Economic and biological evolution:
A non-equilibrium thermodynamic theory

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Abstract

Economic and biological systems, as open dissipative systems, need to extract low entropy from the environment to compensate for continuous dissipation. This process can be represented by lognormal processes, which in turn can be mapped into a thermodynamic equation. From here, we develop an analytic thermodynamic theory of economics. Since a thermodynamic equation is of first order in temporal dimension, economic and biological systems as thermodynamic systems are intrinsically evolutionary. Most people agree that thermodynamic theory is a sounder foundation to describe living systems than Newtonian mechanics, which is the physical foundation of general equilibrium theory. As it is often the case, an analytical framework that is built on sounder physical foundation delivers more intuitive and simpler results. This theory, for the first time in economic literature, provides an analytic framework that explicitly represents the relation among fixed costs, variable costs, uncertainty of the environment and duration of a project, which is the core concern in most economic decisions. Since all economic and biological activities represent the extraction and transformation of low entropy from the environment, this analytic thermodynamic theory offers a unified framework to understand the general pattern in economic and biological evolution.

Keywords: analytical framework; thermodynamic foundation of economics; variable costs; fixed costs; tradeoff between competitiveness and flexibility; non-equilibrium

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1. Introduction

After the works of Schrodinger (1944), Wiener (1948), Shannon (1948) and others in the 1940s, there is a consensus that life process in general and human activities in particular are thermodynamic processes. Since economic activities are thermodynamic processes instead of mechanical processes, one will expect economic theories will be built on the theory of thermodynamics instead of rational mechanics, which is the physical foundation of general equilibrium theory. However, the theory of thermodynamics only has limited impact on economic theory as no analytical thermodynamic theory of economics has been established. Since Georgescu-Roegen (1971) outlined his vision of the thermodynamic foundation of economics about thirty years ago, the works along this line remain qualitative. The lack of an analytical paradigm prevented the thermodynamic theory to offer a detailed and quantitative analysis to concrete economic and business problems. Recently, Chen (2000) developed an analytical framework of thermodynamic foundation of economics based on option theory. In this work, we will derive the foundations of economics from the thermodynamic theory directly.

Economic and biological systems need to extract low entropy from the environment to compensate for continuous dissipation. (Schrodinger, 1944; Georgescu-Roegen, 1971; Prigogine, 1980) This process can be represented by lognormal processes, which contain a growth term and a dissipation term. The lognormal processes in turn can be mapped into a thermodynamic equation. From the entropy law, the thermodynamic diffusion of an organic or economic system is spontaneous. The extraction of low entropy from the environment, however, depends on specific biological or institutional structures that incur fixed or maintenance costs. In this work, we solve the thermodynamic equation to derive, for the first time in economic literature, an analytic formula that explicitly represents the relation among fixed costs, variable costs, uncertainty of the environment and the duration of a project, which is the core concern in most economic decisions. This analytical representation of various factors in production processes greatly simplified the understanding of economic activities. Since a thermodynamic equation is of first order in temporal dimension, economic and biological systems as thermodynamic systems are intrinsically evolutionary.

From this framework, it can be derived that as fixed costs increase, variable costs decrease rapidly in a low volatility environment and decrease slowly in a high volatility environment. This result explains a general pattern in biological and economic evolution. Take industry development as an example. When a new industry emerges, the degree of uncertainty is high. Small companies, as low fixed cost systems, flourish for they are more flexible. As an industry matures, the degree of uncertainty becomes low. In a low uncertainty environment, variable costs decrease rapidly as fixed costs are increased. Large companies, as higher fixed cost systems, therefore enjoy competitive advantages over lower fixed cost systems. In general, high fixed cost systems tend to dominate mature structures. We generally associate the change from low fixed cost systems to high fixed cost systems as a sign of progress.

However, successful high fixed cost systems have certain characteristics that make them inherently unstable. First, higher fixed cost systems require more resources to sustain themselves. (Daly, 1991) This makes high fixed cost system more vulnerable to resource depletion. In human history, most highly developed societies eventually collapsed because of that. Second, higher concentration of wealth or low entropy of a system will increase the incentive for other systems to extract wealth from it. This will increase the uncertainty of the system. (North, 1981; Weitzman, 2000) Third, internal coordination in higher fixed cost systems is more complex and difficult than in lower fixed cost systems, which makes it difficult for higher fixed cost systems to adjust to a changing environment. More than eighty years ago, Keynes acutely observed:

> "Very few of us realise with conviction the intensely unusual, unstable, complicated, unreliable, temporary nature of the economic organisation by which Western Europe has lived for the last half century. We assume some of the most peculiar and temporary of our late advantages as natural, permanent, and to be depended on, and we lay our plans accordingly. On this sandy and false foundation we scheme for social improvement and dress our political platforms, pursue our animosities and particular ambitions, and feel ourselves

> with enough margin in hand to foster, not assuage, civil conflict in the European family." (Keynes, 1920, p. 1)

In general, any economic or biological system, as a dissipative system, is only metastable instead of absolutely stable. Its survival and growth depend crucially on its institutional or biological structure, which may or may not be able to adapt to the changing environment in the course of time. The main theme of economic and biological evolution is the tradeoff between competitiveness of high fixed cost systems in a stable environment and flexibility of low fixed cost systems in a volatile environment. Since there is no dominant strategy in all environments, the beautiful and diverse ecological system does not reach an equilibrium state, even after four billion years of biological evolution. For the same reason, economic organizations and systems will not converge to an equilibrium state.

Since all economic activities represent the extraction and transformation of low entropy for use by human societies, the thermodynamic theory provides a unified framework. For example, since information is a reduction of entropy and information processes are thermodynamic processes (Shannon, 1948; Bennett, 1988), the information economy or the new economy can be easily understood in light of this thermodynamic framework. Indeed, the most striking feature of this theory is its extreme simplicity. This is because the economic activities, which are thermodynamic processes, are directly modeled with analytical thermodynamic theories.

How is this analytical thermodynamic theory related to other branches in economics? This analytical theory directly models the extraction of low entropy natural resources and the diffusion of high entropy environmental waste. It provides an analytical framework for ecological and environmental economics. From the second law of thermodynamics, it is far easier for a system to disintegrate than to maintain its structure. Only certain institutional structures, which developed effective ways to extract low entropy from the environment, can compensate the universal tendency of increasing disorder. Therefore the problems of institutions and industrial organizations naturally emerge as the central issue in the thermodynamic theory.

The paper is organized as follows. Section 2 develops the basic theory. From the thermodynamic equation that represent the fundamental life processes and economic processes, we derive the analytical formula that explicitly represents the relation among fixed costs, variable costs, uncertainty of the environment and the duration of a project. This representation offers a simple framework to analyze the performance of various production modes in different environments. In Section 3 we apply the theory to problems of different time scales to demonstrate the generality of this analytical thermodynamic framework. First the theory is applied to understand the product life cycle. It is then extended to analyze the rise and fall of various institutional structures throughout human history. To gain deeper insights into the evolution of human societies, we proceed to investigate the general patterns in biological evolution since biological data contain much richer samples over much longer time periods than data on the human species. The statistical results show that the fast evolving and highly specialized species, which are often more efficient and tend to dominate ecological systems, are more prone to extinction than the slow evolving and unspecialized species, which are less efficient, less competitive but more flexible. Section 4 concludes.

2. Basic theory

All biological systems, human or non-human, need to extract low entropy from the environment to compensate for continuous dissipation. In human societies, most human activities are measured by economic value. Recently, Chen (2002) developed an entropy theory of value, which identifies economic value as the reduction of entropy mathematically and explains the relation between economic value and physical entropy. This entropy theory of value is very similar to information theory developed by Shannon (1948), which identifies information as the reduction of entropy.

Suppose S is the amount of low entropy of a biological system, r, the rate of extracting low entropy from the environment and σ, the rate of diffusion of the low entropy into the environment. Similarly in an economic system, S represents economic value, r, the rate of return and σ, the rate of uncertainty. Then the process of S can be represented by the lognormal process

$$\frac{dS}{S} = r\,dt + \sigma dz \,. \tag{1}$$

Solving (1) for S yields

$$S = S_0 e^{(r-\frac{1}{2}\sigma^2)t+\sigma z_t}, \tag{2}$$

in which S_0 is the initial value of S. From (2), the average growth rate of S is

$$r - \frac{1}{2}\sigma^2. \tag{3}$$

This shows that economic growth depends on the expansion of natural resources and the reduction of diffusion of low entropy. The utilization of energy and machinery represents the increase of r. Legal codes, cultures and the advance of information technology represents the decrease of σ. They play different roles in determining the rate of return.

A production system is parallel to a biological system. A firm, which has blueprint to produce a product, such as cars, is similar to a biological entity, which has genes to produce offspring. The production of a good involves fixed cost, K, and variable cost, C, which are functions of the S, the value of the product. If the discount rate of a firm is q, from Feymann-Kac formula, (Karlin and Taylor, 1981; Øksendal, 1998) the variable cost, as a function of S, satisfies the following equation

$$\frac{\partial C}{\partial t} = rS\frac{\partial C}{\partial S} + \frac{1}{2}\sigma^2 S^2 \frac{\partial^2 C}{\partial S^2} - qC \tag{4}$$

To solve for variable cost from this equation, we need to determine the initial condition for variable cost at the time zero. Suppose the duration of a fixed asset is T. When the duration of fixed cost is infinitesimal small and have only enough time to produce one piece of product, the relation between variable cost, fixed cost and the value of the product should satisfy the following.

If the fixed cost is lower than the value of the product, the variable cost should be the difference between the value of the product and the fixed cost to avoid arbitrage opportunity. If the fixed cost is higher than the value of the product, there should be no extra variable cost needed for this product. Mathematically, the initial condition for variable cost is the following

$$C(S,0) = \max(S - K,0) \tag{5}$$

where S is the value of the product and K is the fixed cost. Solving the equation (4) with the initial condition (5) yields the following solution

$$C = Se^{(r-q)T} N(d_1) - Ke^{-qT} N(d_2) \tag{6}$$

where

$$d_1 = \frac{\ln(S/K) + (r + \sigma^2/2)T}{\sigma\sqrt{T}}$$
$$d_2 = \frac{\ln(S/K) + (r - \sigma^2/2)T}{\sigma\sqrt{T}} = d_1 - \sigma\sqrt{T}$$

The function $N(x)$ is the cumulative probability distribution function for a standardized normal random variable. When the discount rate is equal to the rate of return, formula (6) takes the same form as the well-known Black-Scholes (1973) formula for European call options

$$C = SN(d_1) - Ke^{-rT} N(d_2) \tag{7}$$

This is easy to understand. Both equation (4) and the Black-Scholes equation are derived from lognormal processes. Equation (4) solves a forward problem with an initial condition and Black-Scholes equation solves a backward problem with an end condition. The similarity between equation (4) and the Black-Scholes equation is the basis for an early version of this theory. (Chen, 2000) It also explains why the real option approach becomes so important in understanding project finance and other economic problems. (Brennan and Schwartz, 1985; McDonald and Siegel, 1985; Dixit and

Pindyck,1994)

This theory, for the first time in economic literature, provides an analytic theory that explicitly represents the relation among fixed costs, variable costs, uncertainty of the environment and the duration of a project, which is the core concern in most economic decisions. “The progress of science is marked by the transformation of the qualitative into the quantitative. In this way not only do notions become turned into theories and lay themselves open to precise investigation, but the logical development of the notion becomes, in a sense, automated. Once a notion has been assembled mathematically, then its implications can be teased out in a rational, systematic way.” (Atkins, 1994, p. 29)

A new theory is ultimately justified by its implications. We will look at the properties and implications of this theory. For simplicity, we will only explore the special case when the discount rate is equal to the rate of return, that is, formula (7). Several properties can be derived from (7). First, when the fixed cost investment, K, is higher, the variable cost, C, is lower. Second, for the same amount of fixed investment, when the duration, T, is longer, the variable cost is higher. Third, when uncertainty, σ, is higher, the variable cost increases. Fourth, when the fixed cost approaches zero, the variable cost will approach to the value of the product. Fifth, when the value of the product approaches zero, the variable cost will approach zero as well. All these properties are consistent with our intuitive understanding with production processes.

The variable cost of a production mode is an increasing function of volatility. As fixed costs are increased, variable costs, calculated from (7), decrease rapidly in a low volatility environment and decreases slowly in a high volatility environment. (Figure 1) In the extreme environment when the volatility reaches infinity, the variable cost is equal to the value of the product, regardless of the level of the fixed cost investment. In this environment, the value of any fixed asset is zero. For example, the elaborate institutional structures of the Roman Empire, which were once of great value, became worthless during the empire’s chaotic collapse. In general, the value of any physical capital, institutional capital and human capital depends highly on the environment.

The above result explains a general pattern in biological and economic evolution. Take industry development as an example. When a new industry emerges, the degree of uncertainty is high. Small companies, as low fixed cost systems, flourish for they are more flexible. As an industry matures, the degree of uncertainty becomes low. In a low uncertainty environment, variable costs decrease rapidly as fixed costs are increased. Large companies, as higher fixed cost systems, therefore enjoy competitive advantages over lower fixed cost systems. However, large companies are less flexible when big environmental change occurs. As we will demonstrate in next section, the tradeoff between competitiveness of high fixed cost systems in a stable environment and flexibility of low fixed cost systems in a volatile environment is the main theme of economic and biological evolution.

Next we will discuss how firms determine investment level with respect to the market size. For simplicity, the initial value of a product, S, is normalized to be one. K is the fixed cost of production and $C(K, \sigma)$ is the variable cost. A producer with the fixed cost of K, who makes Q units of output, has total cost of

$$C(K,\sigma)Q + K. \tag{8}$$

The return that this producer earns is

$$\ln\left(\frac{Q}{C(K,\sigma)Q + K}\right) = -\ln\left(C(K,\sigma C + \frac{K}{Q}\right) \tag{9}$$

Figure 2 is the graphic representation of (9) for different levels of fixed costs. Several properties can be observed from Figure 2. First, the higher the fixed cost, the more a system needs to produce in order to break even. So the level of the fixed asset investment is limited by the size of the market. When small groups of people from a technological advanced society migrated to a small and isolated island, the advanced technologies were often abandoned because of high maintenance cost. (Diamond, 1997, p. 258) Second, the higher fixed cost systems have lower variable costs and hence benefit more from increasing return, which is often considered as the main reason for the non-equilibrium nature of economic activities. (Kaldor, 1972)

3. Applications

In this section, we apply the theory to problems of different time scales to demonstrate the generality of the analytical thermodynamic theory developed in the last section. First the framework is applied to analyze the temporal pattern of product development, or product life cycles. When an industry is new, there is a lot of uncertainty about the future development. It offers opportunities for the small companies with low fixed cost as they are more flexible. Since the uncertainty is high, the increase of fixed cost will not reduce the variable cost very much. (Figure 1) The economy of scale is not significant, which permits many companies to compete. When an industry becomes mature and uncertainty decreases, the increase in K, the capital investment and accumulated human capital, drives down variable costs rapidly, which permits leading companies to lower the product prices to drive out small high variable cost companies. So, in a mature industry only very few big companies can stay in business. In fact, without the anti-trust legislation, many industries with high capital intensity, or high fixed assets would probably end with monopolies or regional monopolies. (Acs and Audretsch, 1988; Klepper,1996, Mazzucato, 2000)

However, these highly competitive large companies will face problems that make them vulnerable to environmental changes. First, large companies often have high fixed costs, which are difficult to trim even when the market demand for their products is low. Second, the high concentration of wealth in the large companies often attracts litigation and other attempts to extract wealth from them. So large companies often incur high legal costs and are cautious in pursuing new opportunities. Third, internal coordination in large companies is much more complex and difficult than in small companies. While it is relatively easy to accommodate innovative ideas by adjusting firm structures in simple and small companies, innovation is often very disruptive to a highly coordinated and efficient complex structure. Large companies often develop highly optimized structures to reduce uncertainty and bring down the variable costs in producing particular products. This however often stifles the innovative spirit inside the companies and makes it difficult for them to adjust to the changing environment.

In general, large companies, which have invested a great amount on an existing technology, may be unwilling to switch to a new and potentially better technology. This opened opportunities for new and small companies when new industries emerge. For example, the champions of IT revolution, such as Microsoft, Intel, CISCO, Oracle, AOL, are all relatively new companies.

Next, we will apply the analytical thermodynamic theory to understand the history of economic developments. Among all economic activities, the application of violence often offers highest returns. So the military industry was developed very early and like most other industries without anti-trust constraints, achieved regional monopolies in most places. Each unit of the monopoly on violence is a state. The monopoly on violence provides a more stable social environment than the free market of violence. (Diamond, 1997) So the existence of a state is essential for economic growth. Since all economic activities are ultimately regulated by the states, the history of economic development is largely shaped by the evolution of the structures of the states, which in turn is largely shaped by the development of military organizations and military technologies. (North, 1981) Since states hold the monopoly on violence, the subjects of most states during most of human history live barely above subsistence level. However, the competition among states favors those which evolve well defined property rights and social structures that enable them to build up human and physical capital and to reduce uncertainty in exchanges. These states enjoy lower variable costs in various economic activities. They tend to expand continuously to achieve even greater economies of scale and accumulate great wealth in the process. However, most of these wealthy states eventually collapse for the following reasons:

First, wealthy states consume more resources or low entropy. (Daly, 1991) The economic development is largely determined by the amount of low entropy that human beings can extract from the environment. The agricultural revolution is a transformation from passively collecting low entropy in nature to actively managing the extraction of low entropy from the sun through certain highly efficient plants. The industrial revolution is a transformation from collecting low entropy from living organisms to the development of technologies that systematically utilize the deposits of biological low entropy, like petroleum and coal. Biological low entropy that is deposited over hundreds of millions of years is transformed for the use by human societies over several hundreds of years. This is the foundation of the economic prosperity in the last several centuries. Many believe that the ultimate natural resources are practically infinite. Although that could be true, there is no logical certainty that a scientific breakthrough will always be in time to provide new ways to utilize resources when the prevailing ways to do so could no longer sustain the existing social structures and life styles. Historical evidence shows that most highly developed societies collapsed before they could find new ways to utilize resources. In most sites of early civilizations, the once rich and productive areas have been turned into desolate regions through over exploitation. (Tainter, 1988; Ponting, 1991)

Second, the successful accumulation of wealth is built on property rights of exclusion. The accumulation of wealth is naturally accompanied by increased inequality. The high concentration of wealth by only a small number of people increases the incentives for others to extract wealth from them. Most wealthy states evolve into welfare states to reduce this incentive. Welfare, however, is a dilution of property rights and discourages economic growth. Externally, as the wealth of a state accumulates, it becomes more and more profitable for other states to extract wealth from it. "As a result, the prospering economy faces ever-growing costs of either bribing the invaders or making increased military expenditures." (North, 1981, p. 115) The decline of the Roman Empire offers a classical example. "Not only were larger and larger payments in gold made to barbarian groups to bribe them not to invade, but the expenses of the legions rose.... At the same time, Rome was feeding 120,000 of its citizens free." (North, 1981, p. 122)

Third, the accumulation of wealth is mainly the accumulation of human capital through specialization of knowledge. While specialization increases the depth of knowledge of a person, it also reduces the breadth of knowledge and makes one less able to determine the value of others' work, which increases uncertainty in exchanges and hence increases the transaction costs. (Barzel, 1982; Wallis and North, 1986) Highly complex formal and informal constraints are developed to reduce uncertainty and transaction costs. (North, 1990) But the constraints often restrict the path of future development of the system as well and make it less responsive to changes in the environment. (David, 1985; Arthur, 1989) In a planned economy, the prices of most commodities are fixed, which greatly reduces price uncertainties and transaction costs. The Soviet Union built up a high capital base and a stable social environment with a planned economy and achieved great economic progress over a very short period of time. However the rigidity of the system made it difficult to transform itself smoothly when the Soviet economy stagnated. Although the shock therapy was able to break down the functioning of the old system, it could not provide the huge resources needed to build up the infrastructures for the smooth functioning of the market economy. (Chang, 2000)

Human history shows that a social system becomes more and more sensitive to uncertainties when the level of fixed costs or living standard increases. In the end, any change of environment or exhaustion of natural resources will spark the inevitable decline of the old system, which is often accompanied by the rise of simpler structured and lower fixed costs systems on the periphery. (Colinvaux, 1980; Tainter, 1988)

All living organisms are characterized by the struggle to extract low entropy from the environment. Since biological data contain much richer samples over much longer time horizon than data on the human species, we will investigate the general patterns in biological evolution in order to gain deeper insights into the evolution of human societies.

The pattern of biological evolution is very similar to the pattern of the product life cycle. Biological species are sometimes classified, according to the relative level of fixed and variable costs, into two categories, the *r*-strategists and the *K*-strategists. The fixed costs are low for the *r*-strategists. They are usually of small size, produce abundant offspring and invest very little in each one. They are the species that prosper in a volatile environment for low fixed costs make them flexible. But they cannot compete well with other species in a stable environment for their marginal costs are high. In contrast, the fixed costs are high for the *K*-strategists. They are usually large in size, produce fewer offspring but invest much more in each one. They are the conservative species that are able to out-compete the *r*-strategists in stable environments, for their marginal costs are low. But they cannot adjust quickly when the environment changes. Between the extreme *r*-strategists such as bacteria and the extreme *K*-strategists such as elephants, there lies the *r* and *K* continuum (MacArthur and Wilson, 1967; Becker, 1993; Holling, 1994)

The usually stable environment may experience sudden changes from time to time, such as a huge asteroid hitting the earth or the quick emergence of a dominant species, such as human beings. During short periods of volatile change, the large size *K*-strategy species are more prone to extinction since it is more difficult for the high fixed cost systems to adjust to the changing environment. Specifically there are three reasons. First, large species need more resources to survive and are often more severely affected by the changes in the environment. (Gould, 1996) Second, large species often contain big concentration of low entropy and become the prime targets of other species. The improvement of the hunting skills of human beings quickly leads to the extinction of most large mammal species. Third, large species usually have more complex structures than small species, which make it more difficult for the large species to develop variations that are well coordinated internally. So large species usually have much lower genetic diversity than small species. For example, two species of fruit flies may only have about 25 percent of their DNA sequences in common while humans and chimpanzees have over 98 percent in common, even though they belong to different genera. (Stebbins, 1982) There are more than five hundred species of fruit flies in Hawaii. (Stebbins, 1982) But there is only on species in the genus *Homo*. The ultimate genetic diversity comes from microbes. (Margulis, 1998) This lack of genetic diversity among large species makes them much more vulnerable to sudden environmental changes. The mass extinction of species, especially the dominant species, during periods of volatile environmental changes, clears the ground for a new round of evolutionary competition. During long periods of relative stability, the small size and less specialized *r*-strategy species tend to branch into new species that are larger or more specialized, which incur higher fixed costs but are more efficient with lower marginal costs. The species that are larger or more specialized hence have a competitive advantage in a stable environment and gradually dominate the ecosystem. (Brown and Maurer, 1986; Colinvaux, 1986; Gould and Eldredge, 1993) Cope (1896) summarized the pattern of evolution more than a hundred years ago.

> "The 'Doctrine of the Unspecialized' ... describes the fact that the highly developed, or specialized types of one geological period have not been the parents of the types of succeeding periods, but that the descent has been derived from the less specialized of preceding ages. ... The validity of this law is due to the fact that the specialized types of all periods have been generally incapable of adaptation to the changed conditions which characterized the advent of new periods. ... Such changes have been often especially severe in their effects on species of large size, which required food in great quantities. ... Animals of omnivorous food-habits would survive where those which required special foods would die. Species of small size would survive

> a scarcity of food, while large ones would perish. … An extreme specialization … has been, like an overperfection of structure, unfavorable to survival. In general, then, it has been the 'golden mean' of character which has presented the most favorable condition of survival, in the long run. " (Cope, 1896, p. 173-174)

Simpson (1944) was the first biologist to apply careful statistical methods for interpreting the pattern of evolution. (Stebbins, 1982) He summarized the findings as the following:

> "Liability to extinction tends to be directly proportional to rate of evolution. Bradytelic (*slow evolving*) lines are almost immortal. The majority of tachytelic (*fast evolving*) lines quickly become extinct and those that survive cease to be tachytelic (*fast evolving*). ...When related phyla die out in the order of their rates of evolution or in the reverse order of their times of origin, it follows that this order is also usually that of degrees of specialization and that more specialized phyla tend to become extinct before less specialized. This phenomenon is also far from universal, but it is so common that it does deserve recognition as a rule or principle in evolutionary studies: the rule of the survival of the relatively unspecialized." (p. 143)

The statistical results show that the fast evolving and highly specialized species, which are often more efficient and tend to dominate ecological systems, are more prone to extinction than the slow evolving and unspecialized species, which are less efficient, less competitive but more flexible.

Our analysis shows that the main theme of economic and biological evolution is the tradeoff between competitiveness of high fixed cost systems in a stable environment and flexibility of low fixed cost systems in a volatile environment. Since there is no dominant strategy in all environments, the beautiful and diverse ecological system does not reach an equilibrium state, even after four billion years of biological evolution. For the same reason, economic organizations and systems will not converge to an equilibrium state.

The tradeoff of performance of the organic systems ultimately rests on the tradeoff of performance of the inorganic systems, which Wiener observed more than fifty years ago:

> "While the prediction apparatus which we had at first designed could be made to anticipate an extremely smooth curve to any desired degree of approximation, this refinement of behavior was always attained at the cost of an increasing sensitivity. The better the apparatus was for smooth waves, the more it would be set into oscillation by small departures from smoothness, and the longer it would be before such oscillations would die out. Thus the good prediction of a smooth wave seemed to require a more delicate and sensitive apparatus than the best possible prediction of a rough curve, and the choice of the particular apparatus to be used in a specific case was dependent on the statistical nature of the phenomenon to be predicted." (Wiener, 1948, p. 9)

Wiener believed that the problems "centered not around the technique of electrical engineering but around the much more fundamental notion of the message, whether this should be transmitted by electrical, mechanical, or nervous means" and thought they had something in common with Heisenberg's Principle of Uncertainty, which itself is a tradeoff between two factors.

4. Concluding Comments

Many early economists held evolutionary views about economic development. However, economics was transformed into an analytical theory while Newtonian mechanics had dominant influence. (Boulding, 1981) Once the general equilibrium framework is established, most researchers will work inside this paradigm (or a systematic collection of fixed assets in the subject) for it greatly reduces the marginal costs in pursuing new research works. (Khun, 1970) In general science, however, there is a consensus that life processes are thermodynamic processes for the past half century. In this work, we derive an analytical thermodynamic theory directly from the fundamental observation that all living systems need to extract low entropy from the environment to compensate dissipation.

In a system where the fixed cost is low, i.e., the departure from equilibrium state is small, equilibrium approaches offer simple and accurate understanding of the economic activities. As our societies become increasingly dependent on complex infrastructures and more people spend longer years in school education, the fixed costs of our social systems have increased tremendously. It becomes more and more difficult for the equilibrium paradigm, which is based on the Newtonian mechanics, to develop simple and coherent theories to understand the increasingly further away from equilibrium societies. For long term problems such as the evolutionary paths of human societies, or high fixed costs industries, such as IT industries, the non-equilibrium thermodynamic theory gives more accurate and simpler descriptions, as dynamics in temporal dimension and nonlinearity of uncertainty become prominent.

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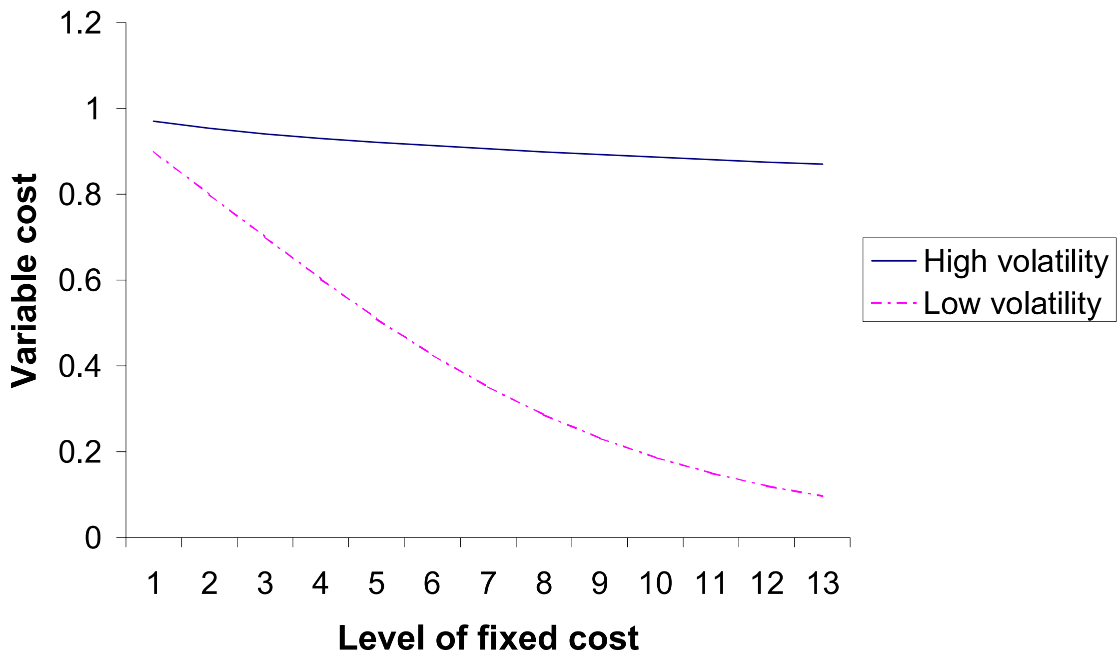
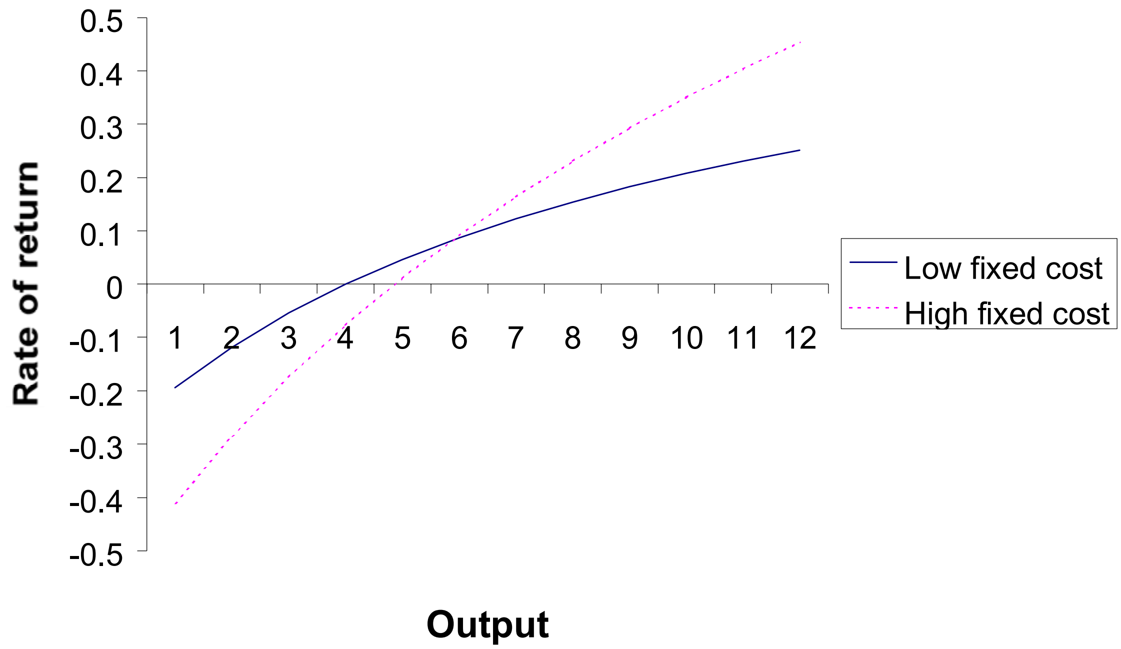
Figure captions

Figure 1. Volatility and variable cost
Figure 2. Output and return with different levels of fixed costs


1.2
1
0.8
0.6
0.4
0.2
0
Variable cost
1 2 3 4 5 6 7 8 9 10 11 12 13
Level of fixed cost
High volatility
Low volatility



0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
Rate of return
1
2
3
4
5
6
7
8
9
10
11
12
Output
Low fixed cost
High fixed cost