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An entropy theory of value

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ABSTRACT

From the properties that the value of commodities should satisfy, it can be derived that the onlymathematical formula to represent value, as a function of scarcity, is the entropy function. From this function, the main factors that influence the value of a commodity are scarcity of the commodity, the number of producers, and the market size. In particular, monopolies and near monopolies, which have small number of producers or service providers, have high valuations. Many of the important institutional structures, such as religions, governments, unions, patents and regulations, obtain high valuation through monopoly.

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1. Introduction

Value is the most fundamental concept in economics. It also has great influence in broader areas of social theory and social science. A good understanding of value should shed light on social structures, economic policies and business strategies.

There are three main theories of value: utility theory, scarcity theory and labor theory. Walras (1873), the chief architect of the neoclassical economic theory, argued that value is a function of scarcity. He said that it is too broad to define utility as value since many things with high utility, such as oxygen, are of no economic value. Likewise it is too narrow to define labor as value, for many things that take little labor have high value. For example, although oil produced in Alberta takes much more labor than oil produced in Saudi Arabia, Alberta oil is not more expensive than Saudi oil. In conventional economic theories, additional terminologies are created, such as rent, to explain this phenomenon. However, this makes the labor theory of value less general.

In this paper, we present an entropy theory of value. Entropy is a measure of scarcity in physics. An entropy theory of value is a scarcity theory of value. From the second law of thermodynamics, or the entropy law, the entropy of a system tends to increase. A display of low entropy state is the universal sign of attractiveness for animals, which include human beings. This explains how subjective utilities are generally entropy related. Since all human activities need to consume low entropy sources – for instance, fresh food is preferred to stale, new clothing is preferred to old, an entropy theory of value includes the labor theory of value. But it is broader than the labor theory of value. From the entropy theory of value, other low entropy resources, such as oil, will have value as well.

Because of the universality of the entropy law, an entropy theory of value has been suggested before. The success of Shannon's (1948) entropy theory of information stimulated many research efforts in economics. Since information is the reduction of entropy, an entropy theory of value is inevitably an information theory of value. However, the information theory of value, or the entropy theory of value, was not developed in economics. Very often, the direction of scientific research is shaped by the thinking of an authority. In an often-cited passage, Arrow wrote, "the well-known Shannon measure which has been so useful in communications engineering is not in general appropriate for economic analysis because it gives no weight to the value of the information. If beforehand a large manufacturer regards it as equally likely whether the price of his product will go up or down, then learning which is true conveys no more information, in the Shannon sense, than observing the toss of a fair coin" (Arrow, 1983 (1973), p. 138).

The Shannon measure actually measures the weight of information. For example, N symbols with identical Shannon measure carry N times more information than a single symbol (Shannon, 1948). Similarly, the value of the information about the future price is higher to a large manufacturer than to a small manufacturer, other things being equal. Later, we show that information as an economic commodity shares most of the important properties of physical commodities.

Georgescu-Roegen observed that "there have been sporadic suggestions that all economic values can be reduced to a com-

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mon denominator of low entropy" (Georgescu-Roegen, 1971, p. 283). However, he thought that linking economic value to low entropy would not be of much help to economists because "he would only be saddled with a new and wholly idle task—to explain why these coefficients differ from the corresponding price ratios" (Georgescu-Roegen, 1971, p. 283). To this argument we may reflect on Shannon's entropy theory of information. The entropy theory of information does not resolve all problems related to information. But it does resolve many important problems in communication. For example, the entropy theory of information provides a measure on the minimal cost of information transmission. Very often, video data can be compressed one hundred times in transmission with little loss of quality. The entropy theory of information provides a theoretical foundation to help us transmit large amount of information at low cost, which is extremely important in today's society.

Similarly, the entropy theory of value will not resolve all problems in economic activities. But it greatly simplifies our understanding on a broad range of social and economic phenomena. It provides a simple mathematical relation to understand how scarcity, the number of producers or service providers, and market size affect values. In the entropy theory of value, economic value is defined as a logarithm function, just as information is defined as a logarithm function. In information theory, the base of the logarithm function is 2, as the information is transmitted in a binary system $\{0, 1\}$. In the entropy theory of value, the base of the logarithm function represents the number of suppliers of a product or a service. When the base approaches 1, the value of the product or service approaches infinity. This indicates that monopoly and near monopoly are the most important ways to increase value.

Governments have monopoly in violence, legal actions and taxation. Patents, intellectual property rights, regulation, industry standards and market dominance help businesses establish and maintain monopolies. Unionization achieves monopolies in bargaining. Monotheistic religions hold monopolies to reach heaven. Indeed, many of the most important functions in human societies are structured in monopoly or near monopoly.

The mainstream value theory is represented by the classical book, *Theory of value; an axiomatic analysis of economic equilibrium* by Debreu (1959). Debreu's theory of value is used to construct a rigorous foundation of equilibrium theory, according to which wealth is maximized in an equilibrium state. In equilibrium, many competitors are assumed to operate in the market. From practical experience, we know that valuation is low in a market with many competitors. Market participants, as individuals or organizations, will actively seek opportunities to gain and maintain monopolies. This feature is ignored by the Debreu model but accurately captured by the entropy theory of value.

This entropy theory of value is largely unchanged since its early development (Chen, 2005, 2016), but the applications have greatly expanded. The rest of the paper is structured as follows. In Section 2, we formally develop the mathematical theory of value as entropy. The influence on value of factors such as scarcity, the number of producers and market size of a commodity can be understood naturally from the logarithm function of value. Since scarcity of resources, including human resources, is often regulated by institutional measures such as immigration laws and patent laws, the value of economic commodities is in great part a reflection of institutional structures. In Section 3, we apply this theory to trade, regulation and competition. In Section 4, we utilize the results from information theory, statistical physics and the theory of evolution to discuss the relation between physical entropy and economic value. We discuss how the entropy theory of value offers a unifying understanding of the objective and subjective theories of value. In Section 5, we discuss how informational and physical commodities share common properties in the light of this entropy theory of value. By resolving the conceptual difficulties that have confounded us for many years, we offer a unified understanding of physical entropy, information and economic value. In Section 6, we discuss the relation between economic value and social welfare. Section 7 concludes.

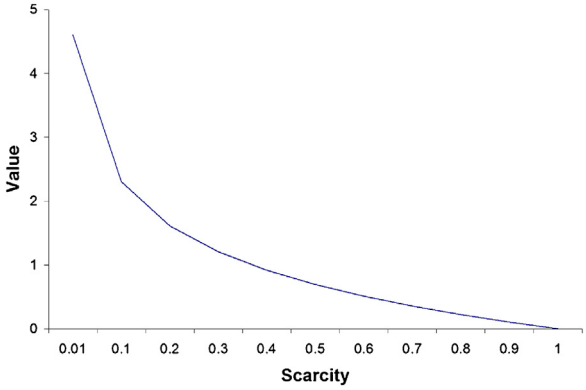

Fig. 1. Value and scarcity.

2. Main properties

Value is a function of scarcity. Scarcity can be defined as a probability measure P in a certain probability space. The value of any product shall satisfy the following properties:

(a) The value of two products should be higher than the value of each of them.
(b) If two products are independent, that is, if the two products are not substitutes or partial substitutes of each other, then the total value of the two products will be the sum of two products.
(c) The value of any product is non-negative.

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

$$V(P) = -\log_b P \tag{1}$$

Where b is a positive constant (Applebaum, 1996). In information theory, the base of the logarithm function is usually chosen to be two because there are two choices of code in information transmission, namely, 0 and 1 (Shannon, 1948). In economics, the base b can be understood as the number of producers. In general, if the scarcity of a service or product, X, can be estimated by the probability measure $\{p_1, p_2, \ldots p_n\}$, the expected value of this product is the average of the value of each possibility, that is

$$V(X) = \sum_{i=1}^{n} p_i(-\log_b p_i)$$

Therefore, value – just as information – in its general form can be defined as entropy, given that they are the same mathematically. In the following, we will discuss the properties of this simple analytical theory of value-as-scarcity.

2.1. Scarcity and value

Fig. 1 is a graph of Formula (1), which shows that value is an increasing function of scarcity. That is why diamonds are worth more than water in most circumstances. In extreme abundance, i.e., when $P = 1$, $-\log P = 0$, the value of a given commodity is equal to zero, even if that commodity is very useful. For example, food is essential for survival. Most countries subsidize food production in various ways to guarantee the abundance of food, which causes

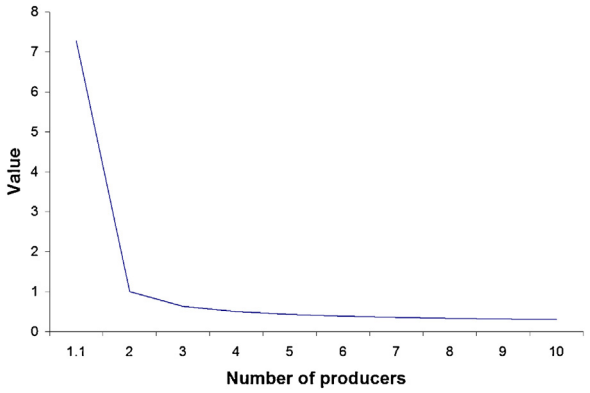

Fig. 2. Value and the number of producers.

its low economic value. This shows that economic value and social value can diverge.

Gold is mined on average at low concentrations and it takes much energy to grind up the rocks. Likewise silver, as compared to copper. In general, a scarce commodity takes more energy and labor to mine than an abundant commodity. The scarcity theory of value is highly consistent with the energy theory of value and the labor theory of value. An advantage of the scarcity theory of value is that it can be formulated as a mathematical theory easily.

2.2. Value and the number of producers or consumers

From Formula (1), value is inversely related to the number of producers of a given product. Fig. 2 displays the relation between value and the number of producers. When the number of producers is small, the value of a product is high. That's why the products of monopolies and oligopolies are valued highly. If the base becomes one, i.e., absolute monopoly without substitution, value approaches infinity.

Governments have the monopoly on violence, legal decisions and taxation. Democratic societies maintain multiparty system and elections. This is to reduce the power, or the value, of governments. But monarchy or one party rule are more common in most of human history. Even in democratic societies, the power of governments, as monopolies, tend to grow over time. Today, governments' powers over citizens and businesses are much broader than (say) in the 19^{th} century. Many important social activities, such as education and (in most countries) medicine, are under government control or influence.

In many countries, education is mostly funded by the government. Students can only go to one school for their elementary and secondary education. This lack of choice in education for students greatly increases the power and hence the value of educators.

The medical systems in some countries, such as Canada, don't allow patients to choose doctors and the types of treatments they can have. Instead, patients can only go to see one doctor, who decides what treatment a patient can get and who the patients can see. With this monopoly over patients, doctors gain extraordinary power and hence enjoy high incomes.

Successful religions, such as Judaism, Christianity and Islam, are monotheistic, while polytheistic religions, such as Buddhism, have difficulties withstand the advance of monotheistic religions. Monotheism, with only one god, exerts much greater control over its believers than polytheism.

The number of providers of most economic goods depends on many factors. In the following, we give a brief discussion about the institutional structures that affect market entry and the number of suppliers for a given product.

Anti-trust regulations aim to prevent price fixing by existing providers of a service or product. They also intend to lower barriers to potential entry. By increasing the number of choices, both measures reduce the value of products, and hence the cost to consumers. For this reason, the value of a product will in general be lower in a more competitive market. Patent rights and commercial secrets legislation, on the other hand, grant monopoly power and discourage the diffusion of knowledge. Patent rights and monopoly power allow the holders to maintain high product prices. The IT industry has less strict patent protection than the biotech industry. As a result, IT develops much faster than biotech. In general, industries with more patent protection develop slower than industries with less patent protection. Technology often progresses very fast during war time, when patent laws are often ignored.

The quota system in trade policy forces the transfer of production technology from the dominant producer to other countries. Ultimately, the diffusion of technology and the increase of the number of producers will reduce the value of the imported goods. This will benefit the importing countries over the long term, instead of the loss suggested in standard literature.

The value of consumers is also negatively related to their numbers. When there is only one dominant customer, it can mostly dictate the terms of trade and hence would like to keep its monopoly power. Producers, on the other hand, would like to increase the number of their customers.

The relation between number of producers and value can help understand many commercial and social phenomena. Each printer manufacturer designs printers in a way that printer ink from other firms cannot operate well. Customers who buy printers from one company can use ink from only the same company. By restricting the choice from customers, producers can sell ink at higher price and obtain higher profits.

Unions form a monopoly of bargaining. With only a single unit of bargaining, a trade union is in a much stronger position than many individuals in bargaining with management. Unions are often formed in many stable professions, such as government employees and teachers. Professions such as physicians, often are certified by a single organization, which increases their monopoly value. Doctors' notes are famously illegible. When fewer people, especially patients, are informed, the value of the profession increases.

Household machines are often designed that they can only be repaired with specialized tools. Once a mixer in our home broke down. I watched a YouTube video to figure out how to have the mixer repaired. When I opened the mixer, I found the design of the mixer had been changed. With the new design, specialized tools are needed to repair the machine. A customer has to buy a new mixer or have the mixer repaired by an expensive technician. Since the value of a product depends very much on the number of producers, the attempt to gain monopoly is often the most important business strategy and political strategy (Baran and Sweezy, 1966).

It is often difficult to determine the exact number of providers of a service empirically. Air travel in vast and thinly populated countries, such as Canada, where alternative modes of transportation are often very time consuming, provides a good testing ground. On March 10, 2005, Jetsgo, a Canadian airline, declared bankruptcy. There are three major operators in the air travel industry in Canada. They are Air Canada, WestJet and Jetsgo. There are regional carriers and international airlines competing for many routes. Most of the profits of airlines come from regional routes where competition is not intense. We can assume four providers for the air travel service for typical regional routes before Jetsgo declared bankruptcy. From (1), the value of each airline can be represented as

$$-\log_4 P \text{ and } -\log_3 P$$

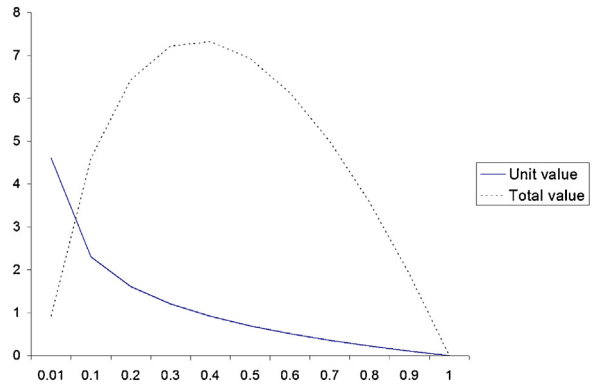

Fig. 3. The unit value and total value of a product with respect to scarcity.

before and after Jetsgo declare bankruptcy. The change of value is therefore

$(-\log_3 P)/(-\log_4 P) - 1 = \log_3 4 - 1 = 0.262$

Jetsgo declared bankruptcy at the evening of March 10, 2005, after the market close. The closing prices of stocks of WestJet and Air Canada at March 10 and 11 are 11.17, 15.6 and 32.19, 37 respectively. The price changes are

$15.6/11.17 - 1 = 0.397$ for WestJet

and

$37/32.19 - 1 = 0.149$ for Air Canada

respectively. The average change of price is

$(0.397 + 0.149)/2 = 0.273$

which is very close to the theoretical prediction of 0. 262.

Some theoretical and empirical results can be further refined. For example, this theory does not distinguish the sizes of different providers of a service. The refinement of the theory is left to the future research.

2.3. Market size, product life cycle and product value

Suppose the potential market size of a product is M. The percentage of people who already have the product is P. Then the unit value of the product is

$$-\log P \tag{2}$$

Since the number of people who have bought the product is MP, The total value of the product is

$$MP(-\log P) \tag{3}$$

From (3), the value of a product is higher with a larger market size. Fig. 3 is the graph of unit value and total value of a product with respect to its abundance. From Fig. 3, we can explore the relation between the value of a product and the product life cycle. When a product is new and scarce, the unit value is high. Its total value is low. As the production increases, the total value will increase as the unit value decreases. When the production quantity is over a certain level, however, the total value of a product will start to decrease as well. Intuitively, this is easy to understand. The market values of manufacturers of mature products are generally low, although the production processes are very efficient. This observation shows that efficiency is not equivalent to value.

The above discussion shows that the implications of identifying value with the scarcity are highly consistent with our intuitive understanding of economic value. It should be noted that in economic processes, a final product embodies many different kind of scarcities: labor, raw materials and equipment. A detailed analysis of the value of a particular product will be much more involved. For example, black and white television sets are less common than color television sets and yet they have less economic value. This is because the process of making color TV takes more scarce resources such as labor. The value of a final product is the combination of total scarcity.

3. Several applications

This value theory can be applied to many different areas. We will present several applications on the impacts of trade policies and regulatory policies

3.1. On the impact of trade policies and trade barriers

Trade policies can be open or restricted. Access to the market can be easy or difficult. What are their effects? In general, trade occurs between regions with differential abundance of a commodity, which could be due to differential concentration of natural resources or the capacity of some manufacturing technology. Most oil exports occur in several countries. High tech industries are highly concentrated in Silicon Valley. To examine the quantitative impacts of a trade policy, we will look at a two region case and calculate a numerical example. (The proof of the general case is available from the author.) Let the market sizes of two regions be 100 and 1000 respectively, with resource concentration of 0.9 and 0.2. This indicates that the smaller region is abundant in a particular commodity. Suppose two regions are segregated. Then the commodity prices at two regions are

$-\ln(0.9) = 0.11$ and $-\ln(0.2) = 1.61$

The commodity price in the abundant area is much cheaper. The total values of the commodity in two regions are

$100 * 0.9 * (-\ln(0.9)) = 9.48$ and $1000 * 0.2 * (-\ln(0.2)) = 321.89$

The global total value of the commodity is

$9.48 + 321.49 = 331.37$

When two regions are integrated into a free trade zone, the global scarcity of the commodity is

$(100 * 0.9 + 1000 * 0.2)/(100 + 1000) = 0.26$

The new price of the commodity is

$-\ln(0.26) = 1.33$

The global value of the commodity is

$1100 * 0.26 * (-\ln(0.26)) = 386.62$

The total value of the commodity in the resource rich region is

$100 * 0.9 * (-\ln(0.26) = 119.99$

The total value of the commodity in the resource poor region is

$1000 * 0.2 * (-\ln(0.26) = 266.64$

In the following, we analyze the winners and the losers in a free trade economy. First, the global value of the commodity in a free trade environment is 386.62, which is higher than 331.37, the global value in a segregated economy. In general, free trade increases the total value of a product.

Second, the total value from the resource rich region in the free trade environment is 119.99, which is higher than 9.48, the total

Table 1
Summary of value changes with market integration.

	Segregated market		Integrated market
	Resource poor region	Resource rich region	
Market size	1000	100	1100
Scarcity	0.2	0.9	0.26
Unit price	1.61	0.11	1.33
Value in segregation	321.89	9.48	331.37 (sum in segregation)
Value in integration	266.64	120	386.62
Difference in value	−55.25		55.25

value in a segregated economy. That is why producers from the resource rich region will promote free trade. The total value from the resource poor region in the free trade environment is 266.64, which is lower than 321.89, the total value in a segregated economy. That is why producers from the resource poor region will resist free trade.

Third, the magnitude of impact to small and large regions are different. For the small region, the change of commodity value is from 9.48 to 119.99, which is very high. For the large region, the change of commodity value is from 321.89 to 266.64, which is moderate. As a result, small regions have stronger incentive to influence trade policies, although large regions are often more powerful. For example, Canada charges 270% tariff on import dairy products to deter US dairy imports. By comparison, US charges 27% tariff on Canadian lumber imports. In general, small social groups often have stronger internal cohesion than large social groups.

Fourth, the unit value of the commodity in a free trade environment is 1.33, which is higher than 0.11, the unit value of the commodity in the resource rich region and lower than 1.61, the unit value of the commodity in the resource poor region in a segregated economy. So ordinary consumers in a resource rich country who do not receive income from the resource industry will resist free trade. Ordinary consumers in a resource poor country who do not receive income from the resource industry will welcome free trade. The main results are summarized in Table 1.

There are two major price indices in the crude oil market: WTI and Brent. Historically, WTI and Brent crude oil prices were very close. However, WTI traded at a deep discount to Brent in recent years as Alberta increased its oil output, most of which was sold in the US. In an attempt to sell more oil at the international price, proposals were made to build or expand several oil pipelines to the coastal area so Alberta oil can be supplied to the international market. This would increase the value of Alberta oil products. Canada produces about three million barrels of crude oil per day. Canadian oil is often sold several dollars per barrel below the international price. Every year the Canadian oil industry loses several billion dollars from this price differential; equivalently, customers of the Canadian oil gain several billion dollars per year from the current situation. From the above analysis, it is easy to understand why there is so much negative publicity and disruption around the pipeline projects.

Next, we will analyze how trade tariff affects import and export countries. From our value theory, product value is a function of scarcity. Tariff policy can often significantly influence output quantity and hence product value, especially when a certain commodity has one big producer and one big consumer. For example, Canada is a big producer of softwood lumber while USA is a big consumer. From value theory, the value of lumber market is represented by VP(−*ln*P), where P is the proportion of lumber that is on the market. Assume V, the total volume of the forest, is 10,000. A consumer country will benefit from a trade policy that increases the production of lumber since it will reduce the value of imported lumber.

Suppose the cost structure of the lumber industry is the following. The total fixed cost in lumber production in country C is 100. The variable cost is 55% of product value. The total value of the lumber products is VP(−*ln*P) and the total cost of production is 100 + 0.55*V*P*(−lnP). Suppose every year, 1% of the all lumber is harvested. The profit on lumber production is equal to revenue minus total cost

$$\begin{aligned}&-VP\ln P-(100+0.55*(-VP\ln P))\\&=-10000*0.01*\ln(0.01)\\&-(100+0.55*(-10000*0.01*\ln(0.01)))\\&=107\end{aligned}$$

In 2001, the USA imposed a 27% import duty on lumber from Canada. If the volume of production remained at the same level, the profit for lumber production would be

$$\begin{aligned}&-VP\ln P*(1-0.27)-(100+0.55*(-VP\ln P))\\&=-10000*0.01*\ln(0.01)*(1-0.27)\\&-(100+0.55*(-10000*0.01*\ln(0.01)))\\&=-17\end{aligned}$$

which means that the lumber industry will lose money. Production of lumber has to be increased to avoid loss. If the production level is increased to P = 1.5%, the profit for the lumber industry will become

$$\begin{aligned}&-VP\ln P*(1-0.27)-(100+0.55*(-VP\ln P))\\&=-10000*0.015*\ln(0.015)*(1-0.27)\\&-(100+0.55*(-10000*0.015*\ln(0.015)))\\&=13\end{aligned}$$

As the production is increased from 1.0% of the total reserve to 1.5%, the unit value of lumber is decreased from –ln(0.01) = 4.6 to –ln(0.015) = 4.2. USA collects 27% tariff on lumber import and enjoy lower price on lumber. Table 1 gives a summary of softwood lumber futures prices, annual production from Canada, revenues and profits from Canfor, Canada's largest softwood producer, in 2000 and 2002, one year before and after USA imposed the 27% tariff on softwood lumber import from Canada.

The data confirm the theoretical prediction that after the tariff, production increased, prices dropped, and corporate profits from lumber producers tumbled. This shows that tariffs are an effective way to shift wealth from producing countries to consuming countries, and contradicts the standard theory that tariffs hurt importing countries by imposing higher prices for consumers.

From the theoretical analysis, as well the data in Table 2, trade policies have huge effects on the distribution of wealth across borders, and this also greatly influences the distribution of jobs across borders. This is why trade policies are such an emotional issue over history.

The scarcity of a commodity is influenced by the market size. For Canadian lumber, the market size is very much determined by the US housing market, which is much larger than the Canadian market. The market size is also greatly affected by transportation costs. For example, petroleum is relatively light compared with coal

Table 2
Summary statistics of softwood lumber futures price, annual production from Canada, revenues and profits from Canfor. Sources of data: CME, indexmundi, Canfor annual reports.

	2000	2002
Softwood lumber futures price (January closing)	346.6	268.7
Production (thousands of cubic meters)	68557	71989
Canfor revenue (millions of dollars)	2265.9	2112.3
Canfor profit (millions of dollars)	125.6	11.5

for the same amount of energy. Therefore, petroleum is a global commodity while coal is much less so. Lumber is six times heavier than coal as a fuel. Hence the market for wood as a fuel is highly localized. But the market for wood as lumber, which is higher priced than fuel, is much larger. Still, the increasing cost of oil decreases the size of the lumber market. Not only do transportation costs increase, but also higher energy prices can make constructing a home more expensive.

3.2. Regulations and other entry barriers in market competition

Regulations and other entry barriers increase fixed costs. Higher fixed cost reduces the number of businesses in an industry, which increases the value of their products or services. We will analyze how the increase of fixed cost affects the return of an industry. Suppose the market size of an industry is M, scarcity is p, the number of businesses in the industry is b. Then the unit value for the product is

$$-\log_b p$$

The fixed cost for each business is K, variable cost is C. Assume each business gets the same amount of revenue. The revenue and total cost for each business are

$$\frac{Mp}{b}(-\log_b p) \text{ and } K + C\frac{Mp}{b}(-\log_b p)$$

respectively. The return for each business is

$$\frac{\frac{Mp}{b}(-\log_b p)}{K + C\frac{Mp}{b}(-\log_b p)} - 1 \tag{4}$$

Suppose M = 1000, p = 0.4, b = 3. The fixed cost of each business is 35 and the variable cost of each business is 60% of the revenue. The rate of return for each business is

$$\frac{\frac{1000\times 0.4}{3}(-\log_3 0.4)}{35 + 0.6\frac{1000\times 0.4}{3}(-\log_3 0.4)} - 1 = 0.09$$

This rate of return is not very high. Now a business persuades the government to increase regulatory measure on this industry. As a result, the fixed cost is increased to 50. Assume other parameters remain the same. The new rate of return for each business, calculated from (4), becomes negative. If the rate of return becomes negative, one business, usually the financially weak one, will drop off the market. Suppose now there are only two businesses in the industry. Assume other parameters remain the same. The new rate of return for each remaining business is

$$\frac{\frac{1000\times 0.4}{2}(-\log_2 0.4)}{50 + 0.6\frac{1000\times 0.4}{2}(-\log_2 0.4)} - 1 = 0.27$$

This is much higher than the previous rate of return. Financially strong companies can use regulatory tools to increase fixed cost. It can reduce the number of competitors and help remaining players achieve high rate of return.

In neoclassical economics, regulation is justified when there is a "market failure". From the above analysis, we see instead that regulation is largely driven by industries themselves to keep a high rate of return. The theory also explains why biological and chemical weapons are banned by international treaties while nuclear weapons, which can cause much more destruction than chemical weapons, are not. Biological and chemical weapons, which are sometimes called poor men's nuclear weapons, are cheap to make. If these weapons are not banned, many people can make them, which will reduce the value of weapons of mass destruction. To maintain the high value of such weapons, international treaties, which are generally initiated by leading political powers, banned those weapons of mass destruction that are cheap to make.

4. Physical entropy, subjective utility and economic value

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, the purpose of agriculture is to obtain low entropy sources of food. Part of health care systems aim to defend our own low entropy sources from viruses and bacteria. The military forces are established to extract low entropy from others and to defend one's own low entropy sources. Clothing and housing reduce 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. Since the entropy law, which states that closed systems tend towards states of higher entropy, is the most universal law of nature, it is natural that the display of low entropy has evolved as the universal signal of attractiveness in the process of sexual selection.

Both natural selection and sexual selection indicate that human beings favor low entropy sources (Chen, 2005, 2016). This observation offers a connection between the entropy theory of value and the subjective utility theory of value. "Mind is an organ of computation engineered by natural selection" (Pinker, 1997, p. 429). It calculates the entropy level and sends out signals of pleasure for accumulating and displaying low entropy and signals of pain for dissipation of low entropy. Jevons "attempted to treat economy as a calculus of pleasure and pain" (Jevons, 1871, p. vi). Pleasure is generally associated with the accumulation or display of low entropy level, such as the accumulation of wealth, and conspicuous consumption. Pain is associated with dissipation of low entropy, such as work and the loss of money. So value in subjective utility theory, as a measure of pleasure and pain, is intrinsically linked to the level of entropy.

Mainstream economic theory states that the value of a commodity is determined in exchange and is a function of supply and demand. From the theory of natural and sexual selection, the demand of an economic commodity is driven by its level of entropy. The supply of an economic commodity is constrained by its scarcity, with entropy as the unique measure of scarcity. The level of entropy offers a natural measure of economic value.

Since the entropy level of a system increases spontaneously, the reduction of entropy in a system represents effort that has been expended and therefore "value-added". Entropy level may thus be the closest to an invariant measure of the value of labor and other commodities.

While economic values of commodities are highly correlated with the level of physical entropy, they are not identical for several reasons. In the following, we will discuss two, one from the perspective of information theory and another from the institutional structures that regulate scarcity and number of producers.

First, the entropy level we perceive of a commodity is different from its objective entropy level. From information theory, the

amount of information one can receive, R, is equal to the amount of information sent minus the average rate of conditional entropy.

$$R = H(x) - H_y(x) \tag{5}$$

The conditional entropy $H_y(x)$ is called the equivocation, which measures the average ambiguity of the received signal (Shannon, 1948). Equivocation arises because receivers don't have complete background knowledge of signals. For example, gold, a scarce commodity, is highly valuable. Another commodity could be as scarce as gold, but unlike shiny and stable gold, it could be very difficult to identify. Most people will not invest much effort to gain knowledge needed to identify this commodity because the cost outweighs the potential benefit. Thus, it registers less attention and is valued less by human beings.

Second, scarcity of a commodity is regulated by the institutional structures that enforce property rights. For example, the value of an invention is influenced by how long and how broad patent protection is granted. The value of a patent is higher in a system where patents are valid for twenty years than one where patents are valid for ten years. If patent protection is defined more broadly, the market is larger and the value of an invention is higher. Economic value, as a function of scarcity, is to a great extent regulated by institutional structures. Among all the institutional measures that regulate scarcity, the most important regulation is the immigration laws that regulate the scarcity of the labor force, which makes persistent large wage differentials across regions possible. Wage differentials can persist for other reasons such as relocation costs, or differences in cost-of-living. Wages in the cities are higher than in the countryside in the same country, with no legal barriers to migration. But these wage differentials are relative minor compared with wage differentials where legal barrier to migration is high.

5. The entropy theory of value and information

The discussion about the relation between information and physical entropy began with the Maxwell's demon (Maxwell, 1871). In 1870s, Boltzmann defined the mathematical function of entropy, which Shannon (1948) identified as information many years later. Because of the equivalence of entropy and information, an entropy theory of value is inevitably an information theory of value. Information is often regarded as a rather unusual commodity. In this section, we will show that informational and physical commodities share most of the same fundamental properties from the perspective of entropy theory. Since Arrow (1999) offered an authoritative description about the special characteristics of information as an economic commodity, our discussion is based on his writing.

> The algebra of information is different from that of ordinary goods. . . . Repeating a given piece of information adds nothing. On the other hand, the same piece of information can be used over and over again, by the same or different producer(s). (Arrow, 1999, p.21)

From Formula (5), the amount of information received is the information of source minus equivocation. Repeating a signal of information helps reduce equivocation. Different types of coding generally maintain a certain level of redundancy to reduce error in transmission. Repetition is the most important method in learning. Reciting poems is one of the most effective ways to study a language or literature. Important genes often have several hundred copies in genetic codes to satisfy heavy work demand (Klug and Cummings, 2003). A song will survive only if people repeat it over generations. A theory will survive only if researchers continue to discuss it over time. Same commercials are repeated many times on TV. From the thermodynamic theory, all low entropy sources have a tendency to diffuse. Repeating the same piece of information is essential to keep it alive and valuable. The essence of a living organism is to repeat and spread the information encoded in its genes.

It is often thought that the use of information does not involve rivalry, since "the same piece of information can be used over and over again, by the same or different producer(s)". This property is not confined to information. The same hammer "can be used over and over again, by the same or different producer(s)". However, the value of the same information will be different for different users or at different time. For example, if an unexpected surge of corporate profit is known by very few people, i.e., when P is very small and $-\log P$ is very high, this information would be highly valuable. Huge profit could be made by trading the underlying stocks. But when it is known to many people, the value of such information is very low. In general, when some knowledge is mastered by many people, its market value is very low.

> The peculiar algebra of information has another important implication for the functioning of the economic system. Information, once obtained, can be used by others, even though the original owner has not lost it. Once created, information is not scarce in the economic sense. This fact makes it difficult to make information into property. It is usually much cheaper to reproduce information than to produce it in the first place. In the crudest form, we find piracy of technical information, as in the reproduction of books in violation of copyright. Two social innovations, patents and copyrights, are designed to create artificial scarcities where none exists naturally, although the duration of the property is limited. The scarcities are needed to create incentives for undertaking the production of information in the first place. (Arrow, 1999, p. 21)

Information is a type of low entropy source. Utilization of low entropy source from others is a universal phenomenon of living systems.

> Once again animals discover the trick first. . . . butterflies, did not evolve their colors to impress the females. Some species evolved to be poisonous or distasteful, and warned their predators with gaudy colors. Other poisonous kinds copied the colors, taking advantage of the fear already sown. But then some nonpoisonous butterflies copied the colors, too, enjoying the protection while avoiding the expense of making themselves distasteful. When the mimics become too plentiful, the colors no longer conveyed information and no longer deterred the predators. The distasteful butterflies evolved new colors, which were then mimicked by the palatable ones, and so on. (Pinker, 1997, p. 501)

The perceived uniqueness of copying information products in human societies is actually quite universal within living systems. Once we look at the living world from the entropy perspective, it can hardly be otherwise. In human societies, the attempt to copy and reproduce valuable assets, whether informational or physical assets, is also universal.

The fashion industry offers an example that illustrates the dynamics of innovation and copying clearly. When a new fashion style is created, it is scarce and hence valuable. This valuable information will be copied by others. As more people copy the style, P increases, $-\log P$ decreases and the value of the fashion decreases. To satisfy the demands for high value fashions, new fashion styles "are designed to create artificial scarcities where none exists naturally".

Protection of an organism's source of low entropy to prevent access by others is also a universal phenomenon of living systems. Animals develop immune systems to protect their low entropy source from being accessed by microbes. Plants make themselves poisonous to prevent their low entropy from being accessed by animals. When space is a limiting factor in survival or reproduc-

tion, animals defend their territory vigorously (Colinvaux, 1978). Whether to enforce the property rights depends on the cost of enforcement and the value of the low entropy source. When information products become an important class of assets, the property rights of physical assets are naturally extended to informational assets.

Arrow stated, "Two social innovations, patents and copyrights, are designed to create artificial scarcities where none exists naturally ..... The scarcities are needed to create incentives for undertaking the production of information in the first place. (Arrow, 1999, p. 21)" But the statement is not consistent with reality. The production of information, in the form of genes, occurred long before the advent of human beings and copyrights. Human societies with no patents or copyrights produce great art, literature and scientific knowledge.

During wartime, warring parties show the least respect toward patents and copyrights. Most scientific and engineering breakthroughs are achieved in times of intense conflict. Historically, latecomers that turned into industrial powers, including the USA, displayed little regard to patents and copyrights in the period of takeoff. It is natural for dominant players to proclaim their sovereignty over important assets, whether physical or informational. It is also natural for the non-dominant majority to utilize resources available at the lowest cost possible.

6. Economic value and social welfare

Economic activities provide low entropy sources for the survival and comfort of human beings. From the second law of thermodynamics, the reduction of entropy locally is always accompanied by the increase of greater amounts of high entropic waste globally. So "externalities" are universal for all economic and social activities. They are not a form of "market failure" but a direct consequence of fundamental physical laws.

A product is developed to satisfy a specific market demand. Its value is easily appreciated by the customers, who are willing to pay for the product. Production facilities are often set by riverside or seaside. Wastes are often diffused quickly to a broad area, so the concentration of waste is generally low. Production facilities are often set in countries where local population have little political power. For example, production of solar panels and other "clean energy" usually generate great amounts of pollution. They are concentrated in China, which is under an authoritarian political system, where the ability to complain is limited, even though the population density affected by the pollution is very great

When human population density and consumption levels are low, most of the high entropy wastes that humans generate are absorbed by microbes and other natural forces with little human effort. This vital recycling business is accorded no economic value. As the population density and the level of consumption increases, however, direct human intervention is needed to move the high entropy waste away from where people reside. Waste management becomes economically valuable.

That the increase of economic wealth is not equivalent to improvement of social conditionis especially clear to see in the case of pollution. When clean water is abundant and unpolluted, water has little economic value. When water becomes polluted and clean water becomes scarce, the scarcity makes water economically valuable.

While economic wealth is not equivalent to social welfare, as a measure of consumption and control of resources, it generally does reflect the social conditions of the time. However, wealth, as low entropy of human society, is ultimately supported by low entropy from nature. In the last several hundred years, worldwide consumption of energy and other resources has been increasing steadily with economic progress. Our current civilization depends heavily on fossil fuel. The increasing cost of fossil fuel extraction will gradually erode the foundation of today's lifestyle (Galbraith, 2014).

In general, wealth represents the total dependence of each on the other in a society. The increase of one's wealth means the increase of the dependence of others on him or her and hence the increase of his or her power. While it is natural for an individual, a company or a nation to pursue strategies that maximize wealth, such strategies ultimately will undermine long term sustainability of ecological and social systems. Currently, the fertility rates in many wealthy societies, which consume large amount resources, are already below the replacement rate. This is a clear sign that these societies are not sustainable.

7. Concluding remarks

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7. Concluding remarks

All systems tend to move from low probability state to high probability state. In physics, this pattern is formalized into the entropy law: entropy tends to increase over time. All living systems, including humans, tap the entropy flow to drive their own activities. It is natural to conceive economic value as entropy. Theories built on a sound physical foundation often provide simple and intuitive results on practical problems. The entropy theory of value establishes an explicit link between economic value and physical entropy. It offers a simple mathematical theory that greatly clarifies our understanding of a broad range of social and economic phenomena.

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