The Economy of Social and Biological Systems: A Physical Theory

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Abstract

Many people have recognized the fundamental flaws in the established economic theories. At the same time, most people feel that it is unlikely to develop an economic theory that is both relevant and analytical tractable. It is often thought that social problems are too complex to be described by a simple mathematical theory. Whether or not a system is complex to the human mind depends on whether we can detect simple mathematical structures among various factors in a system. Recently, a mathematical theory of economics of social and biological systems has been derived from the laws of statistical thermodynamics. The main result is a formula of variable cost as a mathematical function of product value, fixed cost, uncertainty, discount rate and project duration. From this formula of variable cost, together with fixed cost and volume of output, we can compute and analyze the returns and profits of different production systems under various kinds of environment in a simple and systematic way. The results are highly consistent with the empirical evidences obtained from the vast amount of literature in economics and biology. Furthermore, by putting major factors of production into a compact mathematical model, the theory provides precise insights about the tradeoffs and constraints of various business or evolutionary strategies that are often lost in intuitive thinking.

Preliminary draft. Comments welcome.

1. Introduction

Many people have recognized the fundamental flaws in the established economic theories. At the same time, most people feel that it is unlikely to develop an economic theory that is both relevant and analytical tractable. It is often thought that social problems are too complex to be described by a simple mathematical theory. To provide a better perspective on this question, we need to look at the history of the understanding of celestial bodies by human societies. Before the development of the rational mechanics, celestial bodies were much more mysterious than the earthly human societies. It is only after the development of mathematical theory in rational mechanics, the movement of planetary systems becomes much simpler than the movement of social systems. Whether or not a system is complex to the human mind depends on whether we can detect simple mathematical structures among various factors in a system. Recently, a mathematical theory of economics of human society and life systems has been derived from the laws of statistical thermodynamics (Chen, 2005; Chen and Galbraith, 2009). It provides a much more realistic and intuitive understanding of economic, social and biological phenomena than the established economic theories. In this paper, we will present an update of this theory. The theoretical structure remains the same. But more examples of applications are provided.

We start the investigation by asking: What are the most fundamental properties of organisms and organizations? How to represent these fundamental properties into a mathematical theory? First, organisms and organizations need to obtain resources from the environment to compensate for the continuous diffusion of resources required to maintain various functions. It can be represented mathematically by lognormal processes, which contain both a growth term and a dissipation term. Second, for an organism or an organization to be viable, the total cost of extracting resources has to be less than the amount of resources extracted, or the total cost of operation has to be less than the total revenue. Costs include fixed cost and variable cost. Lowering variable cost generally requires higher fixed cost. Fixed cost is largely determined by the structure of an organism or an organization. Variable cost is a function of the environment. From the above considerations, we derive the thermodynamic equation that variable cost of a production system should satisfy. We set the initial condition of the equation so that total cost is equal to the amount of resource extracted or revenue generated. Since an organism or a project have finite life spans, we can integrate the equation over the duration of the project to obtain a formula of variable cost as a mathematical function of product value, fixed cost, uncertainty, discount rate and project duration. From this formula of variable cost, together with fixed cost and volume of output, we can compute and analyze the returns and profits of different production systems under various kinds of environment in a simple and systematic way. The results are highly consistent with the empirical evidences obtained from the vast amount of literature in economics and biology. Furthermore, by putting major factors of production into a compact mathematical model, the theory provides precise insights about the tradeoffs and constraints of various business or evolutionary strategies that are often lost in intuitive thinking.

Product value, fixed cost, variable cost, discount rate, uncertainty, project duration and volume of output are major factors in production. These factors naturally became the center of investigation in early economic literature. However, because of the difficulty in forming a compact mathematical model about these factors, discussion about these factors becomes peripheral in current economic literature. With the help of this analytical production theory, theoretical investigation in economics may refocus on important issues in economic activities.

Among the various relations of different factors, the relation between fixed cost and variable cost is probably the most important. We will elaborate on this relation further. People observed that useful energy comes from the differential or gradient between two parts of a system. In general, the higher the differential between two parts of a system, the more efficient the work becomes. At the same time, it is more difficult to maintain a system with high differential. In other words, a lower variable cost system requires higher fixed cost to maintain it. This is a general principle. We can list several familiar examples from physics and engineering, biology and economics.

In an internal combustion engine, the higher the temperature differential between the combustion chamber and the environment, the higher the efficiency in transforming heat into work. This is the famed Carnot's Principle, the foundation of thermodynamics. At the same time, it is more expensive to build a combustion chamber that can withstand higher temperature and pressure. Diesel burns at higher temperature than gasoline. This is why the energy efficiency of diesel engine is higher than that of gasoline engine and the cost of building a diesel engine is higher as well. In electricity transmission, higher voltage will lower heat loss. At the same time, higher voltage transmission systems are more expensive to build and maintain because the distance from the line to the ground has to be longer to reduce the risk of electric shock. The differential of water levels inside and outside a hydro dam generates electricity. The higher the hydro dam, the more electricity can be generated. At the same time, a higher hydro dam is more costly to build and maintain. A TV with remote control is easier to operate than one without remote control. But to keep the remote control active, electricity is consumed 24 hours a day in a TV.

Warm blooded animal can run faster than cold blooded animals because their body temperature is maintained at high levels to ensure fast biochemical reactions. But the basic metabolism rates of warm blooded animals are much higher than the cold blooded animals. This production theory provides a clear understanding to the patterns of temperature regulation, which has not been fully understood in physiological research.

> The fact is that we do not fully understand the advantage of any given body temperature. In any event, it would be a mistake to interpret a low body temperature as a sign of "primitive" and thus inadequate temperature regulation. It has been said that the egg-laying echidna is halfway to being a cold-blooded animal and is unable to regulate its body temperature adequately. In fact, the echidna is an excellent temperature regulator and can maintain its core temperature over a wide range of ambient temperature down to freezing or below, although it has poor tolerance to high temperature. (Schmidt-Nielson, 1997, p. 245)

From the new production theory, higher temperature represents higher fixed cost and low variable cost. Whether a system will evolve toward higher temperature is determined by whether such evolution will help improve return from such a change. Specifically, how much the increased temperature will help increase efficiency in catching prey and avoiding predators. For mammals of low temperature, their prey may be insects or other animals that do not run very fast. So animals with low temperature (30C) are fast enough to catch slow moving prey. Avoiding predator faster may not fully compensate the cost of increasing body temperature. Therefore, our theory turns the discussion into a problem of quantitative measurement.

The tradeoff between fixed cost and variable cost is also universal in economic activities. Shops located near high traffic flows generate high sales volume per unit time. But the rent costs in such locations are also higher. Well trained employees work more efficiently. But employee training is costly. People with higher education levels on average command higher income. But education takes time, effort and money. The tradeoff between lower variable cost and higher fixed cost is often not explicitly discussed in the same literature and is often not considered in policy issues. For example, electricity generated from solar panel is considered clean energy because solar panel does not need fuels that will cause environmental problems. But the manufacturing of solar panels is highly resource intensive and highly pollutive. However, the pollution from manufacturing solar panels, the fixed cost part of the solar electricity, is rarely mentioned in policy discussion. While it is in the interest of the promoters of "clean" energy and "renewable" energy to avoid discussing such issues, a good economic theory should provide guidance to understand the big pictures.

From the production theory, it can be calculated that when the fixed cost is zero, the variable cost is equal to the product value, and profit is zero. This means that any organisms or organizations have to make a fixed investment before earning a positive return. Stiglitz made similar observation:

> Timing (and sequencing) is everything. These are not just issues of pragmatics, of "implementation": these are issues of principle. …Trade liberalization is supposed to enhance a country's income by forcing resources to move from less productive uses to more productive uses; as economists would say, utilizing comparative advantage. But moving resources from low-productivity uses to zero productivity does not enrich a country... It is easy to destroy jobs, and this is often the immediate impact of trade liberalization, as inefficient industries closed down under pressure from international competition. IMF ideology holds that new, more productive jobs will be created as the old, inefficient jobs that have been created behind protectionist walls are eliminated. But that is simply not the case …. It takes capital and entrepreneurship to create new firms and jobs. (Stiglitz, 2002, p. 60)

The determination of the proper level of fixed cost and variable cost to attain high level of return under various environments will be jointly affected by other factors. We will discuss in greater detail after deriving the mathematical theory of production.

This theory is an integrated theory of social and biological systems. Many people observe striking parallels between social and biological systems. Yet it is often assumed that there is a fundamental difference between the two: genetic mutations are generally considered random while human activities are considered purposeful (Ormerod, 2005). This assumed chasm between social and biological systems limited the knowledge flow between social and biological sciences. However, more precise observation shows that biological evolution is not completely random. When, where and how fast genes mutate depends on many environmental factors. The regulation in genetic and epigenetic changes in organisms is highly directed to enhance their survival under different kinds of environments (Jablonka and Lamb, 2006; Rando and Verstrepen, 2007; Moalem and Prince 2008). Since a directed and informed change provides a higher rate of return than a complete random one, purposeful changes evolve both in social and biological systems. Therefore there is no reason to segregate the study of social systems from the rest of biological systems.

There are many advantages for such an integrated approach. Biological studies cover many more species over a much longer time period than social studies. Therefore principles derived from biological studies tend to be more general and more robust than those from social studies. For example, according to mainstream economic theory, regulation is required in social systems only when the market is "imperfect". However, regulation is essential for all biological entities. Those "higher" animals, which presumably are more "perfect", generally require more physiological regulations than the “lower” animals, which presumably are less “perfect”. If the public demand that economic policy be consistent with biological principles, many policy disasters, such as the deregulation of the highly leveraged financial industry, could have been avoided.

This economic theory is derived from physical laws. Recently, there have been a lot of criticisms about aping economic theory after physical theory. To respond to this type of criticism, we have to understand what a physical theory is. According to Schrodinger,

> Today, there are not a few physicists who … regard the task of physical theory as being merely a mathematical description (as economical as possible) of the empirical connections between observable quantities … without the intervention of unobservable elements. (Schrodinger, 1928, p. 58)

So a physical theory is a mathematical description of the empirical connections between observable quantities. However, today’s economic theory is mainly built on unobservable elements. Individuals are supposed to maximize “utility”. Market is the most “efficient” way to allocate resources. But nonetheless laws and regulations are required because of “externality”. Human beings are “rational’ most of the time but are subject to “irrational” emotion sometimes. Most patterns in economic activities are caused by “imperfect” competition. Rarely fundamental concepts in established economic theories are based on observable quantities. Instead, our theory is built on observable quantities.

This paper is an update from earlier works (Chen, 2008, Chen and Galbraith, 2009). The rest of this paper is structured as follows. Section two presents a historic review of related ideas and mathematical techniques. Section three presents the derivation of the production theory. In section four, we will provide a systematic analysis on the relation of various factors and returns. Section five concludes.

2. A historic review of related ideas and mathematical techniques

Because of the fundamental link between thermodynamics and life, many attempts have been made to develop analytical theories based on the principle of thermodynamics and apply them to living systems and human society. These include Lorenz’ chaos theory and Prigorgine’s far from equilibrium thermodynamic theory. Lorenz, a meteorologist, simplified weather equations, which are thermodynamic equations, into ordinary differential equations. He found chaos properties from these equations. Prigorgine developed the theory from some chemical reactions. The theories of Lorenz and Prigorgine greatly influenced the thinking in biology and social sciences. However, they do not model life process or social activities directly. Chaos theory and Prigorgine’s theory, while providing good insights to the research in biological and social sciences, are mostly analogies. Many of the recent works on the application of physics to economics are summarized in Farmer et al. (2005). These works apply the techniques from research in physics to economics and do not directly model economic activities as physical processes.

Since uncertainty is an integral part of life processes, the advancement of stochastic calculus is essential for the development of an analytical thermodynamic theory of life and human society. In the past several decades, some fundamental works in the area of stochastic calculus were undertaken by people with very diverse backgrounds. Three works are particularly relevant to the development of our theory. The first is Ito’s Lemma, which provides a rule to find the differential of a function of stochastic variable. Ito’s Lemma was obtained in 1940s. But its importance was not recognized until its wide spread application in financial economics several decades later. Ito was awarded Gauss Prize in 2006, sixty years after his theory was initially developed.

The second tool is Feynman-Kac formula, which maps a stochastic process into a deterministic thermodynamic equation. Richard Feynman (1948) attempted to simplify calculation in quantum mechanics by transforming problems in stochastic processes into problems in deterministic processes. The new mathematical technique enabled him to perform many computations in quantum mechanics which were very difficult in the past. With this he established the theory of quantum electrodynamics. The breakthrough in physics is often generated by the breakthrough in new mathematical methods, which enables us to describe the subtler parts of the nature. An important motivation in Feynman's research was his seek for universality. "The question that then arose was what Dirac had meant by the phrase 'analogous to,' and Feynman determined to find out whether or not it would be possible to substitute the phrase 'equal to.'" (Feynman and Hibbs, 1965, p. viii) Feynman, together with Tomonaga and Schwinger, was awarded Nobel Prize in physics for this work in 1965. Despite its highly technical nature, Feynman-Kac formula is a very general result and has proved to be extremely useful in many different fields. In particular, Feynman-Kac formula has been widely used in the research in finance recently. It was even suggested that "Feynman could be claimed as the father of financial economics" (Dixit and Pindyck, 1994, p. 123).

The third is Black-Scholes (1973) option pricing theory, which provides an analytical formula of observable variables to price a financial instrument whose payoff depends on a stochastic process. This is a landmark contribution in social sciences. It shows that a complex economic problem can be effectively modeled by a stochastic process, a simple and deterministic analytical theory about it can be developed and much information about it can be obtained through such an analytical theory. Fischer Black, one of the co-developers of the Black-Scholes theory, was a legendary figure in finance. Jack Treynor, who introduced Fischer Black to the field of finance, had the following observation:

> Fischer never took a course in either economics or finance, so he never learned the way you were supposed to do things. But that lack of training proved to be an advantage, … since the traditional methods in those fields were better at producing academic careers than new knowledge. Fischer's intellectual formation was instead in physics and mathematics, and his success in finance came from applying the methods of astrophysics. Lacking the ability to run controlled experiments on the stars, the astrophysist relies on careful observation and then imagination to find the simplicity underlying apparent complexity. In Fischer's hands, the same habits of research turned out to be effective for producing new knowledge in finance. (Mehrling, 2005, p. 6)

Black-Scholes option theory provides the earliest inspiration in developing an analytical thermodynamic theory of life and human society. More detailed discussion about its history can be found in Chen (2005).

3. A mathematical theory of production

The theory described in this section can be applied to both biological and economic systems. For simplicity of exposition, we will use the language of economics. However the extension to biological system is straight forward.

A basic property in economic activities is uncertainty. While a business may face many different kinds of uncertainty, most of the uncertainties are reflected in the price uncertainty of the product.

Suppose S represents unit price of a commodity, r, the expected rate of change of price and σ, the rate of uncertainty. Then the process of S can be represented by the lognormal process

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

where

$dz = \varepsilon\sqrt{dt}, \quad \varepsilon \in N(0,1)$ is a random varaible with standard Gaussian distribution

The production of the commodity involves fixed cost and variable cost. In general, production factors that last for a long term, such as capital equipment, are considered fixed cost while production factors that last for a short term, such as raw materials, are considered variable costs. If employees are on long term contracts, they may be better classified as fixed costs, although in many cases, they are classified as variable costs. Firms can adjust their level of fixed and variable costs to achieve high level of return on their investment. Intuitively, in a large and stable market, firms will invest heavily on fixed cost to reduce variable cost, thus achieving a higher level of economy of scale. In a small or volatile market, firms will invest less on fixed cost to maintain high level of flexibility. In the following, we will derive a formal mathematical theory that focuses on this issue.

In natural science, there is a long tradition of studying stochastic processes with deterministic partial differential equations. For example, heat is a random movement of molecules. Yet the heat process is often studied by using heat equations, a type of partial differential equations. In studying quantum electrodynamics, Feynman (1948) developed a general method to study probability wave function. Kac (1951) extended this method into a mapping between stochastic process and partial differential equations, which was later known as the Feynman-Kac formula, whose use is very common in natural sciences (Kac, 1985). Recently, the Feynman-Kac formula has been widely used in the research in finance. Our goal is to apply the Feynman-Kac formula to derive variable cost in production as a function of other parameters.

Let K represent fixed cost and C represent variable cost, which is a function of S, the value of the commodity. According to the Feynman-Kac formula (Øksendal, 1998, p. 135), if the discount rate of a firm is r, the variable cost, C, as a function of S, satisfies the following equation

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

with the initial condition

$$C(S,0) = f(S) \tag{3}$$

To determine $f(S)$, we perform a thought experiment about a project with a duration that is infinitesimally small. When the duration of a project is sufficiently small, it only has enough time to produce one unit of product. In this situation, 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 the variable cost is the following:

$$C(S,0) = \max(S - K,0) \tag{4}$$

where S is the value of the commodity and K is the fixed cost of a project. When the duration of a project is T, solving equation (2) with the initial condition (4) yields the following solution

$$C = SN(d_1) - Ke^{-rT} N(d_2) \tag{5}$$

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. Formula (5) takes the same form as the well-known Black-Scholes (1973) formula for European call options.

Formula (5) provides an analytical formula of variable cost as a function of product value, fixed cost, uncertainty, duration of project and discount rate of a firm. Similar to understanding in physics, the calculated variable cost is the average expected cost (Kiselev, Shnir, Tregubovich, 2000; Tong, 2008).

We will briefly examine the properties of this formula. First, the variable cost is always less the value of the product when the fixed cost is positive. No one will invest in a project if the expected variable cost is higher than the product value. Second, when the fixed cost is zero, the variable cost is equal to the value of the product. When the fixed cost approaches zero, the variable cost will approach the value of the product. This means that businesses need fixed investment before they can make a profit. Similarly, any organisms need to invest in a fixed structure before extracting resources profitably. Third, when fixed costs, K, are higher, variable costs, C, are lower. Fourth, for the same amount of the fixed cost, when the duration of a project, T, is longer, the variable cost is higher. Fifth, when uncertainty, σ, increases, the variable cost increases. Sixth, when discount rate becomes lower, the variable cost decreases. This is due to the lower cost of borrowing. All these properties are consistent with our intuitive understanding of production processes.

Suppose the volume of output during the project life is Q, which is bound by production capacity or market size. We assume the present value of the product to be S and the variable cost to be C during the project life. Then the total present value of the product and the total cost of production are

$$SQ \text{ and } CQ + K \tag{6}$$

respectively. The return of this project can be represented by

$$\ln(\frac{SQ}{CQ+K}) \tag{7}$$

and the net present value of the project is

$$QS-(QC+K)=Q(S-C)-K \tag{8}$$

It is often convenient to represent S as the output from a project over one unit of time. If the project lasts for T unit of time, the net present value of the project is

$$TS-(TC+K)=T(S-C)-K \tag{9}$$

Unlike a conceptual framework, this mathematical theory enables us to make quantitative calculations of returns of different projects under different kinds of environments. In the next section, we will provide a systematic analysis on the relation of various factors and returns.

4. Systematic analysis of the performance of a project

The profit or return of a project is determined by fixed cost, variable cost and total output during the life of the project. Variable cost is a function of product value, fixed cost, uncertainty, duration of the project, and discount rate. At the project level, how much to invest or commit to at the beginning of the project is the most important decision to make. At the country level, how much to invest in roads, public schools, libraries and other public assets is often the defining characteristic of a state. At the project level, the cost of borrowing often determines the viability or structure of a project. At the country level, the main tool for many central banks to fine tune economic activities is by adjusting discount rates. Biological species are often classified as *K* and *r* species. In general, *K* species have high fixed investment and *r* species have high discount rate. Therefore, fixed cost and discount rate are often the most important factors in investment decision making. In this section, we will discuss how different factors are related to each other in affecting the performance of investment projects. We will group the factors first by fixed cost and then by discount rate.

Fixed cost and discount rate:

We discuss how the level of fixed cost affects the preference for discount rates. We will calculate how variable costs change with different discount rates. When discount rates are decreased, the variable costs of high fixed cost systems decrease faster than the variable costs of low fixed cost systems (Figure 1). This indicates that high fixed cost systems have more incentive to maintain low discount rates or lending rates. This result helps us understand why prevailing lending rates are different at different areas or times.

In poor countries, lending rates are very high; in wealthy countries, lending rates charged by regular financial institutions, other than unsecured personal loans, such as credit card debts, are generally very low. To maintain a low level of lending rates, many credit and legal agencies are needed to inform and enforce, which is very costly. As wealthy countries are of high fixed cost, they are willing to put up the high cost of credit and legal agencies because the efficiency gain from lower lending rate is higher in high fixed cost systems. In the last several hundred years, there is in general an upward trend in living standard worldwide. There is also a downward trend in interest rates (Newell and Pizer, 2003).

Empirical investigations show that the human mind intuitively understands the relation between discount rate and different level of assets. In the field of human psychology, there is an empirical regularity called the "magnitude effect" (small outcomes are discounted more than large ones). Most studies that vary outcome size have found that large outcomes are discounted at a lower rate than small ones. In Thaler's (1981) study, respondents were, on average, indifferent between $15 immediately and $60 in a year, $250 immediately and $350 in a year, and $3000 immediately and $4,000 in a year, implying discount rates of 139%, 34% and 29%, respectively (Frederick, Loewenstein and O'Donoghue, 2004). Since human mind is an adaptation to the needs of survival and reproduction, evaluating the relation between discount rate and amount of investment must be a common task in our evolutionary past.

Differences in fixed costs in child bearing between women and men also affect the differences in discount rates between them. Women spend much more effort in child bearing. From our theory, the high fixed investment women put in child bearing would make women's discount rate lower than men's. An informal survey conducted in a classroom survey showed that discount rates of the female students are lower than that of the male students.

Our understanding about discount rate and fixed cost is similar to an earlier work by Ainslie and Herrnstein (1981):

> The biological value of a low discount rate is limited by its requiring the organism to detect which one of all the events occurring over a preceding period of hours or days led to a particular reinforcer. As the discounting rate falls, the informational load increases. Without substantial discounting, a reinforcer would act with nearly full force not only on the behaviors that immediately preceded it, but also on those that had been emitted in past hours or days. The task of factoring out which behaviors had actually led to reward could exceed the information processing capacity of a species.

Fixed cost and duration of the project:

We will study how the level of the duration of projects affects the rate of return. If the duration of a project is too short, we may not be able to recoup the fixed cost invested in the project. If the duration of a project is too long, the variable cost, or the maintenance cost may become too high. With the mathematical theory, we can make quantitative calculations. To be specific, we will compare the profit level of one project with that of two projects with duration half long while keeping other parameters identical. We also assume the annual output of two types of projects are the same. We find that when duration is short, the profit level of one long project is higher than two short projects. When duration is long, the profit level of one project is lower than two short projects. This is consistent with intuition. The detailed calculation is illustrated in Figure 3. It explains why individual life does not go on forever. Instead, it is of higher return for animals to have finite life span and produce offspring. This also explains why most businesses fail in the end (Ormerod, 2005).

Calculation also shows that when the level of fixed cost increases, the length of duration for a project to earn a positive return also increases. This suggests that large animals and large projects, which have higher fixed cost, often have longer life. There is an empirical regularity that animals of larger sizes generally live longer (Whitfield, 2006). The relation between fixed cost and duration can be also applied to human relation. In child bearing, women spend much more effort than men. Therefore we would expect women value long term relation while men often seek short term relation, which is indeed the case most of the time (Pinker, 1997).

From calculation, when the duration of a project keep increasing, the return of a project will eventually turn negative. Hence, duration of a project or an organism cannot become infinite. For life to continue, there has to be a systematic ways to generate new organisms from old organisms. From earlier calculation, for a system to have a positive return, fixed assets have to be invested first. Thus old generations have to transfer part of their resources to younger generations as the seed capital before younger generations can maintain positive return. Therefore, there is a universal necessity of resource transfer from the old generation to the younger generation in biological world. "Higher" animals, such as mammals, generally provide more investment to each child than "lower" animals, such as fish. In human societies, parents provide their children for some years before they become financial independent. In general, wealthy societies provide more investment to children before they start to compete in the market than poor societies. In businesses, new projects are heavily subsidized at their beginning stages by cash flows from existing projects.

Since project life or organism life cannot last forever, resource transfer from organism to organism or from project to project is unavoidable. However, the process of transfer is often complicated and difficult. Businesses prefer lower tax rates. Educational institutions prefer higher government revenues. Each child wants full attention from parents. Parents would like to distribute resources more or less even among different children. Mature industries, which need little R&D expense, prefer low tax systems. High tech industries, which rely heavily on universities to provide new technologies, employees and users, strongly advocate government support in new technologies. In good times, financial institutions preach the virtue of free market to pursue high profits. In bad times, the same institutions will remind the public how government support can ensure financial stability of the nation. The amount of resource transfer and the method of resource transfer often define the characteristics of a species or a society.

Generational turnover not only provides continuity in species and societies, but also provides opportunities for resource reallocation. Businesses reinvest in potentially more profitable new projects that are not necessarily in their original fields. For example, Nokia was a forestry company before entering the cell phone business. Governments collect taxes from all industries but mainly reinvest, in the form of university education and research funding, in high fixed cost industries that have strong scale economy. Female animals prefer to mate with dominant males. In this way, genetic or social compositions of systems keep evolving to adapt to the changing environment.

Calculation also shows that when the level of fixed cost increases, the length of duration for a project to be of positive return also increases. This suggests that large animals and large projects, which have higher fixed cost, often have longer life. There is an empirical regularity that animals of larger sizes generally live longer (Whitfield, 2006). Since higher fixed cost systems have longer life span than lower fixed cost systems, the mutation rates of lower fixed cost systems are faster. This gives lower fixed cost systems advantages in adapting changes. For example, AIDS virus is much smaller than human beings and can mutate much faster. This makes it difficult for humans to develop natural immune response or develop drugs to fight against AIDS virus. However, higher animals develop a general strategy in immunes systems that has been very effective most of the time. Instead of developing one kind of antibody, our immune systems produce millions of different types of antibodies. It is highly likely that for any kind of bacteria or viruses, there is a suitable antibody to destroy them. This strategy is very effective but very expensive, because our body needs to produce many different kinds of antibodies that are useless most of the time. When we are too young, too old or too weak, our bodies don't have enough energy to produce large amount of antibodies. That is when we get sick often.

Fixed cost and uncertainty:

By calculating variable costs from (5), we find that, as fixed costs are increased, variable costs decrease rapidly in a low uncertainty environment and change very little in a high uncertainty environment. To put it in another way, high fixed cost systems are very sensitive to the change of uncertainty level while low fixed cost systems are not. This is illustrated in Figure 2.

The above calculation indicates that systems with higher fixed investment are more effective in a low uncertainty environment and systems with lower fixed investment are more flexible in high uncertainty environment. This explains why mature industries, such as household supplies, are dominated by large companies such as P&G while innovative industries, such as IT, are pioneered by small and new firms. Microsoft, Apple, Yahoo, Google, Facebook and countless other innovative businesses are started by one or two individuals and not by established firms.

Similarly, in scientific research, mature areas are generally dominated by top researchers from elite schools, while scientific revolutions are often initiated by newcomers or outsiders (Kuhn, 1996).

Fixed cost and the volume of output or market size:

We now discuss the returns of investment on projects of different fixed costs with respect to the volume of output or market size. Figure 4 is the graphic representation of (7) for different levels of fixed costs. In general, higher fixed cost projects need higher output volume to breakeven. At the same time, higher fixed cost projects, which have lower variable costs in production, earn higher rates of return in large markets.

We can see from the above discussion that the proper level of fixed investment in a project depends on the expectation of the level of uncertainty and the size of the market. When the outlook is stable and the market size is large, projects with high fixed investment earn higher rates of return. When the outlook is uncertain or market size is small, projects with low fixed cost breakeven easier.

In the ecological system, the market size can be understood as the size of resource base. When resources are abundant, an ecological system can support large, complex organisms (Colinvaux, 1978). Physicists and biologists are often puzzled by the apparent tendency for biological systems to form complex structures, which seems to contradict the second law of thermodynamics (Schneider and Sagan, 2005; Rubí, 2008). However, once we realize that systems of higher fixed cost provide higher return in the resource rich and stable environments, this evolutionary pattern becomes easy to understand. An example from physiology will highlight the tradeoff between fixed and variable cost with different levels of output.

> An increased oxygen capacity of the blood, caused by the presence of a respiratory pigment, reduces the volume of blood that must be pumped to supply oxygen to the tissues. …The higher the oxygen capacity of the blood, the less volume needs to be pumped. There is a trade-off here between the cost of providing the respiratory pigment

> and the cost of pumping, and the question is, Which strategy pays best? It seems that for highly active animals a high oxygen capacity is most important; for slow and sluggish animals it may be more economical to avoid a heavy investment in the synthesis of high concentrations of a respiratory pigment. (Schmidt-Nielson, 1997, p. 120)

This is another example of fixed cost, variable cost trade-off. For high output systems (highly active animals) investment is fixed cost (respiratory pigment) is favored while for low output systems (slow and sluggish animals) high variable cost (more pumping) is preferred. Pumping is variable cost compared with respiratory pigment because respiratory pigment lasts much longer.

With the volatile commodity market, people become aware of the problem of resource depletion. Many people have advocated the increase of efficiency as a way of reduce energy consumption. Will the increase of efficiency reduce overall resource consumption? Jevons made the following observation more than one hundred years ago.

> It is credibly stated, too, that a manufacturer often spends no more in fuel where it is dear than where it is cheap. But persons will commit a great oversight here if they overlook the cost of improved and complicated engine, is higher than that of a simple one. The question is one of capital against current expenditure. … It is wholly a confusion of ideas to suppose that the economic use of fuel is equivalent to the diminished consumption. The very contrary is the truth. As a rule, new modes of economy will lead to an increase of consumption according to a principle recognized in many parallel instances. (Jevons, 1965 (1865), p. xxxv and p. 140)

Put it in another way, the improvement of technology is to achieve lower variable cost at the expense of higher fixed cost. Since it takes larger output for higher fixed cost systems to breakeven, to earn a positive return for higher fixed cost systems, the total use of energy has to be higher than before. That is, technology advancement in energy efficiency will increase the total energy consumption. Jevons' statement has stood the test of time. Indeed, the total consumption of energy has kept growing, almost uninterrupted decades after decades, in the last several centuries, along with the continuous efficiency gain of the energy conversion (Inhaber, 1997; Smil, 2003; Hall, 2004).

Take hybrid cars as an example. Hybrid cars have two engines, one internal combustion engine, like conventional cars and one electric engine. This adds to the manufacturing cost (and hence resource consumption) of hybrid cars. If the owner of a hybrid car drives very little, the total resource consumption from a hybrid car is actually higher than a conventional car. Only when a hybrid car is used extensively, it becomes less wasteful relative to a conventional car. Therefore, the use of a hybrid car, when manufacturing cost is included, guarantees high resource consumption. This is true for almost all of the "clean energy", such as solar panels, whose production is highly pollutive.

Discount rate and project duration:

When the discount rate or interest rate becomes lower, the variable cost of a project will decrease and profit will increase. Projects with different lengths of duration will be affected differently from the reduction of discount rates. Figure 5 presents the ratios of profits between projects at low and high discount rates at different levels of project duration. As project lengths are increased, the ratios increase as well. This indicates that projects with longer duration benefit more from the reduction of interest rates.

Next we calculate the breakeven point of a project with respect to the project duration and the discount rate. Let us assume that project output per unit of time is one. The calculation from formula (7) shows that it requires lower discount rate to breakeven when the project duration is lengthened. When the project duration is sufficiently long, the discount rate could become negative at the breakeven point. This is illustrated in Figure 6. In the following, we will present more empirical evidences about the inverse relationship between discount rate and duration of project or span of life. Fecundity, as well as mortality rate, is proximity for discount rate. Lane (2002) provided a detailed discussion about the tradeoff between longevity and fecundity in the biological systems.

> Notwithstanding difficulties in specifying the maximum lifespan and reproductive potential of animals in the wild, or even in zoos, the answer is an unequivocal yes. With a few exceptions, usually explicable by particular circumstances, there is indeed a strong inverse relationship between fecundity and maximum lifespan. Mice, for example, start breeding at about six weeks old, produce many litters a year, and live for about three years. Domestic cats start breeding at about one year, produce two or three litters annually, and live for about 15 to 20 years. Herbivores usually have one offspring a year and live for 30 to 40 years. The implication is that high fecundity has a cost in terms of survival, and conversely, that investing in long-term survival reduces fecundity.
>
> Do factors that increase lifespan decrease fecundity? There are number of indications that they do. Calorie restriction, for example, in which animals are fed a balanced low-calorie diet, usually increase maximum life span by 30 to 50 per cent, and lower fecundity during the period of dietary restriction. … The rationale in the wild seems clear enough: if food is scarce, unrestrained breeding would threaten the lives of parents as well as offspring. Calorie restriction simulates mild starvation and increase stress-resistance in general. Animals that survive the famine are restored to normal fecundity in times of plenty. But then, if the evolved response to famine is to put life on hold until times of plenty, we would expect to find an inverse relationship between fecundity and survival. (Lane, 2002, p. 229)

Lane went on to provide many more examples on the inverse relation between longevity and fecundity.

In human society, we often use longevity, or duration of human life as an indicator of the quality of a social environment. At the same time, societies that enjoy a long life span, such as Japan, are often concerned about below replacement fertility. Our calculation shows that there is a negative correlation between duration of life and fertility. Intuitively, the aging population needs a great amount of resources to maintain their health, which reduces the amount of resources available to support children. Hence, there is a natural tradeoff between longevity and fertility. This result has important implications in policy making. In a society with below replacement fertility, should we continue to increase the funding on the needs of the seniors at the expense of the children and the unborn? With increasing longevity and decreasing fertility, seniors form the increasingly dominant voting block. This poses a great challenge to maintain a sustainable society.

Discount rate and uncertainty

Variable cost is an increasing function of discount rate. When uncertainty is low, variable cost is much lower with a low level of discount rate. When uncertainty is high, variable costs are not sensitive to discount rate. Therefore, it is only important to reduce discount rate in a stable environment. Figure 7 presents the ratios of variable costs between low and high levels of uncertainty at different levels of discount rates. It shows that the reduction of the variable cost is much more significant at a low uncertainty level. This explains why *r* species, which have high discount rates, often thrive in highly uncertain environments. It may show why low interest rates, in a climate of economic crisis, have little effect on the level of perceived profitability and therefore on activity. This is called "pushing on a string."

The same idea about the relationship between discount rate and uncertainty had been reached earlier. "The same discount curve that is optimally steep for an organism's intelligence in a poorly predictable environment will make him unnecessarily shortsighted in a more predictable environment (Ainslie, 1992, p. 86).

Volume of output and uncertainty

In the earlier part of this paper, we assumed that the volume of the output of a company does not affect other factors in production. However, when the size of a company increases and the business expands, the internal coordination and external marketing becomes more complex. This can be modeled with uncertainty, σ, as an increasing function of the volume of the output. Specifically, we can assume

$$\sigma = \sigma_0 + lQ$$

Where σ_0 is the base level of uncertainty, Q is the volume of output and $l > 0$ is a coefficient. With the new assumption, we can calculate the return of production from formula (7). The result from the calculation is presented in Figure 8. From Figure 8, the rate of return initially increases with the production scale, which is well known as the economy of scale. When the size of the output increases further, the rate of return begin to decline. This is the law of diminishing return. If the size of the output keeps increasing, the rate of return will eventually drop below zero.

5. Concluding remarks

We present an economic theory of social and biological systems derived from physical laws. As this theory is new, it is difficult to assess its implications precisely. We will reflect on the implications of the development of rational mechanics first and try to infer some possible implications of this new economic theory.

First, rational mechanics provides simple and systematic methods to compute the movements of objects that were difficult or impossible to perform before. Second, after the development of rational mechanics, the movements of celestial bodies and earthly bodies began to be understood by the same physical laws. Third, before the development of the rational mechanics, Earth occupied the unique place: The center of the universe. Everything falls naturally to Earth. After the development of the rational mechanics, Earth still occupies a unique place: Somewhere between Venus and Mars in the solar system. But now there is a need to explain why things fall to Earth.

The new economic theory has some parallel implications. First, it provides simple and systematic methods to compute the return of investment by social and biological entities that were difficult or impossible to perform before. Second, the evolution of social and biological systems can be understood from the same economic theory. Third, from the mainstream economic theory, human beings have the unique position as the dominant species on Earth because of some unique qualities of human beings. From the new economic theory, human beings are still unique. All species are unique. But the current dominant position of human beings in the ecosystem has to be explained. As many people have argued eloquently from the basic biological principles, the current affluent lifestyle enjoyed by many in the wealthy countries and few in the poor countries cannot be sustained.

The new economic theory is deeply connected to the theory of rational mechanics. The theory is derived from Feynman-Kac formula. Feynman's formulation of quantum mechanics is a generalization of the least action principle, which is the Lagrangian formalization of rational mechanics. In a roundabout way, this economic theory fulfills Leon Walras' dream to derive an economic theory from rational mechanics.

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Figure captions

Figure 1. Fixed cost and discount rate: When discount rates are decreased, variable costs of high fixed cost systems decreases faster than variable costs of low fixed cost systems.

Figure 2. Fixed cost and uncertainty: In a low uncertainty environment, variable cost drops sharply as fixed costs are increased. In a high uncertainty environment, variable costs change little with the level of fixed cost.

Figure 3. Fixed cost and duration of the project: Comparison of the profit level of one project with that of two projects with duration half long while keeping other parameters identical. Assume the annual output of two types of projects are the same. When duration is short, the profit level of one long project is higher than two short projects. When duration is long, the profit level of one project is lower than two short projects.

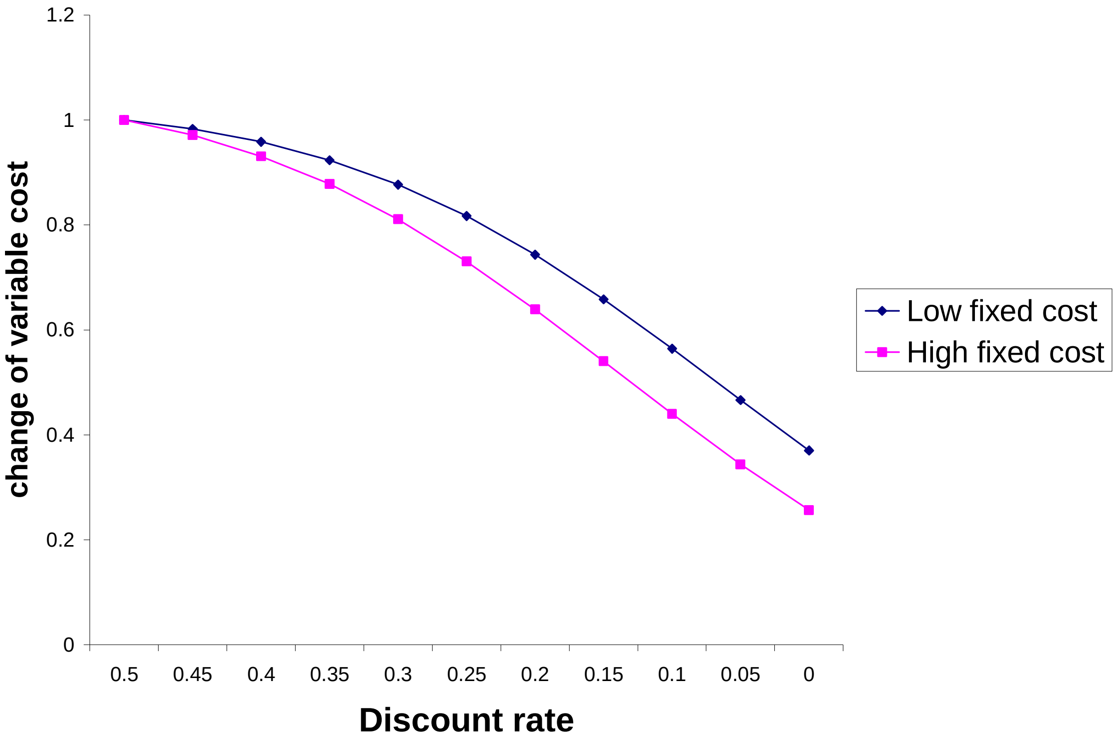
Figure 4. Fixed cost and the volume of output: For a large fixed cost investment, the breakeven market size is higher and the return curve is steeper. The opposite is true for a small fixed cost investment.

Figure 5. Project duration and discount rate: the ratios of profits between projects at low and high discount rates at different levels of project duration

Figure 6. Longevity and population growth rate: The tradeoff between longevity and population growth

Figure 7. Uncertainty and discount rate: the ratios of variable costs between low and high levels of uncertainty at different levels of discount rates

Figure 8. Volume of output and the rate of return: The rate of return of a project with respect to volume of output, when diffusion is an increasing function of volume of output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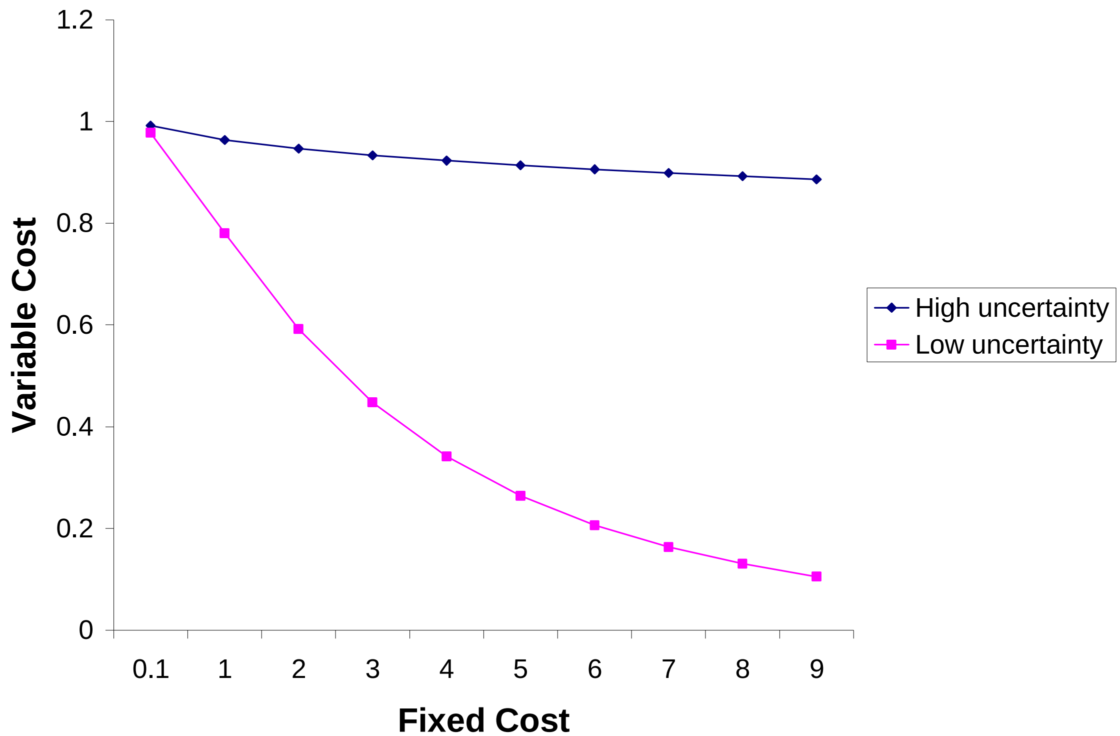
Discount rate
Low fixed cost
High fixed cost



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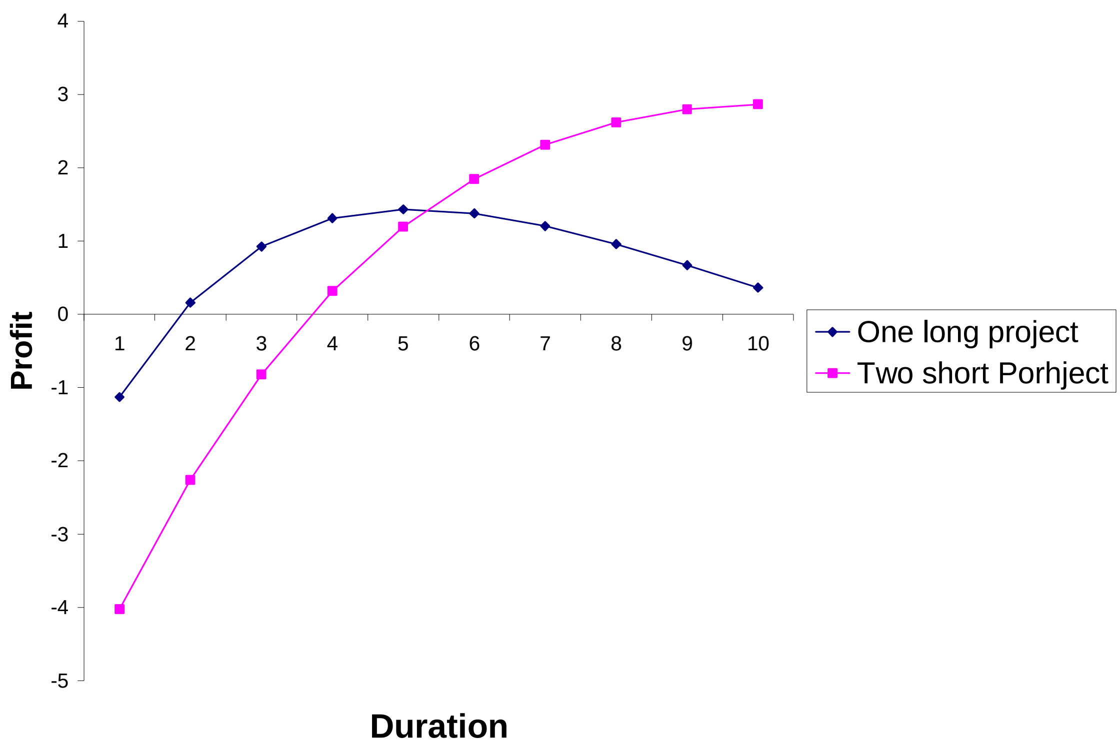

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Profit
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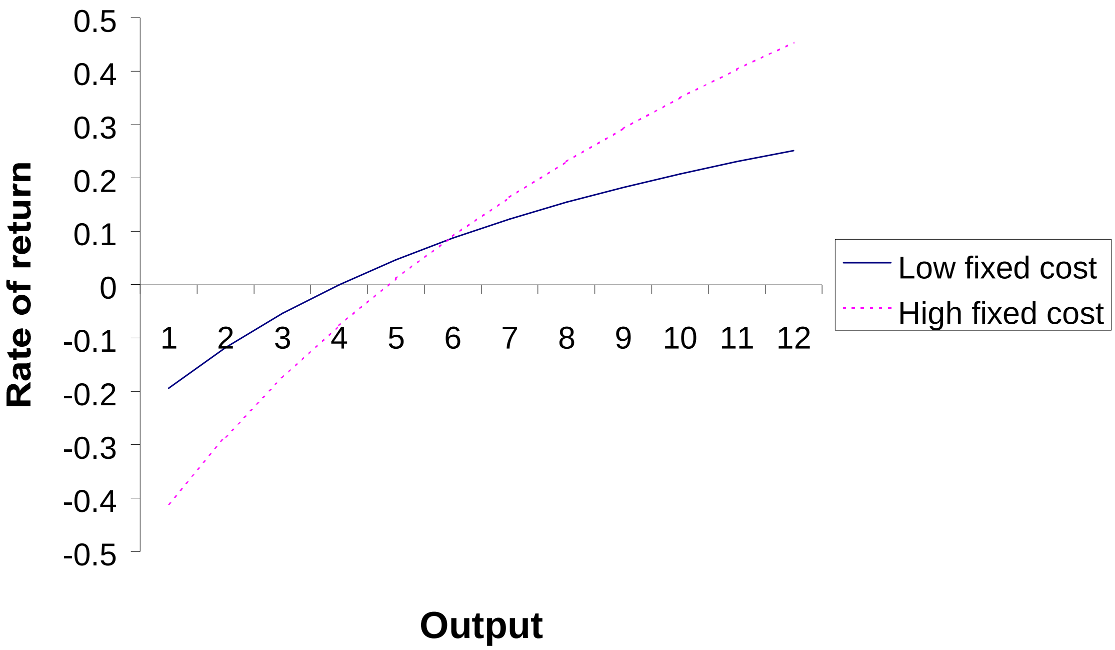
Duration
One long project
Two short Porhject



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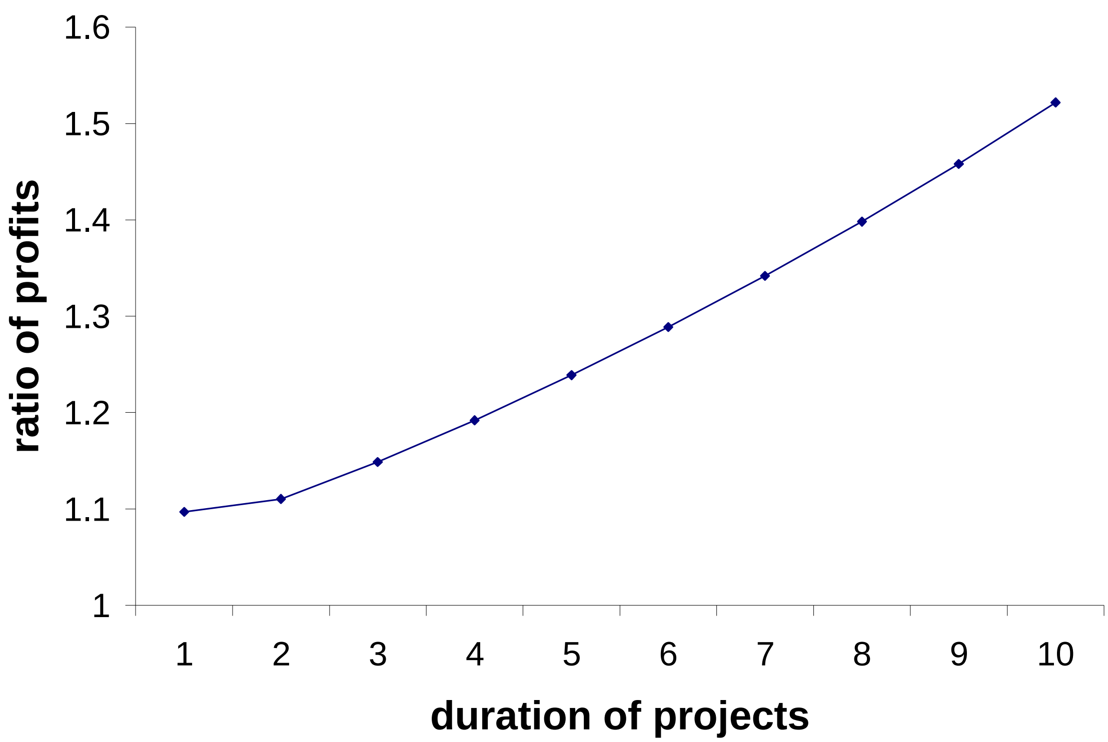
Output
Low fixed cost
High fixed cost



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ratio of profits
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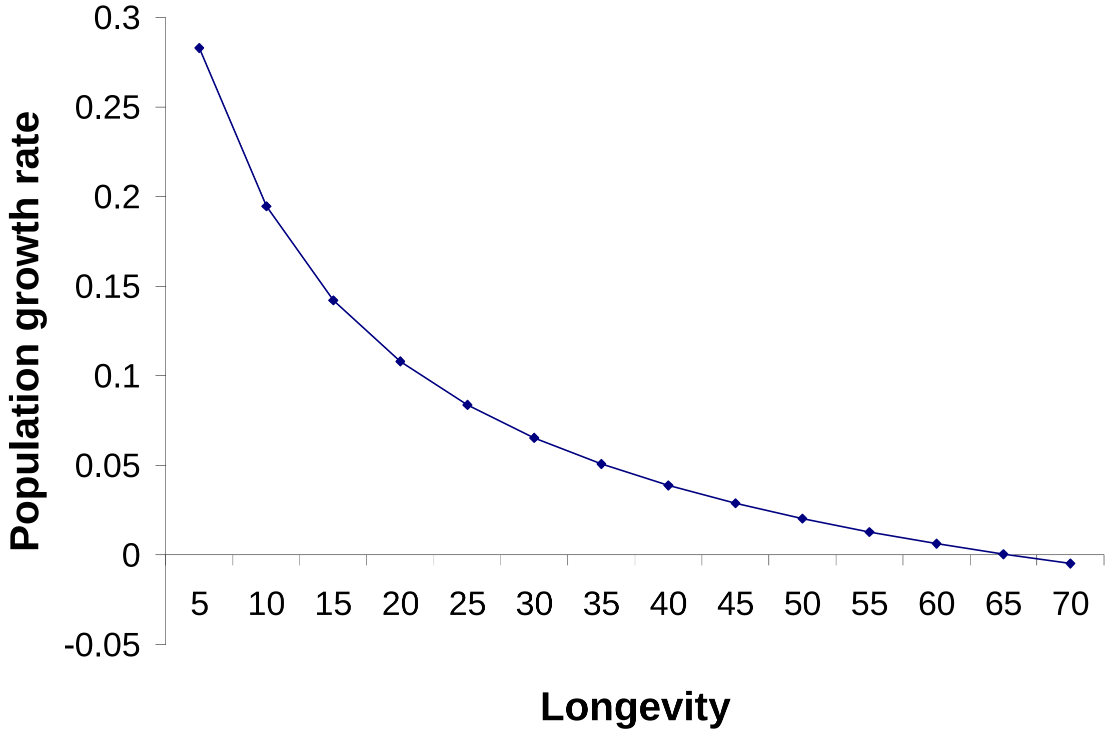
duration of projects


Population growth rate
Longevity
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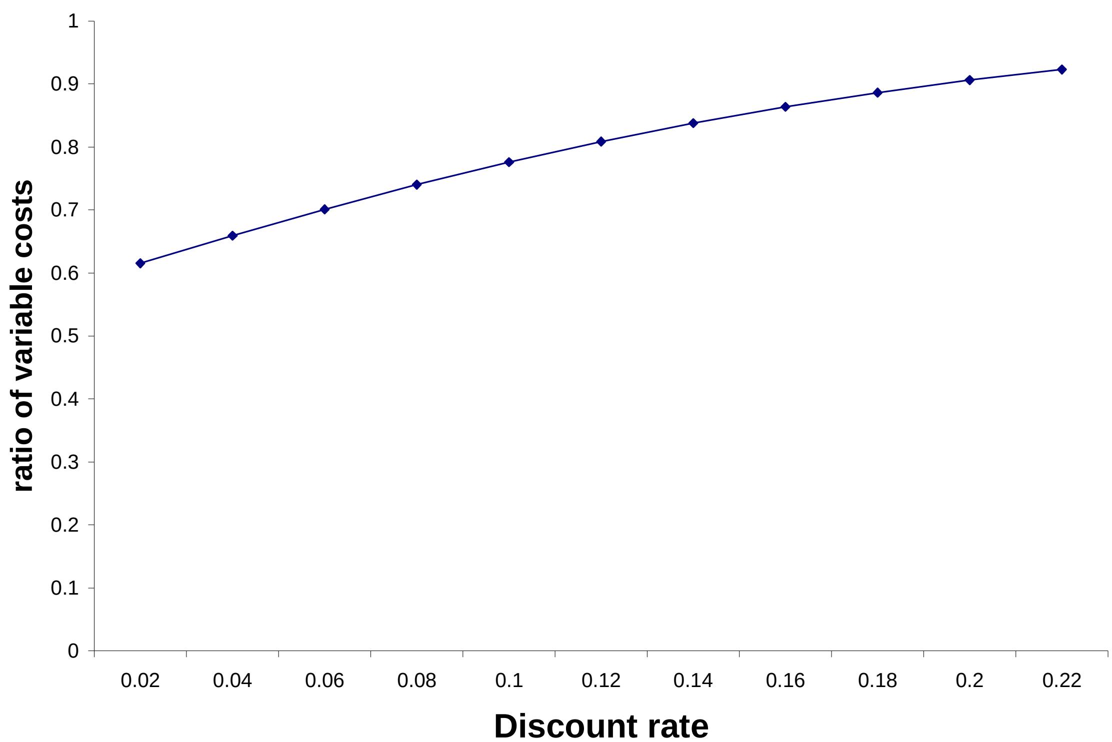
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ratio of variable costs
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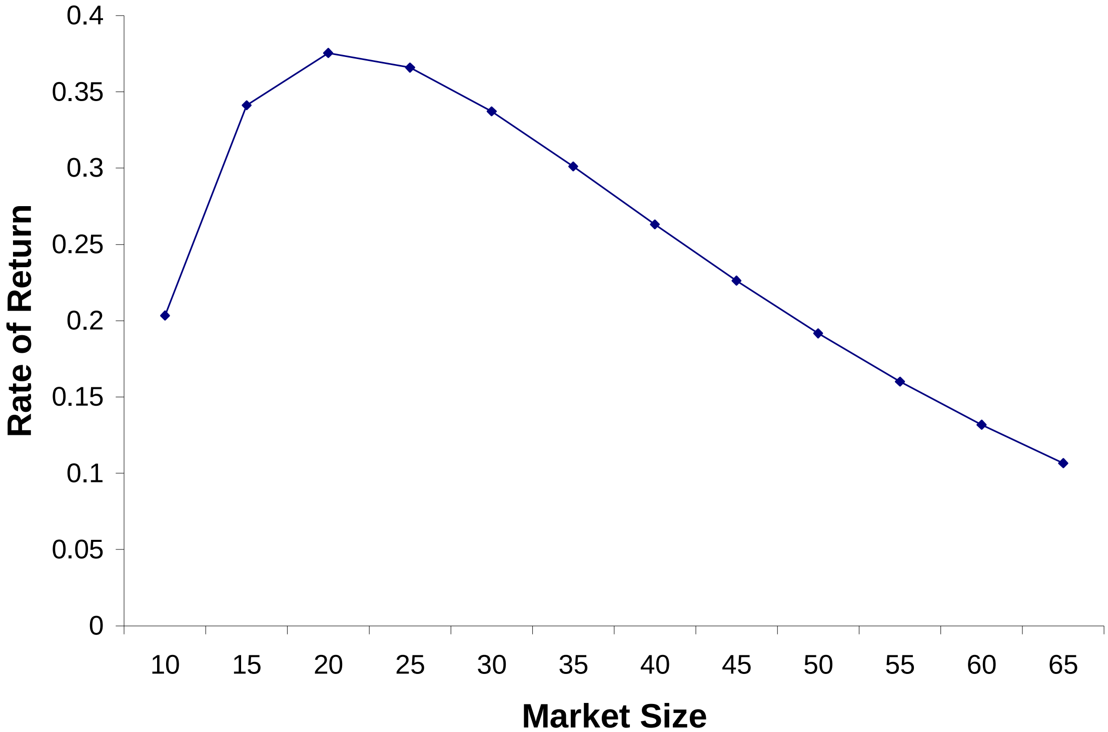
Discount rate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Rate of Return
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Market Size