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THE PHYSICAL FOUNDATION OF ECONOMICS
An Analytical Thermodynamic Theory

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Preface

After the works of Schrodinger (1944), Wiener (1948) and others, there is a consensus that life processes in general and human activities in particular are thermodynamic processes. Economic activities may be characterized and studied as mechanical processes, but at a more fundamental level of nature they are thermodynamic processes. Thus one would expect that more accurate economic theories could be built on the foundation of thermodynamics instead of rational mechanics, from which neoclassical economic theory emerged. However, the theory of thermodynamics only has had a very limited impact on economic theory to date as no analytical thermodynamic theory of economics has been established. In *The Coal Question*, first published in 1865, Jevons systematically discussed many aspects of economic activities from an energy perspective. Georgeucu-Roegen (1971) and others subsequently provided a more updated economic theory based on thermodynamics. Their approaches, however, remain qualitative. The lack of an analytical paradigm prevented thermodynamic theory from offering a detailed and quantitative analysis applicable to concrete economic and business problems. In this book, we will develop an analytical thermodynamic theory of life systems, which include social system as a special case, and show how it provides much more realistic and intuitive understanding of economic and social phenomena than neoclassical economics.

The entropy law states that systems tend toward higher entropy states spontaneously. Living systems, as non-equilibrium systems, need to extract low entropy from the environment to compensate for continuous dissipation. This process is the most fundamental property of life. It can be represented mathematically by lognormal processes, which contain a growth term and a dissipation term. 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. Higher fixed cost systems generally have lower variable costs. In Chapter 3 of this book, we derive the thermodynamic equation that variable cost of a production system should satisfy, determine the initial value and then solve the thermodynamic equation to derive an analytic formula that explicitly represents the relation among fixed costs, variable costs, uncertainty of the environment and the duration of a production system, which is the core concern in most economic decisions. This analytical representation of various factors in production processes enables us to directly compute and analyze the returns of different production systems under various kinds of environment in a simple and systematic way.

Human activities are predominantly economic activities, which are chiefly regulated by the exchange value of different economic commodities. "The problem of value must always hold the pivotal position, as the chief tool of analysis in any pure theory that works with a rational schema." (Schumpeter, 1954, p. 588) The mainstream value theory, which is systematically represented in Debreu's *Theory of Value*, does not provide a measurable quantity for value. Since all human activities represent extraction and transformation of low entropy from the environment, it is natural to relate economic value to low entropy. From the properties that the value of commodities should satisfy, we derive that the only mathematical formula to represent value, as a function of scarcity, is the entropy function. This is parallel to the case where the only mathematical formula to represent information, as a function of probability, is the entropy function (Shannon, 1948). The entropy theory of value offers a unified understanding of physical entropy, information and economic value. It provides a quantitative measure of value that is highly consistent with our intuitive understanding. Just like the entropy theory of information provided a clear understanding of the fundamental problems in communication theory, the entropy theory of value provides clear understanding of the fundamental problems in social activities. In Chapter 2 of this book, we will discuss some of the conceptual difficulties that prevent the development of the entropy theory of value in the past and how they are resolved.

Many people do not agree that theories of social sciences should be derived from physical laws. They argue that physical laws are fixed while the human mind is free. However, the human mind is shaped by natural selection and sexual selection (Pinker, 1997). Living organisms need to extract low entropy from the environment, to defend their low entropy sources and to reduce the diffusion of low entropy. The struggle to stay in low entropy non-equilibrium states is called natural selection. Sexual selection is the struggle between the individuals of one sex, generally the males, to communicate their attractiveness to the other sex in order to form a partnership for reproduction. Human beings, as well as other sexually reproducing species, are the successful descendants of the earliest sexually reproducing species about a billion years ago (Margulis, 1998). For the system of communication to be successful in different kinds of environments over such a long time, the mode of communication has to be simple, stable and universal. Since the entropy law, which states that closed systems tend towards states of higher entropy, is the most universal law of the nature, it is natural that the display of low entropy levels evolves as the universal signal of attractiveness in the process of sexual selection. As both natural and sexual selection favor low entropy state, the pursuit of low entropy becomes the main motive in human mind and animal mind. In Chapter 1, we will show that some psychological patterns reflect the constraints of thermodynamic laws. Others are evolutionary adaptations to enable efficient processing of information, which is the reduction of entropy. Still others are mental attitudes that help us survive the constant dissipation of energy endured by all non-equilibrium systems. Therefore, entropy theory offers a unified understanding of the human mind. In this way, the understanding of matter and mind is unified on the foundation of physical laws. Just like the movement of particles is governed by physical laws, thinking is governed by physical laws, albeit in more complex ways.

In the rest of the book, we will apply the theory to understand other fundamental problems in social sciences. All the problems are analyzed with the unified methodology. This is in sharp contrast to analysis based on neoclassical economic theory, where many different models are developed for different problems. Even patterns easily understood by most people, such as increasing returns, have to be described by extremely ingenious and arcane mathematical models. Very often reality cannot fit into these models very well. The discrepancy between theory and reality is often attributed to imperfection of reality, such as "imperfect market", "imperfect information", "imperfect contract", "imperfect competition", "inefficient property right", "market failure", "government failure", "externality". A brief review of the concept of imperfection in old astronomy will help us gain more understanding about it. Ancient people had long observed that stars moved in perfect harmony in the sky. Several planets, however, moved in irregular trajectories. It was thought that this was caused by the imperfectness of the planets. There were many elaborate theories why the planets were imperfect. Kepler, however, derived that all planets moved in perfect elliptic orbits around the sun. This story tells us that "imperfection of the world" often reflects imperfection of the theory that is used to understand the world instead of the world itself. In the book, we will show how this analytical thermodynamic theory offers a unified understanding of various "imperfection" or "externality".

Since a thermodynamic equation is of first order in temporal dimension, social and biological systems as thermodynamic systems are intrinsically evolutionary and dynamic, which is very different from the static view of general equilibrium theory. Given the dynamic nature of our economic activities, one may wonder why an equilibrium theory becomes the dominant paradigm in economics. Schumpeter apparently anticipated such a question when he discussed the concept of equilibrium:

> Now, an observer fresh from Mars might excusably think that the human mind, inspired by experience, would start analysis with the relatively concrete and then, as more subtle relations reveal themselves, proceed to the relatively abstract, that is to say, to start from dynamic relations and then proceed to working out the static ones. But this has not been so in any field of scientific endeavor whatsoever: always static theory has historically preceded dynamic theory and the reasons for this seem to be as obvious as they are sound --- static theory is much simpler to work out; its propositions are easier to prove; and it seems closer to (logical) essentials. The history of economic analysis is no exception. (Schumpeter, 1954, p. 964)

Neoclassical economics was founded around 1870 by Jevons, Walras and others, who believed that economics should be built on a sound physical foundation. When neoclassical economics germinated in the 1870s, work on statistical mechanics by Boltzmann happened to appear in the same decade. However it was more than thirty years later that Boltzmann's theory was generally accepted by the physicist community.

Since the dominant platform of physics in Jevons and Walras' time was Newtonian mechanics, it was natural for them to adopt this platform. However, Jevons clearly pointed out that "I believe that dynamical branches of the Science of Economy may remain to be developed, on the consideration of which I have not at all entered." (Jevons, 1957, p. vii) The analytical thermodynamic theory, as a dynamic theory of economics, is a natural continuation of their pursuits. This was very much like statistical mechanics was a natural extension to Newtonian mechanics, although it took many years for people to realize that (Isihara, 1971). Most people today agree that statistical mechanics is a sounder foundation to describe living systems than Newtonian mechanics, which is the physical foundation of general equilibrium theory in economics. As it is often the case, an analytical framework that is built on sounder foundation of physical science delivers more intuitive and simpler results. Most of the contents in the book have been taught at undergraduate classes and the students embrace the ideas enthusiastically. Since all results in this book are simple analytical formulas, they can be applied easily by researchers and students. Many examples on different applications are provided in the book. Although the book is written as a research monograph, it can be used as a textbook or reference book for many courses.

This analytical thermodynamic theory transforms the study of human societies into an integral part of physical and biological sciences. A unified framework enables us to utilize knowledge gained from biology and various branches of economics and social sciences systematically to understand particular problems. The mainstream economic theories often emphasize the uniqueness of human beings that somehow enables us to escape the physical constraints that is binding for all other living organisms. Of course, human beings are unique. All species are. But the progress of science is often marked by further recognition that human beings are not "higher" than other living organisms.

I have been contemplating an analytical thermodynamic theory of life systems since I was a college student more than twenty years ago. My neglect of other things often put me into difficult situations. I am very grateful to Nam Sang Cheng, Jin-Chuan Duan, Yonggeng Gu, Hemantha Herath, Ling Hsiao, Joel Smoller, Changyun Wang, Michael Wong, Lixin Wu, Shing-Tung Yau and many others for their kind help in my difficult times.

Many people have provided helpful comments or encouragement during various stages of the development of the theory. They include Rishi Basak, Avi Bick, David Carter, Liang Chen, Sungchul Choi, Steven Clark, Mick Common, Alan Conway, Ted Creese, Balbinder Deo, Han Donker, Carmen Durney, Tony Fang, David Faulkner, Barry Feldman, Flobert Feng, Michael Ghiselin, Peter Hwang, Michael Jongmans, Kevin Keen, Xiaoying Kong, Jens Joerg Lauschke, Yan Ma, Donald Manson, Bill McGill, Alex Ng, Brendon Ogmundson, Peter Ostrowski, Eric Rapaport, Frank Schmid, Myron Scholes, Wei Shao, Jeff Smith, Joseph Vogel, Richard West, Bill Williams, Morgen Witzel, Yi-Cheng Zhang, Ralf Zurbrugg, Dale Domian, Raluca Lorgulescu Polimeni, Dietrich Stauffer and many others. Ted Creese, Kevin Keen, Peter Ostrowski and Richard West read part of the manuscripts and offered very helpful comments. My papers, most of which are about various aspects of this theory, listed on SSRN have generated more than six thousand downloads. I would like to thank readers for taking an interest on it.

I met Yubing Zhai, Commissioning Editor of World Scientific, in ASSA meeting in San Diego and told her about my plan to write the book. She browsed my website and encouraged me to submit a book proposal. This was how the book was originated. I am very grateful to Yubing for taking an active interest to a new theory from an unknown author. Cheong Chean Chian and Huang Wei guide me through the details of publication matters.

A person is a product of the environment. The unconditional and complete love from my parents gives me the peace of mind to work at this theory for more than twenty years without any visible progress until recent years. My sister has been a constant source of support and encouragement.

My single minded pursuit of this theory over the years was unfortunately not conducive to steady employment. But this circumstance was mitigated by the unwavering support of my wife, Coral for whom I reserve the utmost gratitude and thanks. Even in our most difficult time, Coral allowed me to pursue my own interest. She shouldered all the burden and anxiety for the family while I worked on the theory, which would never have been developed without her love and devotion.

Jing Chen

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Chapter 1

The Entropy Theory of Human Mind

1.1. Introduction

People generally think that physical laws only have limited utility in understanding human behavior because our mind is free. However, human mind is shaped by natural selection and sexual selection (Pinker, 1997). Living organisms need to extract low entropy from the environment, to defend their low entropy sources and to reduce the diffusion of the low entropy. The struggle to stay in low entropy states is called natural selection. In human societies, agriculture is the main low entropy source. Part of health care systems aim at defending our own low entropy sources to be accessed by viruses and bacteria. The military forces are established to extract low entropy from others and to defend own low entropy sources. Clothing and housing reduces the diffusion of low entropy.

Sexual selection is the struggle between the individuals of one sex, generally the males, to communicate their attractiveness to the other sex in order to form a partnership for reproduction. Human beings, as well as other sexually reproducing species, are the successful descendants of the earliest sexually reproducing species about a billion years ago (Margulis, 1998). For the system of communication to be successful in different kinds of environments over such a long time, the mode of communication has to be simple, stable and universal. Since the entropy law, which states that closed systems tend towards states of higher entropy, is the most universal law of the nature, it is natural that the display of low entropy levels evolves as the universal signal of attractiveness in the process of sexual selection.

As both natural selection and sexual selection favor low entropy state, the pursuit of low entropy becomes the main motive of human mind and animal mind. Indeed the low entropy state is the main way of advertisement for most sexually reproducing species. Large body size, colorful and highly complex feather patterns with large amount of information content and exotic structures are all different representations of low entropy states. Since a low probability event corresponds to a state of low entropy, a novel feature is often attractive in the competition for reproduction. It has been generally recognized that sexual selection is the main drive of diversity (Miller, 2000).

Besides communication with members of the opposite sex, social animals need to communicate their attractiveness and power in order to influence the behavior of others (Wilson, 1975). For the same reason as in sexual selection, the most general signal is display of low entropy. Among all social species, human beings have developed the most complex social structure. The creation of distinct art works, the demonstration of athletic prowess, the accumulation of wealth, and conspicuous consumption - all of which represent different forms of low entropy - are the major methods of advertising one's attractiveness.

As the social groups become larger and the division of labor becomes finer, people become less familiar with each other in their daily interactions, which make it more difficult for people to judge the ability of others. The need for people to advertise their attractiveness through external accumulation of low entropy also becomes stronger. People usually signal their capability by buying more expensive houses, cars, clothes, going to more expensive restaurants and attending more exclusive schools. The great efforts human beings put into non-food activities reflect the high cost of communication in a large and complex society. Historical evidences show that the transaction costs have been increasing over time (Wallis and North, 1986).

The main function of mind is information processing. The concept of information has been intimately related to entropy for over a century. In a thought experiment, Maxwell (1871) reasoned, if information is costless, the entropy of a system can be decreased. But this would violate the second law of thermodynamics. Maxwell went on to conclude that the physical cost of obtaining information must be at least as much as the value of information. Many years later Shannon (1948) identified information as entropy formally, at least at the mathematical level. (Shannon, 1956)

The remainder of the chapter is structured as follows. Section 1.2 introduces the generalized entropy theory of information. Information theory provides natural measures of the cost of obtaining information and of information asymmetry. Section 1.3 shows that entropy theory offers a unified understanding of the patterns of human psychology. Section 1.4 concludes.

1.2. What is Information?

The value of information is a function of probability and must satisfy the following properties:

(a) The information value of two events is higher than the value of each of them.
(b) If two events are independent, the information value of the two events will be the sum of the two.
(c) The information value of any event is non-negative.

The only mathematical functions that satisfy all the above properties are of the form

$$H(P) = -\log_b P \tag{1.1}$$

where H is the value of information, P is the probability associated with a given event and b is a positive constant (Applebaum, 1996). Formula (1.1) represents the level of uncertainty. When a signal is received, there is a reduction of uncertainty, which is information.

Suppose a random event, X, has n discrete states, $x_1, x_2, \ldots, x_n$, each with probability $p_1, p_2, \ldots, p_n$. The information value of X is the average of information value of each state, that is

$$H(X) = -\sum_{j=1}^{n} p_j \log(p_j) \tag{1.2}$$

The right hand side of (1.2), which is the entropy function first introduced by Boltzmann in the 1870s, is also the general formula for information (Shannon, 1948).

After the entropy theory of information was developed in 1948, its technique has been applied to many different problems in economic and finance. (Theil, 1967; Maasoumi and Racine, 2002 and many others) However, the standard economic theory of information, represented by Grossman and Stiglitz (1980) was not built on the foundation of entropy theory. An entropy theory based economic theory of information can be simply stated as:

> Information is the reduction of entropy, not only in a mathematical sense, as in Shannon's theory, but also in a physical sense. The rules of information transmission developed in Shannon's theory, as mathematical rules, apply not only to communication systems, but also to all living organisms.

In the following, we will discuss some distinct properties of this new information theory. First, information that is more valuable is in general more expensive to obtain. From the second law of thermodynamics, Maxwell concluded that information of higher value is of higher physical cost. Since economic cost is highly correlated to physical cost, (Georgescu-Roegen, 1971) more valuable information is in general more expensive to obtain. The relation among entropy, information and economic value will be discussed in greater detail in Chapter 2.

Second, the amount of information one can receive depends on the person's background knowledge about that particular information. The most important result from Shannon's entropy theory of information is the following formula

$$R = H(x) - H_y(x) \tag{1.3}$$

where R is the amount of information one can receive, H is the amount of information a source sent and $H_y(x)$, the conditional entropy, is called equivocation. Formula (1.3) shows that the amount of information one can receive would be equal to the amount of information sent minus the average rate of conditional entropy. Before Shannon's theory, it was impossible to accurately assess how much information one can receive from an information source. In communication theory, this formula is used to discuss how noises affect the efficiency of information transmission. But it can be understood from more general perspective. The level of conditional entropy $H_y(x)$ is determined by the correlation between senders and receivers. When x and y are independent, $H_y(x) = H(x)$ and $R = 0$. No information can be transmitted between two objects that are independent of each other. When the correlation of x and y is equal to one, $H_y(x) = 0$. No information loss occurs in transmission. In general, the amount of information one can receive from the source depends on the correlation between the two. The higher the correlation between the source and receiver, the more information can be transmitted.

The above discussion does not depend on the specific characteristics of senders and receivers of information. So it applies to human beings as well as technical communication equipments, which are the original focus in information theory in science and engineering. However, the laws that govern human activities, including mental activities, are the same physical laws that govern non-living systems.

$H_y(x)$ in Formula (1.3) offers the quantitative measure of information asymmetry (Akerlof, 1970). Since different people have different background knowledge about the same information, heterogeneity of opinion occurs naturally. To understand the value of a new product or new production system may take the investment public several years. To fully appreciate the scope of some technology change may take several decades. For example, the economic and social impacts of cars as personal transportation instruments and computers as personal communication instruments were only gradually realized over the path of several decades. This is why individual stocks and whole stock markets often exhibit cycles of return of different lengths. This property is very different from Grossman-Stiglitz information theory, where economic agents can recognize the value of information instantly and pay according to its value.

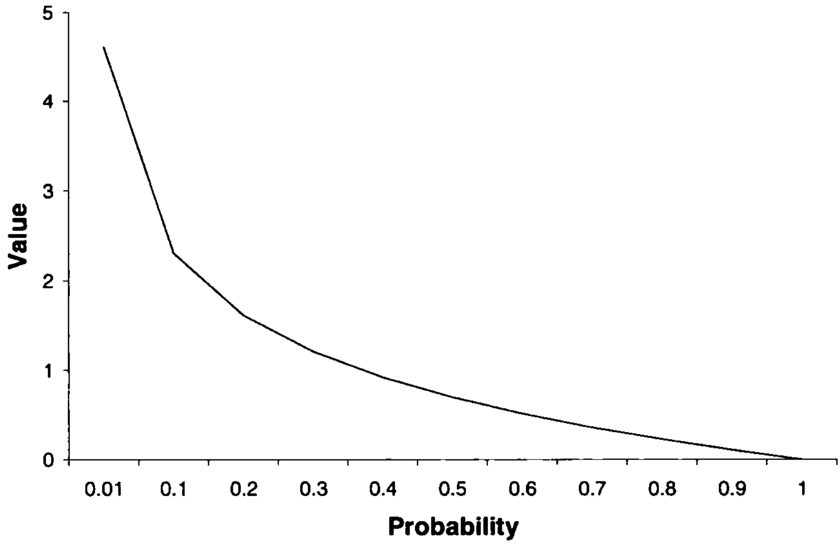

Figure 1.1. Information value and probability.

Third, the same information, when known to more people, becomes less valuable. Figure 1.1 is a graph of (1.1), where H is a function of P, the probability of any given event. From Figure 1.1, value is a decreasing function of probability. In the standard information theory, P represents the probability that some event will occur. In this theory, P is generalized to represent the percentage of people or money that is controlled by informed investors. When $P = 1$, $-\log P = 0$. Thus the value of information that is already known to everyone is zero. When P approaches zero, $-\log P$ approaches infinity. Therefore, the value of information that is known to few is very high. The following example will illustrate this point. Figure 1.2 shows overnight rate of return and trading volume of shares of WestJet, a Canadian airline, surrounding the announcement of the bankruptcy of Jetsgo, the main competitor of WestJet. Jetsgo announced bankruptcy at the evening of March 10, 2005. If one bought stock at March 10, he would have made a return of 40% overnight. Judging from the trading volume of March 9, some people did buy WestJet stock before information was released to the public. After the announcement made the information public, trading volume was very high and the rate of return is near zero. Figure 1.2 neatly illustrates the