticality where a

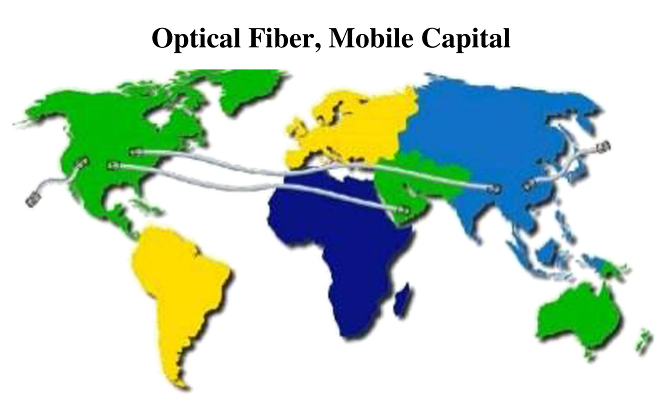

Fig. 11. Optical fiber, mobile capital.

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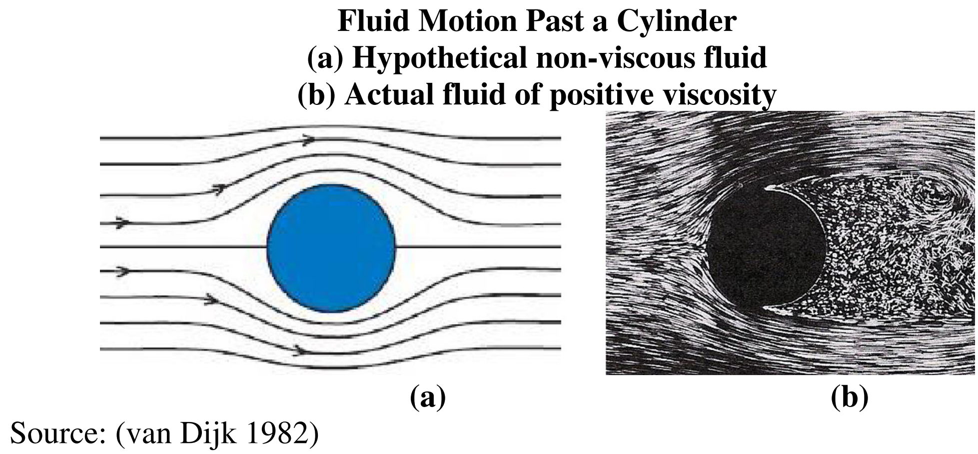

Fig. 12. Fluid motion past a cylinder. (a) Hypothetical non-viscous fluid. (b) Actual fluid of positive viscosity.
Source: (van Dijk, 1982).

phase transition is likely. Markers include increased volatility, increased autocorrelation and a drop in the value of the power law exponent signifying a slowing of adjustment speed and fattening of the tail determining the probability of extreme observations (Dai, Vorselen, Korolev, & Gore, 2012; Kaizoji, 2006; Scheffer et al., 2002; Sornette, 2014; Sugihara, 2013).

The common features of complexity work on financial crises are: 1) viewing the economy and financial system as complex systems and 2) viewing financial crises and other extreme events as phase transitions between distinct states. In another paper, I characterize one state as the general equilibrium state economists associate with full employment, and the second as a less efficient state where credit is allocated by non-price rationing. Once we admit financial crises into our analysis, we must reconsider conclusions based on the assumption of a single equilibrium state (Rutledge, 2014). In particular, the existence of credit crises changes the role of cash in optimal portfolios.

Imagine a multi-period framework in which an investor must choose each how to allocate current wealth between cash and equities for the following period. At the beginning of period 1, the investor knows the economy is in State A, the general equilibrium state. The investor also knows that there is a known probability that the economy will experience a credit crisis—a phase transition from State A to State B, the non-price credit rationing state where the economy will remain for a fixed period before switching back to State A. In State A, cash earns a standard money market return. In State B, credit is in short supply and commands a high opportunity cost, or shadow price.

In deciding how much cash to hold, the investor will view cash as a composite security giving the investor a money market return this period plus an embedded real option to choose between a cash return and an equity return the following period.[7] If markets turn out to be a credit crisis state in the following period, the investor will have the option to keep the scarce cash and earn a correspondingly high shadow-price return or use the cash to buy stock at depressed, credit crisis prices and enjoy a high return when the economy switches back to the equilibrium state and prices return to normal.[8] The value of this option should depend on the probabilities of switching between the equilibrium state and the non-price rationing state, the likely time interval between phase transitions, the expected cash return in each state, the likely size of the drop and subsequent recovery in stock prices, and a discount rate.

As an illustration, in the hypothetical case where there is a 70% chance the economy will find itself in the general equilibrium State A in which cash earns a 2% money market yield at the end of next period and a 30% chance it will find itself in non-price credit rationing State B in which the shadow price of cash is 20% per year. Under these conditions, the investor can calculate that the expected return on cash for the following period is 7.4%, which can be viewed as a riskless security paying 2% interest in either state plus an option to own a security paying the shadow price of 20%, in the event the economy finds itself in State B. In this case, the value of the option expressed as a return would be 5.4% per year. It should be apparent that optimal portfolios in such two-state worlds will contain more cash and less equities than standard textbook models, a question I have examined in another paper (Rutledge, 2014).

This world of multiple states and phase transitions also has interesting implications for option pricing models. Standard models use the assumption of a fixed risk-free rate to calculate the level of volatility implied by current options prices. In the two-state world described above, there is no fixed risk-free rate and the expected return on cash is much higher than its coupon yield. Inserting this value into option pricing models would result in higher estimates of implied volatility than the result of standard models.[9]

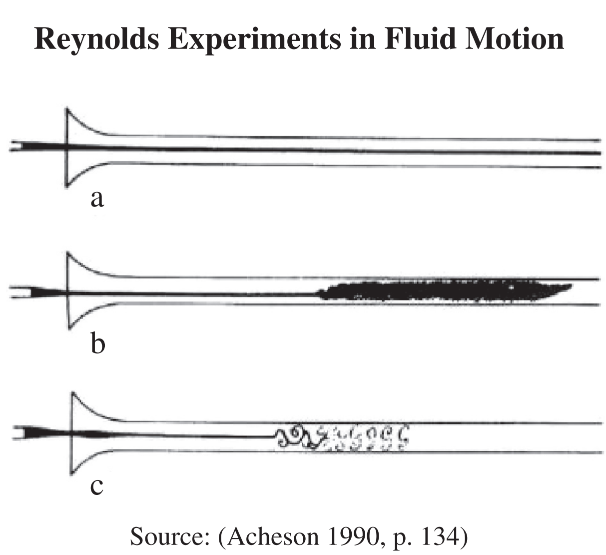

Fig. 13. Reynolds experiments in fluid motion.
Source: (Acheson, 1990, p. 134).

[7] See (Dixit & Pindyck, 1994) or (Trigeorgis, 1996) for a classic introductions to real option theory.

[8] In the non-price rationing state, expected returns on cash and equities should satisfy a no-arbitrage condition, just as they do in the equilibrium state, but at much higher returns.

[9] Indeed, in such cases, one could use simple but reasonable assumptions about expected volatility to calculate an implied risk-free rate, research that is underway now at Claremont Graduate University (Kownatzki, 2014).

Laminar Flow (a) and Turbulence (b)

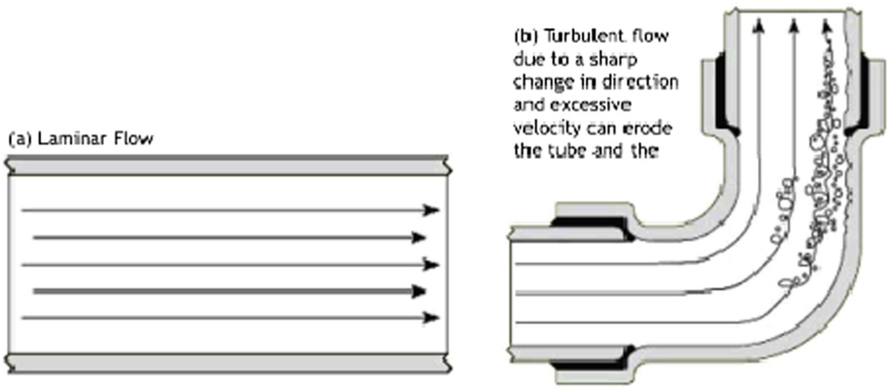

Fig. 14. Laminar flow (a) and turbulence (b).
Source: http://www.coppercanada.ca/publications/is-97-02-publication-e.html. (Downloaded July 9, 2007).

8. Conclusions and future research

The energy framework presented in this article gives us a new way to look at economic issues. When the economy is at or near price-clearing equilibrium it behaves in a way that is consistent with the conclusions of general equilibrium models. When the economy finds itself in the general equilibrium state it will tend to remain so, and when the economy is near equilibrium (perhaps following a modest shock) the forces of arbitrage—the second law—will drive the economy back to equilibrium in an orderly manner.

When the economy is far from equilibrium, however, perhaps due to a cascading network failure of the banking system, the energy framework leads to dramatically different predictions. The phase transition from general equilibrium to the credit crisis state can be violent, as we learned in 2008. An economy that finds itself in this inefficient credit-crisis state can remain in the new state for a considerable length of time before it experiences the reverse phase transition which can also produce extreme change. And changes of state can produce entirely new structures—laws, institutions, political alliances—that may be permanent. For this reason, economies that go through abrupt phase transitions in and out of crisis may end up considerably different that they started.

Here are a few of the items on my research agenda for the energy framework.

1. We need to model the properties of the economy in the nonequilibrium state and keep both states in mind when doing economic analysis.
2. We need to understand the nature of the phase transitions from equilibrium to nonequilibrium and back again. There is no presumption in NET that they should be symmetric.
3. We need to examine previous financial crises to look for statistical markers of criticality in the period leading up to the crisis and statistical markers signaling the phase transition back to equilibrium.
4. We need to examine policies that can make the financial network less vulnerable to cascading failure, make phase transitions less violent, and shorten the time the economy spends in the nonequilibrium state.
5. We need to re-examine the accepted propositions of equilibrium theory to ask if they still hold in a world with periodic financial crises. For example, do Taylor Rules only apply to the equilibrium state? Is there a way to re-state them so they embrace both states?
6. We need to revisit the welfare propositions of equilibrium analysis—gains from trade, costs of inflation, costs of unemployment, welfare properties of different exchange rate regimes—in light of phase transitions.
7. We should re-examine results derived from no-arbitrage conditions to ask if they apply in a two-state world with phase transitions. For example, if cash embodies option value as I suggested above, should we include the option value in the risk-free rate we use in options?

My hope is that the ideas in this paper help people think in new and productive ways.

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Please cite this article as: Rutledge, J., Economics as energy framework: Complexity, turbulence, financial crises, and protectionism, *Review of Financial Economics* (2015), http://dx.doi.org/10.1016/j.rfe.2015.02.003