COMMITTEE I
Unity of Science: Organization and
Change in Complex Systems

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SELF-ORGANIZATION AND TECHNOLOGICAL CHANGE IN THE ECONOMIC SYSTEM

by

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1. Introduction

The second law of thermodynamics has been causing confusion and consternation since it was first formulated by Clausius in 1847. Once it was clearly recognized that processes are of two distinct kinds--reversible and irreversible--and that entropy is unchanged in the former but increases in the latter, an evolutionary principle or law of sorts was evident for the physical universe. This follows from the fact that isolated thermodynamic systems not at equilibrium (but near it) *must approach equilibrium irreversibly*, since equilibrium is characterized--in fact, defined--by maximum entropy. Moreover, since entropy in an isolated system never decreases (according to the second law), no such system can depart further from equilibrium than it is to start with, whereas many processes, being irreversible tend to push the system in the direction of thermodynamic equilibrium unless acted upon by external forces.

The discouraging aspect of the situation is that thermodynamic equilibrium is a changeless state in which all matter is uniformly distributed and there are no temperature or concentration differences hence no gradients and no structure or order.[1] If the universe continues to expand physically without limit, such an asymptotic limit might be envisioned: Nernst called it "heat death" (Warmetod) of the universe. It is a state of absolute uniformity and maximum disorder or mixing.

Almost at the same time thermodynamics was being developed, Charles Darwins's theory of biological evolution by the mechanism of natural selection was also formulated. Notwithstanding some severe challenges from physicists (notably William

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[1] Order is unvoidably a somewhat anthropomorphic concept. However, in normal usage, it implies sorting or separation, as opposed to mixing. A more general definition relates order to long-range spatial (or momentum) correlations. It is important to emphasize that the term "order" is often used improperly (e.g. by Schrodinger, 1945) and that disorder is not necessarily equivalent to entropy, as suggested by Boltzmann. Disorder corresponds with entropy only in three very special (and unrepresentative) cases, the perfect gas, a crystal at low temperature, and isotopic mixing (McGlashan, 1966).

Thompson, Lord Kelvin) during the 19th century,[2] Darwin's work in biology presented a clear and convincing story of evolution of living systems towards ever increasing complexity and structure/organization, at least on the Earth's surface, culminating in the development of the human brain. Given the fossil record and other evidence, this trend towards increasing organization appears indisputable. It can be argued that order is not necessarily the same as organization though the concepts are clearly related. But, for a long time, it was very hard to positively reconcile Darwin's theory with the second law of thermodynamics. On the other hand, there has been no convincing evidence of any absolute contradiction between biological evolution and thermodynamics.

New developments in mathematics and in non-equilibrium, non-linear thermodynamics in the past three decades have created the basis for such a reconciliation. In particular, Glansdorff, Nicolis and Prigogine (1971, 1977) have constructed models of simple chemical systems that exhibit stable, coherent "self-organizing" behavior, yet are far from thermodynamic equilibrium. Eigen (1971) has even shown convincingly how complex macromolecules can reproduce themselves from simple "building blocks" via stable "hypercycles", but can also evolve by random mutation (copying errors) and selection according to an optimization principle that is definable in molecular terms.

Modern physicists are beginning to use the term essergy[3] which will be adopted hereafter. Intuitively, this hypothesis helps explain at least two observable aspects of biological evolution.

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[2] The objection raised by Thomson had to do with the geological age of the earth. Lacking any inkling of the true source of the sun's heat of the earth's interior heat (nuclear reactions), physicists calculated a maximum age for the earth to be of the order of 25 million years, or less--far too little for Darwins' theory of slow natural selection to accommodate.

[3] Essergy is formally defined as a general measure of departure from thermodynamic equilibrium and is, in fact, the most general such measure (see Tribus and McIrvine, 1971). It actually reduces to other measures such as Helmholtz free energy, Gibbs free energy, and Keenan's index of availability under appropriate constraints.

- Organisms that use essergy (food) most efficiently will tend to complete best, ceteris paribus, within a given niche)
- Organisms will evolve to utilize any and all available sources of essergy, including wastes. This implies ever-increasing diversity: the development of specialized scavengers and parasites, as well as a hierarchy of levels of predators.

However, it is still unclear whether Lotka's principle or any of its variants is equivalent to Darwin's principle of natural selection on the basis of "survival of the fittest", or Eigen's micro optimization principle. That question also lies outside the scope of this paper.

2. Order, Entropy and Information

As noted previously, there there is a critical distinction between two usages of the term order. The first, which we retain, is order-in-(thermodynamic)-equilibrium and is exemplified by the formation of a crystalline solid such as a snowflake. The second kind of order occurs in systems that are stable but far from thermodynamic equilibrium, maintained so by a continuous renewable flow of essergy from outside the system. Examples range from relatively simple chemical systems such as the "Brusselator" (Nicolis and Prigogine 1977) or the "Oregonator" (Field, 1985) to living cells (Schrodinger, 1945).

For most chemical systems, and some physical systems as it happens, the concept of thermodynamic equilibrium is well-defined and characterized by a minimum value of the Gibbs free energy G.[4] The forces driving the system toward equilibrium in a chemical system are also well defined and, in simple cases, can be expressed quantitatively as a function of "distance" ΔG from equilibrium. In general, the governing relationships are non-linear. It has been shown that, for open systems far from equilibrium, non-linear equations can have multiple solutions, only one of which

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[4] By definition $G = U + PV - TS$. The Gibbs free energy is the correct measure of departure from equilibrium only for processes that take place at constant temperature and pressure, whence
$\Delta G = \Delta U + P\Delta V - T\Delta$.

reduces to the solution of the linearized equation that describes the situation near equilibrium. (Glansdorff and Prigogine, 1971; Nicolis and Prigogine, 1977).

Far from equilibrium there are solutions corresponding to situations where G is at a local but not global, minimum. Such a state may characterize a non-isolated system at finite temperatures and entropy (because of the term -TS in the free energy function) but it depends on a continuous inflow of essergy from the environment. Such stable states tend to involve "coherent" behavior, which is equivalent to long-range order in phase space. The term "dissipative structure" has been applied to such systems by Nicolis and Prigogine (1977). Transitions from the disordered state to a coherent (ordered) state of a system occur suddenly. Such transitions, between two solutions of a non-linear equation, have been classified topologically and termed "catastrophe's" by the mathematician Thom (1972)

Unfortunately in most complex open systems, equilibrium conditions cannot be specified in explicit terms and in highly organized/structured biological systems, for instance, the notion of long-range correlation seems inappropriate and thermodynamic variables may not be definable at all. It is simply assumed that in such cases, "forces" driving the system toward equilibrium are zero at equilibrium and increase, in general, with "distance". Again the (unknown) equation governing reaction rates is likely to be non-linear, with multiple solutions, only one of which corresponds to the linear near-equilibrium case. However, detailed quantitative examples are still scarce.

As noted above, the notions of order in the two situations are very different. Boltzmann's famous "order principle"--relating order to entropy--is not generally true and, in any case, applies only in the near-equilibrium case (termed the "thermodynamic branch" by Glansdorff and Prigogine). Away from equilibrium, however, entropy can still be defined in terms of Boltzmann's rule

$$S = - k \log W$$

where W is a measure of the number of "complexions" or the inherent probability of an eigen-state of the system and k is the so-called Boltzmann constant. However, order may have to be defined independently of entropy for a dissipative structure. Intuitively, the orderliness of a structure such as DNA molecule is a function of its complexity or, equivalently, the amount of information needed to describe it. This is a perfectly well-defined concept, applicable in principle to any system, including physical, chemical, biological, social and even technological systems. It even offers a bridge between the various disciplines.

Information, like energy, is a primitive. It cannot really be defined in terms of anything more fundamental. Information is what communications channels transmit and what computers process. It is absolutely required for purposes of decision-making and control. It is conventionally measured in "bits" and both channel capacity and computer power are measured in bits/sec.

The existence of a close relationship between information and entropy has been suspected since the 19th century debates on irreversibility and "Maxwell's demon". There is a famous proof of equivalence, due to Brillouin (1953). Assume a Maxwell demon operating a valve between two chambers and shunting fast ("hot") molecules into one chamber and retaining slow ("cold") molecules in the other chamber. In time, a finite temperature gradient would be observable and the total entropy of the system would decrease. But, to select "hot" and "cold" molecules the demon requires information about the state of each approaching molecule in order to decide on the correct valve setting. Acquisition of this information--first called negentropy by Szilard (1929) --in turn, results an entropic increase within the closed system at least as big as the decrease achieved by the activity of the valve demon.

In modern information theory, developed principally by Claude Shannon (1948) a measure of inherent uncertainty with regard to the (information) contents of a message was introduced.[5] This measure closely resembles the Boltzmann statistical definition of entropy, above. It was so identified at the suggestion of John von Neumann, (Tribus and McIrvine, 1971) although the identity was originally based on form alone. However, Jaynes (1957) soon rederived statistical mechanics from information theory by an entropy maximization principle, and Tribus (1961) showed that the laws of thermodynamics can also be derived from information theory in this way.

The physical identification of information as negentropy suggests the possibility that "stocks of information--in particular, technological information--can be regarded in some sense as reserves or storehouses of negative entropy that can be utilized to <u>increase the autonomy of dissipative systems</u>. This perspective will be elaborated further hereafter.

3. Information and Organization

Three new notions are suggested by the identification of information stocks with negative entropy: first, a dissipative structure far from equilibrium may conceivably "store" negative entropy for future use in the form of organization or structure. Second, *intelligence* can be defined, tentatively as the ability of a dissipative system to capture and store (or embody) negentropy in structure. By this definition all living organisms are intelligent, to some degree, but intelligence need not be restricted to biological organisms. The third new idea is that intelligence, as defined above is the argument of Eigen's maximization principle (1971). From this point on, incidentally, I will generally be talking about very complex systems which are self-evidently dissipative, but for which no straightforward quantitative relationship between reaction rate and distance from equilibrium can be defined. Biological organisms,

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[5] More recently, so-called algorithmic information theory has been developed to estimate the amount of information (in bits) required to describe an object or, equivalently, the number of instructions needed by a general purpose computer to reproduce that object. The two kinds of information theory are essentially equivalent.

ecosystems, human societies and techno-economic systems all fall under this heading.

That organisms, societies, etc. acquire and "store" pure information in physical structures is obvious, on reflection. The gene is nothing more nor less than a packet of information in molecular form (Schrodinger, 1945). It contains both morphological and functional information needed by the organism. The information embodied in genes tells cells how and when to divide, how and when to differentiate, how to manufacture various enzymes, hormones, etc. It also tells the organism as a whole how to react to various stimuli, what food to eat, when and how to mate, where to lay eggs, etc. This information store is the result of long evolutionary learning process, described by Darwin as natural selection and by Eigen as "value maximization". The cumulative nature of the process is evident from the fact that the higher organisms, arriving later on the evolutionary scene, carry far more genetic information than the simplest, earliest organisms (Fig. 1). The ability of the higher organisms to reproduce this information can be regarded as evidence of increasing intelligence in the sense defined above.

As to the use of "stored negentropy -as-structure" to cut down on the need for a continuous flux of essergy, Polgar, (1961) has identified four mechanisms viz. <u>persistence</u>, <u>replication</u>, <u>environmental modification</u> and <u>social evolution</u>. On deeper reflection Polgar's classification is unsatisfactory, since self-replication and environmental modification are merely two mechanisms for extending the life of a system. In this sense "self modification" must surely be considered as another.

At the molecular (i.e. genetic)level, Schrodinger (1945) showed that persistence, as reflected by the low rate of natural mutation, can be explained in terms of quantum chemistry. At the level of chemical systems--recently applied to order--disorder phenomena in physics-- Glansdorff, Nicolis, Prigogine et al (1971, 1977) have given an explanation in terms of non-equilibrium thermodynamics.

Replication is, of course, one of nature's basic long term survival (and growth) mechanisms. A detailed understanding of replication at the cellular level may still be years away, but the famous discovery of the double helix structure of DNA and the so-called genetic code provided a very useful starting point (Crick, 1962). The other important natural means whereby living systems ensure their own long-term survival are by self-modification and environmental modification. The former has been explained, at the macro-level, by Darwin's theory of natural selection, and at the micro-level by Eigen (1971) and need not be discussed here at length.

By comparison, environmental modification has received much less attention, though it is enormously important. Living organisms have modified the atmosphere and the ocean enormously over the past 2 billion years. The earth's original atmosphere was 99% carbon dioxide (CO_2) with <u>no</u> free oxygen or nitrogen, while the primitive oceans were much smaller and saltier. Life as we know it today could not survive in such an environment. Environmental modification in some form is practiced today at the micro-level by viruses (upon their host cells), by wasps that paralyze their prey and lay eggs in them, by every nest-building species, and quite spectacularly by some animals such as beavers. On a larger scale, tropical forests create their own meso-environment. (Deforestation commonly leads to desertification). Coral reefs are the undersea analog. Of course, human activities such as agriculture and fossil fuel consumption have enormous environmental impact, which we need not consider here at length.

Another way in which negentropy-as-structure in the biosphere operates to cut down on the essergy flux per unit of biomass (and thus retard the rate of global entropy increase) is by means of species diversity and specialization. Most of the biosmass on the earth (by weight) is vegetation that extracts essergy directly from sunlight by photosynthesis. Assume a population of efficient specialized plants of one species. Each such community would, in principle, reach some stable natural level of total biomass depending on the availability of some limiting factor--usually water or a mineral nutrient. This was first pointed out by Leibig in 1876 (See Lotka, 1950). At this point, photo synthetic production would automatically adjust itself to satisfy replacement needs only. If water were the limiting factor, as in an African oasis, new plants could only grow when old ones died and no longer called on the limited water supply. If some mineral element were the limiting factor, new plants could only grow after old ones had released their soluble mineral contents back to the environment.[6] (This is exactly the situation in the Amazon basin today).

How does species diversity alter the situation? The key is that there must be relationships between function and structure. For instance,a second species of plant having a different function (i.e. a different niche) will have a different structure--hence a different microcompositon. The second plant can be expected to require a somewhat different combination of inputs than the first, so that the limiting factor will be different. Thus the total biomass of two species combined can generally be larger than that of either alone. A third species, with a different specialization, can add still more to the total biomass without exhausting the available resources.

In fact, the remarkable fact is that a hierarchy of animals can live off of the plant kingdom (and each other) because continuous harvesting actually increases the photosynthethic activity level of the plants. In fact, every homeowner knows that grass grows faster immediately after it has been cut. Commercial logging is similarly predicated on the fact that young trees grow faster than mature ones. Agriculture is based on the same phenomenon: it is a general law of ecology that young plant communities are the most photo synthetically productive. The role of animals and decay organisms, then, is to maximize the overall productivity level of the photo synthesizers by efficiently recycling minerals (and where it is scarce, water). Deliberate fertilization and irrigation by humans is a straightforward extension

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[6] Needless to say, decay organisms facilitate this recycling.

of this natural phenomenon.

The lowest trophic level of animals obtain their food mainly as carbohydrates or cellulose, directly from photo synthetic plants. Higher animals, in turn, are able to exploit lower animals and obtain their food mainly as proteins and fats which are more useful and easier to digest. The top predators are therefore able to eat and digest much less bulk than they otherwise would have to, by consuming foods more similar to their own tissues and more easily broken down to sugars and amino acids for reassembly. This enables active carnivores to consume more food (essergy) but spend much less time eating and digesting than the herbivores they prey on.

Significantly, the amount of genetic information required to reproduce an organism tends to increase with its trophic level in the predator-prey hierarchy. So, in general, does the information processing capacity of the organism itself: the processing capacity of its brain and central nervous system increase with trophic level (Figure 1). For higher mammals, the storage capacity fo the brain vastly exceeds the storage capacity of the genetic material.

The situation sketched above is comparable for animal and human social systems and for the economic system. Humans are not the first organisms in nature to transmit non-genetic information from generation to generation. Most mammals and birds teach their young to some degree at least. Humans are, however, the first species to store non-genetic information in external repositories (e.g. libraries) that are maintained by the society as a whole.[7] Moreover, in recent centuries, this kind of intergenerational information accumulation and transfer has quantitatively approached, if not surpassed the genetic transfer process, as indicated in Figure 2.

In the case of a human society, the systematic use of stored information to simplify the food gathering and production process need hardly be elaborated.

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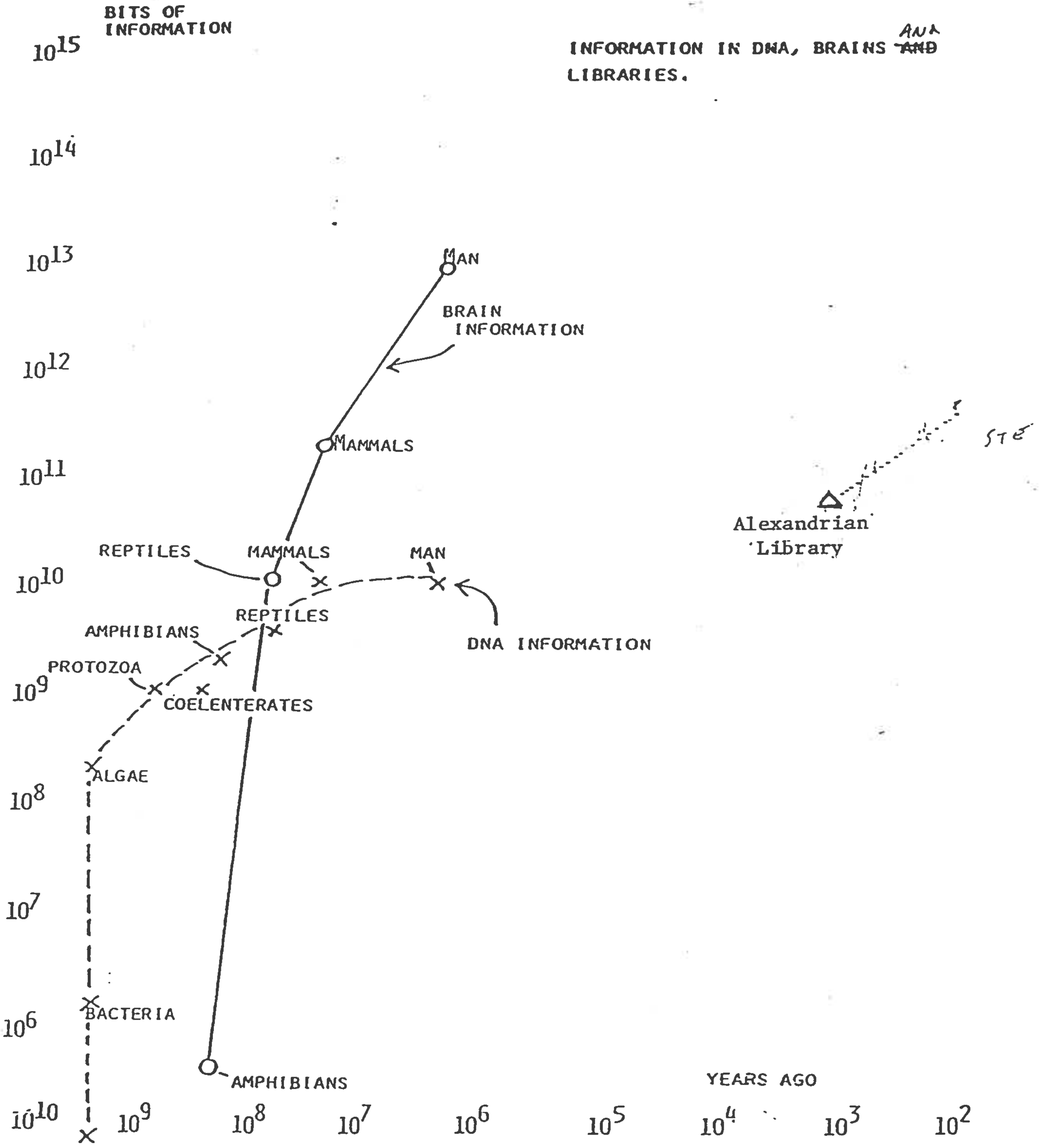
[7] The development of spoken and, later, written languages were obviously critical steps.

Figure 1

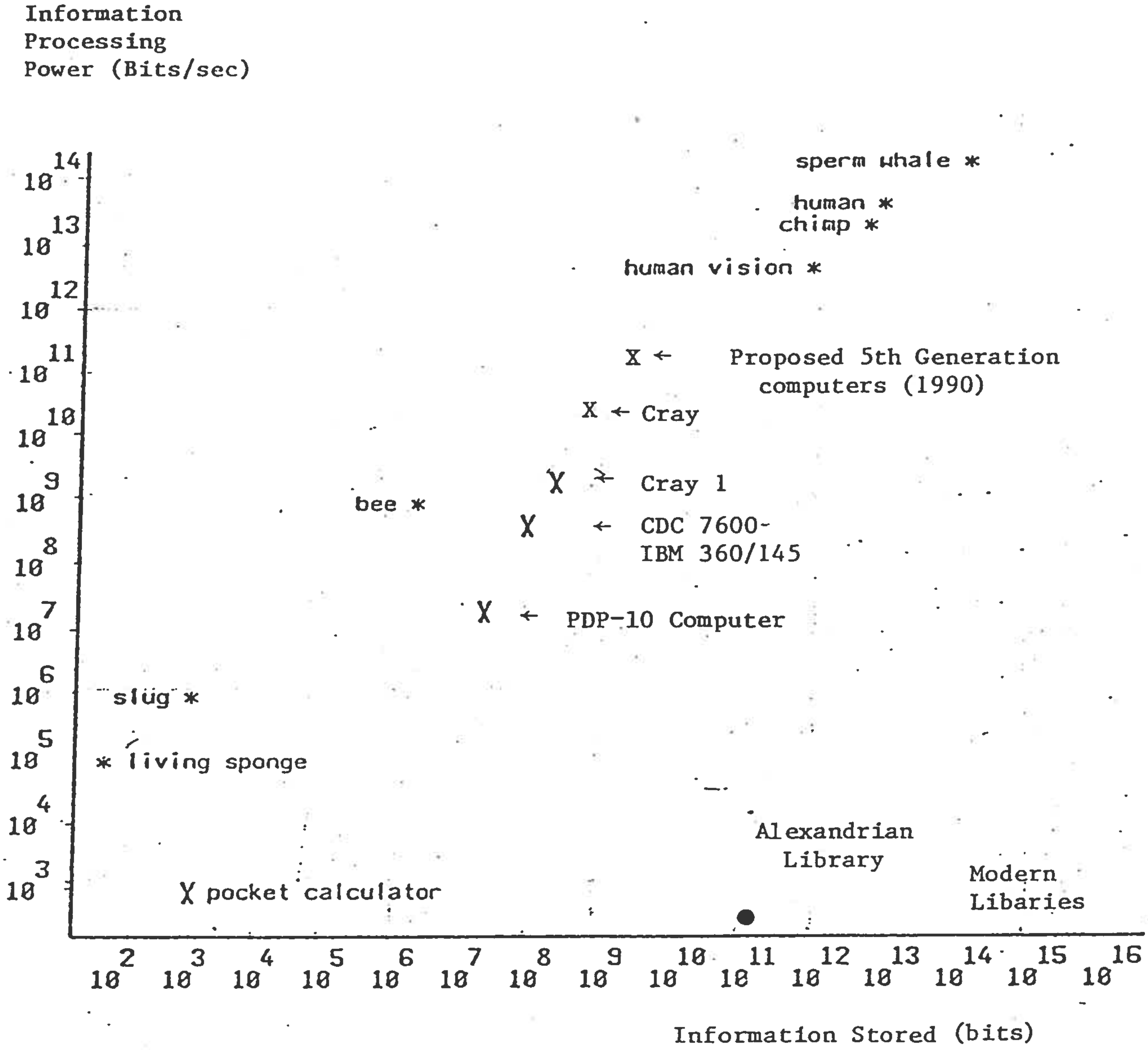
INFORMATION IN DNA, BRAINS ~~AND~~ AN
LIBRARIES.



Source: Sagan

FIGURE 2

Computer vs. Living Systems



Source: H. Moravec (1982)

Knowledge about plant reproduction, animal behavior, weather, climate, geography and even astronomy[8] had an immediate payoff in terms of increasing the ability of a human population to support itself and prosper in prehistoric times. At first, much of this knowledge was acquired by accident. More recently, the application of knowledge to increase production has become increasingly systematic and intentional. The process of learning about nature and applying that knowledge for the benefit of man is now institutionalized, as well be discussed later.

The notion of "pure" technological information as an effective substitute for resource inputs is suggested by the notion of using embodied information (knowledge) to increase the efficiency of capture of "natural" information in the form of essergy. The equivalence is neatly summarized by the proverb: "Give a man a fish and he can feed his family for a day. Teach him how to fish and he can feed his family forever." Ancient man obtained copper, silver, iron and other metals from nearly pure nuggets. Modern man has learned how to obtain these metals (and others) from low grade ones. As one resource is exhausted, typically, another is exploited. Thus charcoal gave way to coke, and whale oil was replaced by kerosene. As the demand for motor gasoline grew raidly in the early 20th century, means of increasing the gasoline and octane output from each barrel of crude oil were actively sought. Using sophisticated modern refinery technology, and anti-knock additives, the gasoline fraction has risen from 15% to as much as 60% of the barrel, while octane levels have doubled. Thus technological knowledge has enormously increased the amount of useful work that can be extracted from crude oil. It is not unreasonable to characterize this enhancement as embodied knowledge (=intelligence) added by the techno-economic system.[9]

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[8] Astronomy evolved historically as means of predicting dates of annual spring runoff in the Tigri–Euphrates Valley, where seasonal changes at lower latitudes are very slight.

[9] Some of the negentropy in question is obviously embodied directly in capital equipment. However, some of it like computer software is quite portable. Moreover, the portable component appears to be increasing in relative importance.

A final observation is relevant: the vast storehouse of fossil fuels in the earth's crust that humans are currently exploiting (and using up) is an accumulation of "surplus" natural negentropy left over from incompletely decayed living organisms in earlier geological periods. It is stored (from a molecular perspective) as chemical structure, i.e. energy-rich hydrocarbon molecules that are quite stable at ambient temperatures, but which combine exothermically with oxygen above ignition temperature. Obviously, humans will have to find other energy sources to replace hydrocarbons within a century, more or less. It is already clear that several alternative possibilities exist,[10] though all of them will require large capital (i.e. stored information) investments, not to mention technologies more advanced than is currently available. In any case, some surplus negentropy in the form of capital will have to be set aside from the existing fossil fuel store to "finance" the eventual changeover.

4. The Economic System as a Dissipative Structure

Economists do not normally think of economic activities and relationships in thermodynamic terms. When economists talk about equilibrium they refer to a balance between supply and demand, or (looking at it another way) between prices, wages and profits. Neo-classical economic models consider labor, capital goods and services to be abstractions. The exception is resource/environmental economics where some physical properties (e.g. mass, toxicity) cannot be neglected.

The proof of the existence of a static equilibrium (Walras, 1877) was one of the great achievements of neo-classical economics because it seems to provide a theoretical explanation of Adam Smith's price-setting "invisible hand". There can be no question that the operation of a money-based free competitive market generates a kind of coherence, or long-range order, in contrast to the unstable price/wage anarchy

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[10] Including fission,fusion and photovoltaic cells on the earth or in space.

that prevails in a barter society, for instance.[11] The static competitive free-market based economic system described in text books does reflect a kind of order. It has also been proved that an idealized market-based system maximizes total welfare (Pareto), although it does not necessarily allocate resources equitably. (Equity is, of course, a moral concept.) Finally, the market system is, in theory, self-regulating and capable of recovering from a perturbation in demand, for instance.

Even the abstract model of the economic system depends on resource *inputs*, although in a closed Walrasian model resources are assumed to be generated by labor and capital. Thus the neoclassical system is, in effect, a perpetual motion machine.[12] In reality, these resource *inputs* are physical: they include air, water, sunlight and material substances, fuels, food and fiber crops, all of which embody thermodynamically available work (essergy). *Outputs*, on the other hand, are "final goods" that are ultimately used up and thrown away or, in rare cases recycled. Available work is expended at every state, viz. extraction, refining, manufacturing, construction and even final consumption (Ayres, 1978). Though total energy is always conserved, essergy is not. Energy inputs such as fossil fuels are rich in essergy, while energy outputs are mostly in the form of low temperature waste heat; oxidation products, or degraded materials. Thus, the economic system, in reality is absolutely dependent on a continuing flow of from the environment. In pre-industrial times, it was the sun that provided almost all essergy in the form of wood, food crops, animals, water power or windpower. Today, the major source, by far, is fossil fuels: petroleum, natural gas and coal from earth's crust. These resources are exhaustible, of course.

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[11] Central planning attempts to introduce order of another kind.

[12] This fact was emphatically pointed out by the Nobel-prize winning chemist F. Soddy in 1922 (See Daley, 1980). Soddy was ignored or ridiculed by virtually all economists of his time. Among the first economists to stress the dissipative nature of the economic system were Georgescu-Roegen (1971). The relevance of mass/energy conservation to environmental/resource economics was particularly emphasized by Kneese, Ayres and d'Arge (1971).

Evidently the real economic system looks very much like a "dissipative structure" in Prigogine's sense: it is dependent on a continuous flow of essergy (the sun, or fossil fuels) and it exhibits coherent orderly behavior. In fact, it is self-evidently capable of growth. Economic growth can be of two distinct kinds. First, an economic system can (in principle) expand like a balloon without technological or structural change. It simply gets bigger, as capital and labor inputs increase proportionally. This kind of quasi-static growth can lead to increased final consumption per capita while maintaining its equilibrium but only by producing more of everything, in fixed ratios. (This is only possible if there are no economies or diseconomies of scale, which is an unrealistic but common economic assumption). The second kind of growth also involves evolutionary changes in structure. These changes are driven by innovations--new products, new processes-resulting not only in quantitative increases in per capita consumption, but also in qualitative changes in the mix of goods and services generated by the economy. In general this kind of growth results in increased complexity and organization.

Quasi-static growth of the first kind can be modelled theoretically as an optimal control model with aggregate consumption (or welfare) as the objective function. The control variable is the rate of savings diverted from immediate consumption to replace depreciated capital and add new capital to support a higher level of future consumption.[13] The rate of growth in this simple model is directly proportioned to the rate of savings which, in turn, depends on the assumed depreciation rate and an assumed temporal discount rate to compare present vs. future benefits. Note that assumptions about the operation of the market play almost no role in this type of growth model. Savings in this model, can be voluntary or enforced by government.

It is noteworthy that most economic development programs in the Third World are based on the generalized Harrod-Domar model assuming a primary role for aggregate

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[13] Aggregative models have been studied by Harrod (1936) and Domar (1956). Sectoral growth models have been studied by von Neumann (1945), Leontief (1953), and Sraffa (1960).

capital investment and depending on central planners to maintain balance between the capital needs of various sectors.[14] Empirical research carried out as early as the 1950's established quite clearly that economic growth in the U.S. cannot be accounted for primarily in terms of increased capital inputs (Abramovitz, 1956; Fabricant, 1954; Solow, 1957). In fact,the linked notions of increasing factor productivity, reflecting technological progress were introduced into economics at this time (Kendrick, 1956). The relatively poor performance of most centrally planned economic development programs is probably due in part to their focus on investment per se, to the neglect of structural adjustment and innovation.

Dynamic growth of the second kind is less dependent on savings and/or capital investment. However, it cannot occur without capital investment since new production technologies, in particular, are largely embodied in capital equipment. Technological innovation is the driver of dynamic growth as will be discussed later. There is ample evidence, incidentally, that technological progress is not an autonomous (i.e. self-organizing) process by itself. On the contrary, knowledge and inventions are purposefully created by individuals and institutions in response to incentives and signals generated within and propagated by the larger socioeconomic system. The techno-system is discussed next.

5. The Techno-System

The techno-system is, by definition, the creator of new techniques new products and new applications. Its activities can and do enable an economy to grow beyond the limits set by any given level of technology by finding more efficient methods to exploit existing resources, discovering new sources, or finding viable substitutes, and discovering new products and processes. The techno-system operates within the

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[14] Harrod called this balancing process "walking on the razor's edge". However, it was later shown that the H-D models extreme sensitivity to balancing is an artifact of its particular choice of production function (Solow, 1956).

larger economic framework, however.[15] In particular, it is the macro- system that determines both demand for technology and its supply. The impressions of certain social critics to the contrary, technology is not an autonomous or self-acting force outside its economic context.

A debate has raged for many decades over the extent to which technology is created in response to exogenously determined demand, vis a vis the extent to which supply, in this case, may sometimes create its own demand--a variant of Say's law in economics. Extensive empirical work by economists and sociologists of science tends toward the view that perceived demand is by far the dominant factor. That is to say, most successful inventors/innovations and most industrial R & D establishments, have responded to a clearly articulated need by consumers, government or industry itself. On the other hand, it could be argued that occasionally a spectacular technological opportunity comes along before there is any immediate need for it. The laser, invented in the early 1960's, seems to be one example. "Genetic engineering may be another. But, in both cases, major future applications; were immediately obvious--to the point of stimulating continuing R & D expenditures.

Quite apart from the question of primacy of demand vs. supply, however, it is clear that the economic (and political) framework determines the pattern of prices (including wages) and profits that actually govern the existing allocation of societal resources to, and within, the techno-system.

The pattern of prices, wages and profits constitute a set of signals, transmitted by society as a whole (i.e. consumers, government and industry) that constitute a guide

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[15] Similarly, the economic system functions in a social framework, which in turn functions in an ecological-biological framework. The latter in turn, functions within climactic geochemcial and astrophysical frameworks. The fundamental laws of physics (e.g. mechanics and thermodynamics) operate directly or indirectly at all levels of the hierarchy including the highest. Basic biological laws also govern social behavior, and so on. On the other hand, higher level laws are irrelevant at lower levels of the hierarchy.

for individual decisions, through established market mechanisms. For example, enrollment in engineering schools, competing with liberal arts schools, directly reflects engineering salaries and job prospects in different fields. Similarly, investment moves out of stagnant or unprofitable sectors and into profitable growing sectors.

Signals are sometimes confused, as when government interference or private collusion distort the operations of the competitive market. In addition, there are pervasive market imperfections. Some of these can only be compensated for by government action. One of these imperfections is the inherent difficulty of protecting technological information, which makes it relatively easy for imitators and "free rider" and inhibits the development of an effective market for exchanging technological knowledge in pure form (i.e. not embodied in product). This, in turn, makes it impossible for those who invest in new knowledge to capture more than a small fraction of the benefits, in most cases. The consequence is to discourage such investment by the private sector. Since, the private sector tends to underinvest in R & D, the public sector must make up the gap--particularly in those areas where the private incentives are most lacking.[16]

6. The Mechanism Driving Technological Progress

It is axiomatic that technological progress is dependent on the knowledge base, and that the knowledge base can be increased, at the margin, by deliberate investment in R & D. The question of interest is: (1) Why should individuals or enterprises invest in R & D? This is tantamount to asking: how and why does an R & D investment pay off in economic terms? The general outlines of an answer to this question have been clear for some time. Many detailed issues, however, still remain to be cleared up. However, in contrast to the case of "quasi-static" economic growth, which is

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[16] One cogent example of such an area is the development technical means for controlling pollutant emissions. Pollution is, in itself, a market imperfection, and there is very little profit motive in this field. Other areas of minimal private incentive are the natural public sector monopolies e.g. defense, public health, public safety.

driven by savings and does not depend on market structure, there is reason to believe that market structure plays a significant role in the process of technology creation. Joseph Schumpeter (1912) first pinpointed the driving force underlying dynamic economic growth as technological innovation by entrepreneurs seeking "supernormal" profits. Such profits arise from a temporary monopoly position conferred by each innovation until successful imitators are able to enter the market.

This simple conception seems to solve the main problem of neoclassical economics at a stroke by providing at once a qualitative explanation of several phenomena: the existence of supernormal profits, capital accumulation from profits, technological obsolescence and "technological progress." Schumpeter regarded formal R & D as a vital mechanism for corporations--especially large ones--to develop a stream of new and innovative product to maintain a level of profits higher than could be achieved in a quasi-static free competitive market (where competition drives profits toward zero). Unfortunately, Schumpeter occupied himself in later years primarily with questions of business cycle theory and political economy (and, for a time, government) and did not work out the full range of implication of his idea. Schumpeter's simple conceptual model also, unfortunately, left a number of key questions unanswered.

Modern theorists tend to associate Schumpeter with two specific hypotheses, (e.g. Kamien and Schwartz, 1982)

1. There is a positive correlation between innovation and supernormal monopoly-profits.

2. Large firms tend to be proportionately more innovative than small firms, ceteris paribus.[17] (This notion was more fully discussed later by Galbraith, 1952).

The first Schumpeterian hypothesis involves two possible causal relations between innovation and monopoly. On the one hand innovation may facilitate achieving monopoly power and profits as originally postulated. But, on the other hand,

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[17] See also Galbraith, 1952.

monopoly power may make it easier to innovate, as he suggested. The second relationship is more controversial. Under various assumptions, monopoly power may be either encouraging or discouraging to further innovation. Positive correlation may arise from technological spinoffs, brand-name identity, product "bundling", common channels of distribution , or the ability to respond quickly to a rival innovation. Another cause may be enhanced ability to finance innovations internally. On the other hand, a firm enjoying supernormal monopoly profits (and expecting them to continue indefinitely) might in some cases have less inherent incentive to take risks to increase them than a firm with normal profits only. In effect, firms may be characterized by declining marginal utility of profits (e.g. Arrow, 1962; Usher, 1964).

Ultimately, the validity of the Schumpeterian hypotheses must be resolved by empirical study. Unfortunately, there are enormous difficulties in defining innovations and measuring R & D inputs, firm size and/or degree of monopoly power, not to mention problems of interpretation. A large number of statistical studies have been carried out, using many different data sets and surrogate measures. (See Kamien and Schwartz, 1982, pp. 49-104). The empirical data tend to confirm that relationships do exist among these variables, but the nature of the underlying pattern remains far from clear. What is fairly clear is that the simple relationship between innovator and firm size is not generally true (except possibly in the chemical industry). A somewhat modified hypothesis has been suggested (e.g. by Scherer, 1967; Scott, 1984): that innovation is optimized by an intermediate market structure, between perfect competition and monopoly. But in many ways, this modification raises more questions than it answers. One is tempted to question whether, in fact, monopoly (or market structure) is the critical factor at all. In all probability other factors play an important role.

7. Thermodynamic Constraints on Economic Growth?

Several themes from the prior discussion can now be summarized, in terms of their implications for economic growth. First, since the economy is, by assumption, a dissipative structure it depends on continuous energy (essergy)and material flows from (and back to) the environment. Such links are precluded by closed neoclassical general equilibrium models, either static or quasi-static. Second, the energy and physical materials inputs to the economy have shifted, over the past two centuries, from mainly renewable sources to mainly non-renewable sources. Third dynamic economic growth is driven by technological change (generated, in turn, by economic forces) which also results in continuous structural change[18] in the economic system. It follows, incidentally, that a long term survival path must sooner or later reverse the historical shift away from renewable resources. This will only be feasible if human technological capabilities continue to rise to levels much higher than current ones. But, since technological capability is endogenous, it will continue to increase only if the pace of deliberate investment in R & D is continued or even increased. In short, the role of knowledge generating activity in retarding the global entropic increase seems to be growing in importance.

Looking at it in another way, external resource constraints in themselves may not constitute an ultimate "limit to growth", since technological improvements and substitutions appear to offer a possible way out. This has always been the basis on which most scientists and economists have criticized the "limits" thesis of the Club of Rome and others. But the critique itself has tended to assume that new technology always appears (essentially) costlessly in response to any perceived scarcity or need. This is not the case in reality. Large scale future substitutions, such as the eventual replacement of motor gasoline by methanol or ethanol will necessarily entail massive R & D investments, not to mention capital outlays. But, because of market failures, the private incentives to invest in this kind of research

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[18] For instance, so-called Leontief input-output coefficients do not remain constant.

may be inadequate, while the (US) government may neglect it for a short term political reasons (e.g., "industry should do it", need to reduce the budget deficit, etc.). The "system" is not working as well as it should.

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