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ENTROPY CONSIDERATIONS IN ENVIRONMENTAL PLANNING

by

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A. Vincent Siciliano

PROLOGUE

"But there is another sort of chaos, which is really
nothing but order in disguise."

August Lösch

The Economics of Location, 1954

"The race is not yet fully aware of what its resources
are."

Robert Murray Haig

"Toward an Understanding of the Metropolis,"

Quarterly Journal of Economics, XL, 1926

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FOREWORD

Entropy is a fundamental concept in the physical sciences, enshrined in the second law of thermodynamics. It is also a fundamental concept in information theory. In other areas it has gained considerable currency, sometimes faddish, sometimes as a powerful operating concept, sometimes an enlightening metaphor. Vincent Siciliano reviews and comments upon a broad variety of usages and conceptions of entropy in the natural sciences, in the social sciences, in art, in philosophy, and even in poetry. In addition to this panoramic survey, he presents some fresh ideas on systems of cities and social organizations.

A minor point pleases me especially. Siciliano is dusting off some of Zipf's ideas. It has been my belief that, although Zipf is a standard footnote on certain subjects, he is seldom read nowadays. Moreover, there are in the product of his eccentric genius many ideas which could be carried further with the greater mathematical and theoretical apparatus current now.

William Alonso

PREFACE AND ACKNOWLEDGMENTS

This paper has its personal intellectual origins in 1971 during the height of the popular awareness of "pollution" and "ecology." It seemed to this author at that time that there must exist a unifying theme with which to analyze the many aspects of the "crisis." Energy seemed the natural candidate, though few others thought so at the time. This paper represents an attempt at laying the theoretical groundwork for a theory of energy and society based on the thermodynamic concept of entropy.

Since this paper has spanned several years during its germination, I owe a debt of gratitude to many persons for their encouragement and stimulation. In particular, I wish to acknowledge the contributions and assistance of Professors Richard Meier, Robert Twiss, William Alonso, and my adviser, Professor Luna Leopold. I also express my thanks to my friends and colleagues at U.C. Berkeley and elsewhere for their suggestions and criticisms.

ABSTRACT

The major focus of this paper is to relate the Second Law of Thermodynamics to the issues of growth and planning in environmental policy making. The Second Law describes the process of energy degradation, or entropy production, as a consequence of energy use by all living systems, including human ones. The paper presents in nontechnical format the concept of entropy in the context of general thermodynamics and provides some illustrative scientific application. The conceptual equivalence of information and negative-entropy is discussed and applied to biological systems to yield principles of action for systems at steady state. The energy and pollution "crises" are then discussed and four strategies for maximizing human welfare within the constraints of the entropy law are described.

CHAPTER I

INTRODUCTION

The science of energy is thermodynamics, a seemingly complicated set of ideas and applications with which the common person has little familiarity or interest. Yet the author believes that applications of thermodynamics are not restricted to certain scientific fields and can be made quite useful in other areas of thought. It is the purpose of this paper to present easily and non-mathematically the essence of the thermodynamic concepts. In particular, the concept of entropy will be examined because it is one of the single most powerful concepts in all of science. In order to illustrate the fundamental nature of entropy considerations in modern science, a few typical applications will be described. The paper will then review some of the early work of general systems theorists who first translated the concept of entropy into the language of other fields, e.g., information theory and biological systems.

More recently, there has been a renewed interest in cross-field applications (see Table 1); in particular, it has been recognized that it is possible to view the energy and pollution "crises" in the context of natural entropic degradation. This paper will summarize and expand that view and will describe strategies for growth and planning which allow us to maximize our welfare within the overall thermodynamic constraints. Indeed, it is one of the purposes of this paper to suggest that as our knowledge progresses, we will discover that thermodynamic principles underlie all of our successful models.

CHAPTER II

THERMODYNAMICS AND THE CONCEPT OF ENTROPY

Thermodynamics comes from the Greek word therme (heat) and dynamis (power). It is historically the study of heat, the most familiar form of energy, and its role in work. Today, however, it deals with all forms of energy and energy exchanges (which can all be evaluated on the basis of heat exchanges), and therefore, as has been suggested by several authors, a more descriptive term might be energetics.

The First Law of Thermodynamics has been variously stated:

"the various forms of energy are equivalent and energy is indestructable," "energy and matter can neither be created nor destroyed," or most simply, "the energy of the universe is constant."¹ In physical terms what this means is that any change in the total energy of one system must be compensated for by an equal and opposite change in the energy of some other system, i.e., energy is transferred by the process of work, but it is never created or destroyed.

In more informal terms, Barry Commoner has restated this law in two of his four basic laws of ecology: "There is no such thing as a free lunch," and "Everything must go somewhere."² In other words, (1) we cannot create a perpetual motion machine, a machine which once started keeps going on its own accord, overcoming friction by "creating" energy--"you can't get something for nothing," to use one more cliché; and (2) we can change energy and matter and "lose" it for our purposes, i.e., "use it up," but it still exists somewhere in some other form. To summarize in the metaphysical terms of Teilhard de Chardin, the universe is "a closed quantum, within which nothing progresses except by exchange of that which was given in the beginning. . . what is gained

on one side is lost on the other."³

However, it is not sufficient to believe that we are just juggling balls of energy from one hand to another. The Second Law of Thermodynamics goes on to say that as we juggle we will keep dropping balls which will roll away irretrievably until we are out of balls altogether.

More formally, the Second Law has several formulations which are useful to present. The first set of these flow from the preoccupation of early investigators with heat engines: "Two bodies which are at different temperatures exchange heat in such a manner that heat flows naturally from the hotter to the colder body," or conversely (according to Clausius), "It is impossible for a self acting machine, unaided by any external agency, to convert heat from one body [at a lower temperature] to another at a higher temperature."⁴ Such a process would again represent perpetual motion because the heat energy created could be used to do work (this would be like an unplugged refrigerator still running).

Additionally, however, in producing work from heat, it is impossible to have a natural process which converts heat to work with none wasted (Kelvin's statement). What this means is that some of the original energy will always be dissipated and remain unavailable, even with the perfect, reversible, friction-free engine (Carnot's statement).

This idea of energy loss leads to the concept of entropy, a Greek word which roughly means "change" or "transformation." In other words, even though the First Law states that energy can neither be created or destroyed, another process operates which causes available energy to continuously change to a more dissipated, less ordered, and therefore less usable form. Entropy is the concept used to measure

this level of disorder. Thus the most general statement of the Second Law is that "the entropy of the universe increases toward a maximum";⁵ it will eventually assume a constant maximum value.⁶

This law tells us quite a bit about our universe because it points out the direction in which all natural or spontaneous processes take place. Naturally occurring processes tend inherently towards a state of equilibrium with their surroundings, which, once achieved, is irreversible, i.e., it will not revert back to its original state on its own accord. For example, a cup of hot tea will eventually cool down to the temperature of the room; we will never see the reverse.

In a more general sense, we can say that natural processes are moving to lower and lower states of order, or disorder. A neat pile of leaves will eventually be blown away by the wind; a house will become dusty and dirty, i.e., disorder will accumulate unless we periodically clean it. These processes are spontaneous because "energy flows down hill," seeking a lower, less ordered state, levelling out differences in energy (or entropy) concentration, seeking equilibrium. Work is accomplished by making use of this "energy gravity," as with earth gravity when we place a power generator (turbine) on a waterfall. The Second Law says that eventually, as all forms of energy are converted to heat which is uniformly dissipated, the universe will suffer its "entropic doom" or "heat death." At equilibrium, the energy becomes randomly distributed and is unavailable for work; no energy gradient is present.

An important consequence of the Second Law is that since energy constantly changes from a higher to a lower form (order), "You can't even break even in the game of energy and thermodynamics," as Isaac

Asimov has stated it.⁷ This is because while the theory does allow for friction-free reversible processes, in reality these do not exist. In other words, once an act is accomplished, we cannot undo it easily. It takes more energy to put together again a lump of burned coal than we received from burning it. All the king's horses and men should be able to put Humpty-Dumpty back together again, though Humpty-Dumpty himself would find this quite impossible.

The example of a deck of cards is often used to illustrate the concept of energy degradation (entropy increase) and irreversibility:

A deck of cards held in one's hand represents order; flung to the floor the deck scatters into 52 individual cards in a random fashion. The intact deck is a stock of potential energy that is in a state of low entropy; once the cards are scattered, a person will have to expend more energy in picking them up and arranging them than the energy originally required to scatter them. Scattered on the floor the cards are high entropy.⁸

Thus Commoner's statement that "there is no such thing as a free lunch" can also be viewed as a restatement of the Second Law because it makes clear that in any process we use up a stock of low entropy forever.

Chardin again expresses it beautifully:

The material concrete universe. . . traces out irreversibly a curve of obviously limited development. And thus it is that this universe differentiates itself from purely abstract magnitudes and places itself among the realities which are born, which grow, and which die. From time it passes into duration; and finally escapes from geometry dramatically to become, in its totality as in its parts, an object of history.⁹

CHAPTER III TYPICAL APPLICATIONS

Because of the unusual universality and generality of these principles, the applications within the scientific fields have been wide ranging. By describing a few of them we can better illustrate their meaning and implications for policy.

As mentioned above, Carnot's statement of the Second Law involved the idea that 100% conversion of heat to work was theoretically impossible even for the perfect engine. This is because if we were able to examine the microscopic nature of some heated steam, we would see many gas particles moving in all different directions. However, in order to do work, we need these molecules to move together in an orderly fashion as do the molecules of a solid piston. Since the total entropy (disorder) of the universe must decrease in order for a process to be spontaneous (i.e., do work for us), if all of the steam particles were to work together to push the piston, i.e., 100% efficiency, we would be increasing the order of the steam particles. This won't happen spontaneously. Thus the result is that while some of the molecules work together, there must be an accompanying running down of the rest of the system so that the net result is an increase in disorder.¹⁰

Carnot figured how to compute this maximum possible efficiency and found it related to the difference of the steam temperature and its cooling water.¹¹

This concept helps us to understand why the human body doesn't work like a steam engine, i.e., using heat as an energy source. Because the temperature tolerance range of most compounds and cells is so narrow, the efficiency of the human body would be quite low if it had to act

like a heat engine. Instead it makes use of chemical energy; however, chemical thermodynamics still adheres to the same principles. In this case we look at the free energy of the system, i.e., that fraction of the total energy of the system which is available to do work under constant temperature (and pressure) as the system proceeds to equilibrium. As with the Carnot heat engine, this available energy is less than 100%. If the process is to run spontaneously, the entropy of the system must increase, and therefore the free energy must decrease.¹²

The important point is that when we create order in one place, we must create at least the same amount of disorder somewhere else or else the process won't work. Of course, individual processes that don't run spontaneously (e.g., an unplugged refrigerator) can be made to run if we add work or energy (e.g., plug in the refrigerator), but the same constraint still holds for the entire system (i.e., the refrigerator and the power plant).

The purpose of going into such details in these examples is to illustrate the applicability of the principles at different levels of interactions (mechanics, chemical reactions, human body) and to illustrate the hardfast nature of the entropy law.

CHAPTER IV
ENTROPY, INFORMATION, AND BIOLOGICAL SYSTEMS

The attempts to measure the amount of entropy in a system and channel its flow (or actually the flow of negentropy, order) led to the development of communications theory from developments in statistical mechanics. Before going into some of the details of this analysis, it is easy to see why there should be a link between information and entropy. We can think of the process of entropy increase as one which destroys information and generates disorder. For example, if a lump of sugar is dropped into a cup of tea which is stirred, the spatial concentration of the sugar molecules, the organized motion of the tea, and the difference of temperature between the tea and its surroundings represent macroscopic information or order. As the sugar dissolves and the tea comes to rest and cools, that information is lost, a less knowable and disorderly state is achieved.¹³ Here entropy is described as the carrier of information; its information content is the measure (in chemical and heat units) of the order of the molecular state. Thus entropy and information can be viewed as equivalent concepts. Information, like entropy, may be regarded as a property of physical systems, a measure of how highly organized they are.

Meier traces classical information theory back to a paper by Leo Szilard when he was attempting to resolve some apparent ambiguities between statistical mechanics and thermodynamics.¹⁴ Szilard was forced to the conclusion that there must be some equivalence between information about the state of a system and the entropy content. Working from this, Shannon first defined a unit of measure for information: the bit, the quantity of information needed to decide between two equally likely

possibilities. He then identified the nonredundant part of a message as that part which contained "surprise" or uncertainty, i.e., something "unguessable" which is the essential part of the information and which adds to our understanding as opposed to mere repetition which adds nothing.¹⁵ Thus the information content of a system is the minimum number of bits needed to describe the system (i.e., the number of bits needed to encode the unguessable component).

It is this element of the unguessable which Shannon measured as the entropy content of the message: the higher the information value the lower the entropy or the higher the negentropy content of the message. Employing a formula first derived by Boltzman and Gibbs which measured the uncertainty associated with statistical descriptions of a physical system, Shannon derived an analogous way to measure the information content (negentropy) of an information system.¹⁶ Basically, this measure is the (weighted log) sum of the probabilities of the different bits possible in a message.

This measure of Shannon's has become widely used as a general measure of diversity or complexity for other systems. This is because the more ways there are to do something, the more complex and varied the system is; but this is just the same thing as saying there is more uncertainty inherent in a situation of complexity, i.e., we don't know which of the many possible ways a system will actually go (the more ways that exist of doing something, the more improbable each one is individually and the larger the formula becomes). Thus ecologists use Shannon's formula as a measure of species diversity and hence of ecosystem stability.¹⁷ In other words, the more information in the form of species diversity contained in the system, the higher order the system is.

However, this equivalence of negentropy or order and information is not a settled concept. While Meier and Layzer consider negentropy and information content to be equivalent, simply different aspects of a single concept,¹⁸ this idea has been challenged by several. Arnheim, for example, criticizes the formulation and equivalence because it ignores structure, i.e., "The entropy principle defines order simply as an improbable arrangement of elements, regardless of whether the macroshape of this arrangement is beautifully structured or most arbitrarily deformed; and it calls disorder the dissolution of such an improbable arrangement."¹⁹ Kenneth Boulding makes a similar argument.²⁰ Eugene Odum and others criticize the formula on similar mathematical terms saying in essence again that the formula says nothing about specific biological activity (i.e., the specific role that species fill in the food web is important in measuring diversity as well as their number and distribution).²¹ In other words, is the complexity or information actually organized into a useful combination or is it a random jumble? The formula arrives at the same value regardless of the workability of the situation.²²

Finally, Gallucci, in summarizing the literature, notes that the association of entropy and information, and information and diversity are analogs which flow from the formal mathematics and that the relation between diversity and stability is dogma--none of these are based on first principles but are phenomenological.²³

Nevertheless, we can still apply the concepts of entropy and information to biological systems to increase our understanding of them. Firstly, all living systems are subject to the Second Law: entropy increases. Thus a molecule, cell, or organism--all highly ordered states--exist only because of an exchange with the exterior. The organism inputs

low entropy or negentropy or usable energy and outputs high energy or "wastes" (of course, one organism's wastes are another's fuel!). It lives on the downhill flow of energy referred to earlier. It creates a little local order at the expense of its source of energy such that the overall entropy of the system has increased.²⁴ In other words, like any machine the organism "burns" fuel (food) to do work (build tissue) but for every iota of added organization, at least one iota of degradation (waste) takes place elsewhere. Of course, all organisms succumb to the Second Law eventually and die; thus we see the real meaning of the phrase "from ashes to ashes." We temporarily gather up localized bits of low entropy so as to create small foci of organization while the surrounding universe runs down. As we get old, our ability to maintain this process decreases and we return to dust.

The power and ability of the organism to survive and, in a sense, even outwit entropy by creating replicas of itself, flows from its ability to handle information. As both Odum and Meier discuss, a small amount of mass (i.e., very little energy potential if we were to burn it up) which is highly organized controls large flows of energy by virtue of its high quality information content.²⁵ These "tiny energies in the right form" (e.g., DNA), in the right control circuit (e.g., the ATP transfer system) are able to "obtain huge amplification and control vast power flows." They do this by "selecting the right combination of ingredients from the environment and constructing replicas of components." Thus the biological systems stand in apparent opposition to the Second Law, always evolving towards more complex organisms and ecosystems. Yet the gain is illusory for all but the participants (and temporary for them) because the entropy law continues

to grind down the universe as a whole though allowing temporary organization of some of the remaining low entropy pieces. Eugene Odum summarizes the strategy of ecosystem development in the following quote; note that it is nothing but the strategy for playing the game of thermodynamics:

The net result of community action is symbiosis, nutrient conservation, stability, a decrease in entropy, and an increase in information. The overall strategy. . . is directed towards achieving as large and diverse an organic structure as is possible within the limits set by the available energy input and the prevailing physical conditions.²⁶

CHAPTER V

ANOTHER LOOK AT THE ENERGY AND POLLUTION "CRISES"

These laws and conclusions, while most often applied to the phenomena described, are perfectly general and can be applied to all systems regardless of level or scale.

The lessons of thermodynamics and ecology provide us with a unique set of symbolic tools with which we can measure the evolution of human culture and of the machine, as well as the energy systems--both biological (food) and synthetic (fuel for technology)--that make that evolution possible.²⁷

In such a spirit we shall take a brief look at two of the great "crises" of our day: energy and pollution. The first point (law) to remember is Commoner's law that "everything must go somewhere." It doesn't disappear; energy is neither created nor destroyed. Herein we have the origins of pollution: high entropy material which we find "unusable" but can be never rid of--garbage, waste heat, air pollution, etc.

The second point (law) is that disorder in the environment, the "environmental crisis," is the inevitable result of the processes of energy conversion. As dictated by the Second Law, any increase in order in our system (electricity, buildings, information, etc.) requires an even greater increase in disorder or entropy in the larger system (our environment). There is no pollution-free process or energy source in this world of ours. Pollution has to happen; there is no free lunch:

What goes in
Must go out
or pile up.

There are no CONSUMERS
of mass or energy
only CONSUMERS.

All events create entropy.²⁸

With respect to energy, the problem is again one of simple interpretation of the Second Law of Thermodynamics. We are not actually running out of energy; all the world is energy convertible by Einstein's famous formula ($E = mc^2$). We are "running out" of low entropy fuels, concentrated or ordered energy usable by our technology (which is information). Our supplies are exhausted when our information can no longer enable us to use the potential energy present in a material, i.e., when it takes as much energy for extraction as is yielded from the source, then the net energy yield is zero. It is more of an "entropy crisis" than an energy crisis.

Yet these conclusions are not necessarily pessimistic; they are just factual. In the same logic of thermodynamics, we find a variety of planning strategies which allow us to maximize our welfare within the overall thermodynamic constraints--just as the ecosystem does. We now turn to these strategies.

CHAPTER VI

PLANNING STRATEGY #1: ENERGY AND MATERIALS CONSERVATION

The first set of policies deals directly with the "substance" we are trying to conserve. In looking at energy and entropy, it is useful to remember that the internal energy and entropy levels of materials are functions of state. What this means is that when the state or condition of a system is altered, the change in any state function depends only on the initial and final states of the system and not on how the change is accomplished. For example, a person who travels from Washington, D.C. to San Francisco changes his position on the globe by an amount that depends only on his initial (Washington, D.C.) and final (San Francisco) states. The distance traveled, however, is dependent on the path chosen and is not a function of state.

To put this more graphically, when climbing a hill, we can go straight up or take a circuitous route: in either case the rise is the same but the distance traveled or "run" is different. We can now return to our concept of energy flowing downhill and construct an "energy slide" which connects the two levels or states (Figure 1). We move down the vertical axis from higher to lower energy levels, i.e., from more ordered (and more useful) energy states to less ordered (and less useful) energy states, or from lower entropy to higher entropy. However, we see immediately that there are an infinite number of possible slopes for the slide. The different slopes compare with the hill example: each slope represents a different way of using the energy and increasing entropy but some get a considerably longer run for each unit "rise" (actually a drop or negative rise in this system). The longer the run, the more work obtained. In Figure 1, path 1 yields 10 units of work,

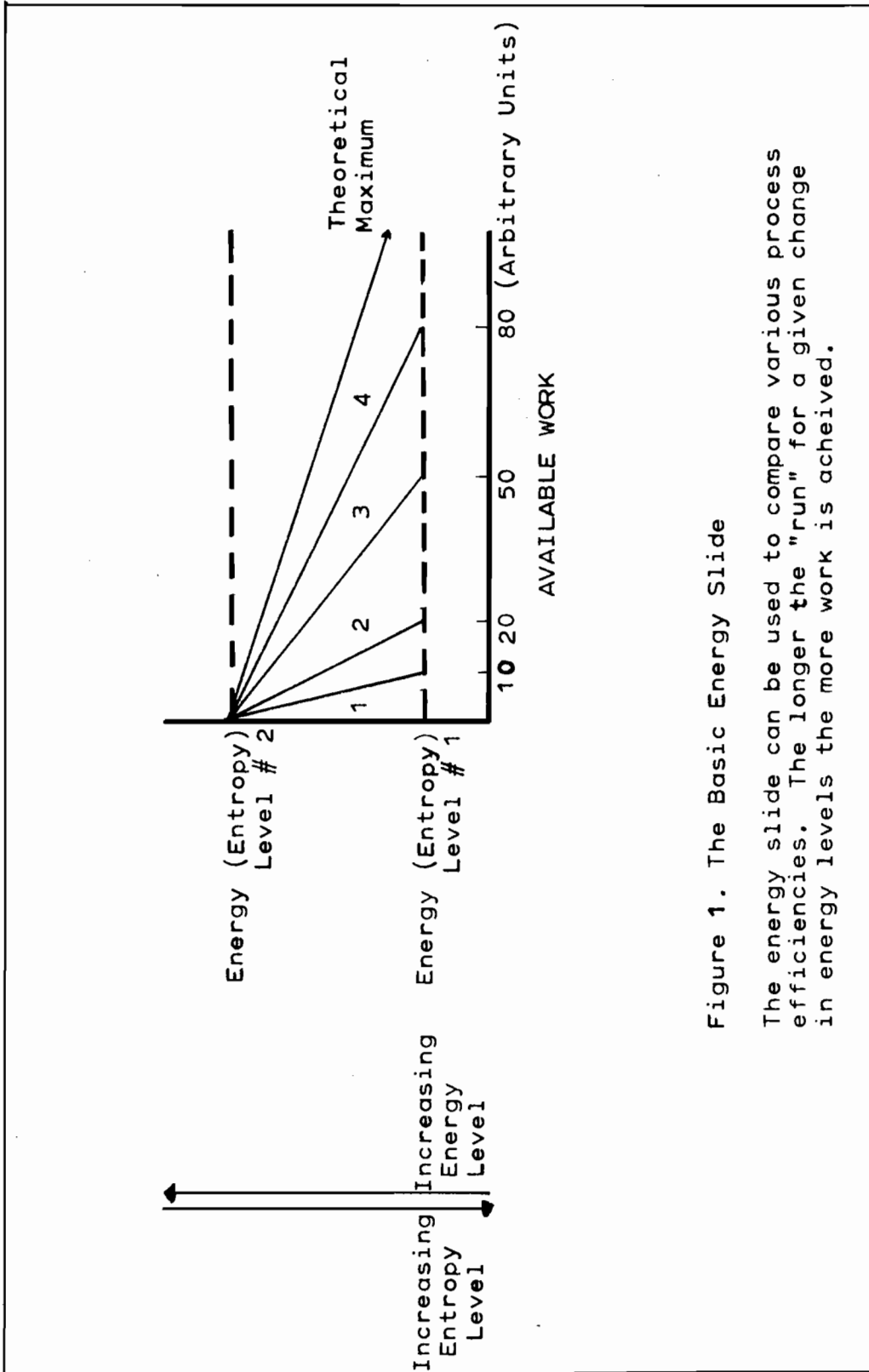


Figure 1. The Basic Energy Slide

The energy slide can be used to compare various process efficiencies. The longer the "run" for a given change in energy levels the more work is achieved.

path 2 yields 20 units of work, and path 4, 80 units of work, all with the same energy consumption.

Thus for every material or energy source, it should be possible to define a thermodynamic potential, i.e., the stored capacity to do work which is a function of internal energy and entropy level. We discussed this earlier as the free energy of a material.²⁹ Thus, for example, high-grade (low entropy) coal or ore has a certain potential to do work or be used which is greater than that for low-grade coal or ore which has a higher entropy content. (In either case the potential is considerably less than 100% according to Carnot.) These latter are still useful but the coal releases less energy and the ore requires more work to put it into the form we want.

By comparing our expected potential with actual yields, we are able to identify room for improvement. Some investigative work in this area has now begun.³⁰ In particular, R.S. Berry et al. define the free energy waste as the difference between the actual thermodynamic potential of a process and the ideal thermodynamic limit.³¹ Comparing this value to the actual consumption figure in a ratio yields a waste factor, i.e., the percent of the consumed potential which is wasted. Finally, by analogy with the economic concept of value added, they define a thermodynamic potential added in each step of a process.

In their work on manufacturing processes they identify three basic policies by which to achieve "thermodynamic thrift": recycling, extended life, and technological developments. In the case of automobiles, they estimate that recycling would achieve an energy savings of about 10%, extended life could achieve a saving of 50 to 100%, while striving for basic improvements in the method of metal recovery and fabrication

offered to reduce thermodynamic costs of an automobile by factors of 5, 10, or more.³² This is a striking example of how information (a low entropy, low energy flow) can amplify our productivity.

Such thinking may also challenge some of our traditional values. For example, R.S. Berry et al. found that a polyethylene bag costs less energy to use and has more potential for reuse than a paper bag!³³ However, their evaluation should be tempered by consideration of the comparative energy costs of cleanup and of efforts to encourage people to recycle; recycling would be very important with polyethylene because it does not degrade very quickly. Such consideration may result in the conclusion that paper bags are still more energy efficient, i.e., their overall energy consumption may be smaller. Thus this example is illustrative of a type of analysis which could help to direct resource allocation in a more efficient way.

Such a thermodynamic evaluation would also help us to identify those processes which are net losers, i.e., we supply more potential than we get out. This is well illustrated when we consider deeply buried coal or oil; the reserve may be of quite high quality, but the net yield may be quite negative because of all the potential needed to get at it. The price we pay in the search must not be forgotten: "The true value of energy to society is the net energy, which is that after the energy costs of getting and concentrating that energy are subtracted."³⁴ The net energy strategy can be likened to the theory of externalities in economics: market imperfections and hidden or unrecognized energy subsidies obscure the true marginal costs involved in our proposed energy strategies; careful analysis of net energy yields would reveal the lessened desirability or even impracticality of some of these

proposals.

In general, therefore, we must look at both the quality and quantity of the energy source, ranging from high flows of dilute (low quality) sunlight, to plant matter, coal, and electricity, to high quality (low flow) human and computer information processing. When we place our hopes on future energy sources and material processes, it is important to perform a net energy evaluation on the entire process under consideration. For example, although the total reserves of oil shale in the western U.S. may be enormous, if it takes 9 units of energy of every 10 delivered to mine, process, concentrate, transport, and meet environmental requirements, then the resource will deliver only 1/10 as much net energy and last only 1/10 as long as was calculated.³⁵ If such a finding were made, it would be reasonable to reassess the utilization of scarce resources in such a marginally productive enterprise. Similarly, Howard Odum claims that man's hopes for food produced from algal cultures are falsely based because they ignore the energy costs of management.³⁶ Or, in a final example, when discussing proposals for bioconversion of wastes to produce gaseous fuel, we should remember that this is not free energy; the wastes which would feed this synthetic energy process are the result of our wasteful, high-energy agriculture in the first place. It would be better from a net energy point of view to first improve the efficiency of the original waste producing processes themselves so as to minimize the first production of wastes and only then to try to reuse the wastes, e.g., as natural fertilizer instead of natural gas, thereby reducing the need for commercial fertilizer produced from natural gas!³⁷

We see, therefore, two major thrusts to this strategy: efficiency through better first use, and subsequent reuse, while always being aware

of net energy losers. Ultimately this is the only way to avoid being swamped out by the inevitable increase in entropy which all our activities produce. Lest we dismiss this as a foolish fear, it should be noted that there is growing speculation and study of the ultimate "waste" of all processes--heat. Thermal pollution could have a variety of effects on the earth system, including local disturbance of flora, fauna and climatic patterns, and alteration of the global heat balance resulting in the melting of the ice caps.³⁸ One observer has totaled up all the waste heat and other disordering produced by human processes in the United States and calculated that the thermodynamic load of the population of the U.S. is equivalent to 4 billion Indians! This type of thinking helps us to reconsider the population problem.

This strategy argues therefore that our processes should minimize the slope on the energy slide, i.e., lengthen the run, something most easily accomplished if we fit our processes into on-going global cycles and recycles. If we focus on renewable flows rather than nonrenewable stocks of low entropy, and produce wastes which can be recycled (by others using solar energy), we will maximize the likelihood of our survival. The only renewable flow of low entropy is the sun; it also has the advantage that the high entropy produced in the manufacture of its energy "pollutes" the atmosphere 93 million miles away. We can lengthen the run from each photon, i.e., the amount of human biomass supported, by more efficient processes. A clear example of this is the difference between vegetarian and meat-eating humans, illustrated in the energy slide diagram of Figure 3. While the final quality of health produced is equivalent, the quantity produced is quite different, i.e., one pathway uses energy less efficiently than the other (consumes more)

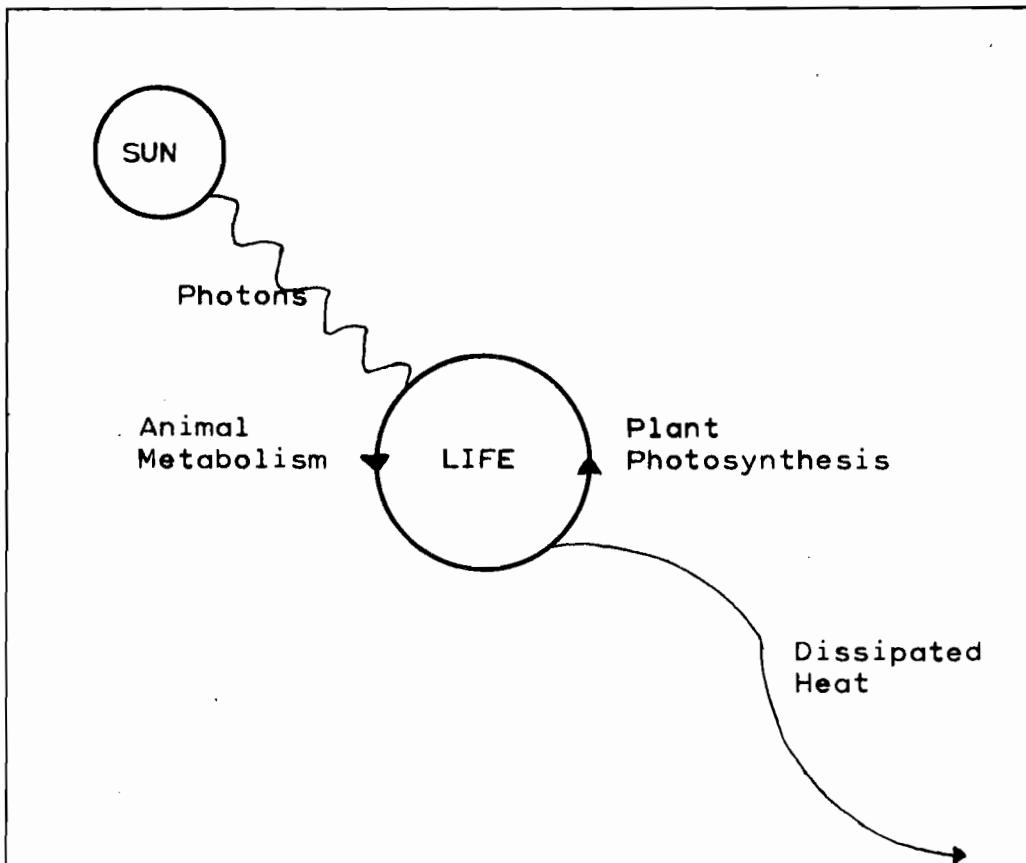


Figure 2. Terrestrial Energy Exchanges

(Adapted from Bent)

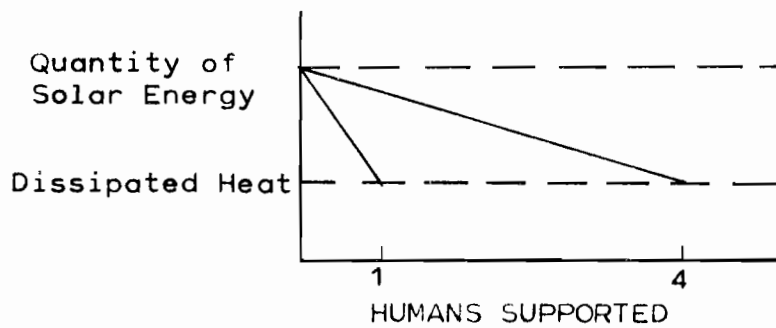


Figure 3. A Comparison of Food Consumption Habits

and is therefore shorter in our diagram.

While it will hopefully not be necessary for us all to become vegetarians, we can see that the concept of thermodynamic valuation is helpful in evaluating alternative strategies of growth. Like the plants, we too should hitch a ride with the sun, work at high efficiencies, export our entropy, and recycle our wastes!

CHAPTER VII

STRATEGY #2: INFORMATION THEORY

As already discussed in some detail, information, "tiny energies in the right form," by virtue of its power of amplification can control vast flows of energy and thus create order. The "fundamental insight" which Richard Meier had in 1955 was that we could conceive of a city as any other open system "that must, if it is to remain viable conserve negative entropy (information)." In his landmark book, A Communications Theory of Urban Growth, he spells out a strategy based on these concepts. "All the discussion that follows is concerned in one way or another with the implications and potentials for viewing urban development that starts from an assessment of social communication."³⁹ It is therefore necessary only to summarize briefly his thinking here.

In an historical analysis that begins with a rural community and person-person exchanges, Meier describes convincingly how the growth of cities seems to be highly correlated with an even greater growth of communications, knowledge, and controls. In this sense, a city is simply a place of accumulation of artifacts for the facilitation of human communications. Such agglomeration brought about external economies for transactions occurring in the public sphere. Thus it can be argued that an increase in the communications rate is a prerequisite for socio-economic growth.⁴¹

Furthermore, the flow of information has many of the same properties as the flow of economic values and actually is a more general case. In particular, communications substitutes for scarcities encountered in other inputs to the production process, especially space and time, and thus affects the social and physical structure of human

settlements in various ways.

Policies to increase the information flow (transaction rate) stumble upon the limits to human, institutional, and overall communications capacity (channel capacity). The arrival of specialized automata such as the computer will relieve man of many tasks and conserve time and energy for higher level information handling. Thus we build to higher and higher orders (negentropy) by using the controlling power inherent in information.

The principles for policy design are then easily derived and reflect the laws of thermodynamics closely: information must be conserved; in order for society to grow, information flows must grow; and in order to prevent overload, the role of automata must increase.⁴¹ We can interpret these policies by referring back to our earlier discussion of stability, diversity, entropy, and information and consider the city to be similar to an organism or ecosystem. By use of the Shannon formula, we see that by maximizing the amount, range, and diversity of possible experiences and transactions (i.e., the quantity and quality of the information flow), we maximize our negentropy, order, or information and achieve a more stable, growing state.

An important application of these principles is in developing countries where the transfer of information (education) must be used as a substitute for other scarce factors of production (natural resources) in order that output can expand vigorously.⁴² Essentially this means that we can increase the efficiency of production and consumption by good use of communication and information. But this is just the same thing as saying once again that we have to make full usage of the inherent thermodynamic potential of our systems.

CHAPTER VIII

STRATEGY #3: BIOECONOMICS

This is essentially a far-reaching extension of Strategy #1: Energy and Materials Conservation. Again, one individual, Georgescu-Roegen, has done much of the current theorizing in the field.⁴³ Georgescu's starting point is that economic processes like evolutionary processes are entropy segregating; as Kenneth Arrow put it, "Economics deals with the production and transformation of goods from one form to another, and that is a physical and chemical process that has direct application to entropy."⁴⁴

The first fundamental point is that current economic thinking is built after the model of mechanics. It is viewed "as a mechanical analogue consisting. . . of a principle of conservation (transformation) and a maximization rule. The economic science itself is thus reduced to a timeless kinematics."⁴⁵ Everything is perfectly reversible and the system--a closed circular process--equilibrates quickly. The problem of pollution is simply one of getting the prices right.

Georgescu points out that this ignores the entropy law and perpetuates the myth of perpetual motion. In reality, he says:

The economic process, like any other life process is irreversible (and irrevocably so); hence, it cannot be explained in mechanical terms alone. It is thermodynamics, through the Entropy law, that recognizes the qualitative distinction which economists should have made from the outset between the inputs of valuable resources (low entropy) and the final outputs of valueless waste (high entropy). The paradox suggested by this thought, namely, that all the economic process does is to transform valuable matter and energy into waste, is easily and instructively resolved. It compels us to recognize that the real output of the economic process (or of any life process for that matter) is not the material flow of waste, but the still mysterious flux of the enjoyment of life. Without recognizing this fact we cannot be in the domain of life phenomena.⁴⁶

He therefore views welfare as a concept of state, or condition, rather than throughput of production or consumption. With the exception of green plants, all organisms speed up the march of entropy with man at the top of the list.

Georgescu also points out the difference between available energy and accessible energy, i.e., net energy, and the consequent importance of the distinction between energy flows (solar) and stocks (available domestic deposits). The earth is a thermodynamic system open only with respect to energy, not material. Thus our "entropic dowry" of materials is limited and if our accumulation of wastes doesn't drown us out, herein lies our doom. The only way to substitute energy for material is through "physico-chemical manipulations" (and information), but we are limited by the net energy concept. Recycling can never be complete either. Thus waste is inevitable, and, as the chemist Henry Bent put it, "The greater our gross national product, the larger the gross national byproduct."⁴⁷ Thus the "entropy law is the taproot of economic scarcity."⁴⁸

Without going into specifics here, he then argues that many of our specific schemes for future supplies of energy and materials are thermodynamically incorrect; he rejects the classical ideas that (1) there is no limit to natural resource availability (plain sophistry which ignores the issue of accessibility and disposability), (2) the power of technology is without limits (the dinosaurs thought likewise), and (3) we can always substitute something less scarce (there is a finite stock of low entropy material). There are no technological solutions to get us around the finite nature of our low entropy resources (unless we learn to operate Einstein's equation in reverse, using solar energy--improbable!).

He concludes, therefore, that not only is unlimited growth impossible, but also that the vision of a steady state is just as fanciful. While he argues that we should shift our energy sources from nonrenewable stocks (fossil fuels) to renewable flows (solar energy), he still concludes that even a solar-based economy will run down eventually, for such an economy would still need to tap the terrestrial dowry for materials. Thus the unescapable conclusion is that "the most desirable state is not a stationary one but a declining one," indeed, it is inevitable.⁴⁹ Georgescu however vigorously resists on historical and evolutionary grounds the idea of drawing a blueprint for survival and instead sets down some basic bioeconomic points from which he derives a set of policies.

Firstly, he notes that man creates exosomatic instruments, i.e., "instruments produced by man but not belonging to his body."⁵⁰ This has brought about two fundamental changes in man: irreducible social conflict (as opposed to the necessary biological action of other species such as bees) and addiction to these exosomatic instruments. Thus man's survival presents a unique set of bioeconomic problems conditioned by the basic asymmetries existent in energy stocks and flows.⁵¹

Finally, the philosophical point on which he grounds his bioeconomic program is "the relationship of the quality of life of one generation with another--the distribution of mankind's [low entropy] dowry among all generations."⁵² He argues that future generations are unable to bid on today's markets no matter how we try to set the prices "right" and that for ethical reasons, they should be guaranteed a share of this dowry and not an ecological crisis. "We must emphasize that every Cadillac or every Zim--let alone any instrument of war--means

fewer ploughshares for some future generation, and implicitly fewer human beings, too."⁵³ He criticizes the Green Revolution because "a highly mechanized and heavily fertilized cultivation does allow a very large population to survive but the price. . . means a proportionately greater reduction of the future amount of life."⁵⁴ Therefore: (1) the production of all instruments of war should be prohibited completely as an absurd use of resources, (2) the lesser developed countries should be brought up to par as quickly as possible so that they can become involved in the needed transformations, (3) the population level should be lowered to one supportable by organic agriculture (i.e., solar inputs only), (4), (5), (6), and (7) we should minimize waste, attempt to cure ourselves of our craving for gadgetry, get rid of fashion, and make goods more durable, and (8) we should cure ourselves of the "'circumdrone of the shaving machine' which is to shave oneself faster so as to have more time to work on a machine that shaves faster," ad infinitum.⁵⁵

In appraising Georgescu's program, we may not agree with his time frame of entropic doom, pessimism about the power of information (technological change), or zero discount rate for the concerns of future generations, but in the long run (whatever that may be), the basic logic is sound; his bioeconomics program makes sense for the design of a resource-conserving society.

CHAPTER IX

STRATEGY #4: THE PRINCIPLE OF LEAST EFFORT

We have already mentioned briefly the point that entropy has a probability interpretation in the context of information theory. To return to the example of the pile of leaves blown away, we can say that it is very improbable that the leaves will reunite into the same neat pile no matter how long we wait; nature "prefers" disorder rather than order. Thus we may say that the probability of a disorderly arrangement is greater than the probability of an orderly arrangement. For example, if we line up nine people and leave each one free to take one step in any of four directions, the probability of an ordered response, i.e., all taking steps in the same direction, is 1 out of 65,536 (4 out of 4^9).⁵⁶ From this point of view, an increase in entropy is a change from a less probable (more orderly) state to a more probable (less orderly state). In the words of Chardin: "Little by little, the improbable combination that they [structures] represent become broken down again into more simple compounds, which fall back and are disaggregated in the shapelessness of probable distributions."⁵⁷

It is possible to carry this concept further in describing our knowledge of a system. Thermodynamic entropy as we have discussed it is a concept of state, a macro concept defined in terms of observable properties. However, there will be quite a considerable number of microstates or detailed arrangements of the components of the system that are associated with a given macrostate. The formulas discussed earlier of Boltzmann and Shannon related the macrostate to the microstate by asserting that the entropy of a system was equal to the (weighted log) sum of all the possible microstates of a system. In our

earlier discussions, these microstates were the possible bits of information and the number of species in an ecosystem. Thus, as entropy increases, we find that the possible microstates increase (or vice versa), and we have less complete knowledge of the macrostate than we had in the earlier macrostate because there are more possible microstates. The macrostate is now more entropic, less ordered, more random in the microstate. Thus entropy can be interpreted as a measure of the disorder of the microstates and as a measure of our uncertainty about the microstate.

An example will help to make this all clear.⁵⁸ Let us consider a deck of cards; the deck has two recognizable macrostates: the shuffled condition in which we have little idea of the order of the cards or the value of the 15th card from the top, and the perfectly ordered state in which the cards are in a known order and we can predict the value of a card from its position in the deck. The actual order of the cards is the microscopic state of the deck. There is only one microscopic state of perfect order (low entropy) but many, many sequences or microscopic states for the shuffled macroscopic state (higher entropy). Further, if we start with the ordered deck and mix the cards, the entropy of the system increases, and our knowledge of the microscopic state drops sharply. Because there is only one sequence in the ordered state and many in the shuffled state, in the long run it is more probable to find the shuffled state.

The statistical interpretation of entropy goes beyond the physical interpretation which is "content" with an increasingly imperfect macro specification (i.e., less and less knowledge of the microstates). While the physical interpretation cannot distinguish between the increasing number of microstates, the statistical interpretation recognizes that

until the entropy of the universe is really at a maximum, we can use our knowledge to attach some sort of probability distribution (or likelihood of occurrence) to the possible microstates and base decisions on these likelihoods.

For example, if one were to act as a "rational" gambler in a game of dice-throwing, you would bet on the outcome which has the best odds, i.e., the greatest chance of occurring or the most probable outcome.⁵⁹ In a single toss of two dice, where we know nothing about the dice and assume they are fair (equal probabilities for all outcomes), there are 36 possible arrangements of numbers that may appear. However, there are only 12 possible totals, with the total of 7 appearing $6/36$ or $1/6$ of the time. Consistent with this amount of information available, a "reasonable" bet would be number 7. If we had more information (e.g., the dice are "loaded"), we would define different probabilities and choose a different strategy. We choose a bet which is maximally noncommittal (unbiased) with respect to the missing information, or, put differently, maximally probable given our uncertainty. Choosing the most probable outcome chooses the most probable microstate (number 7) for our given macrostate (2 "fair" dice).

To recapitulate, the maximum entropy principle in spatial planning means using the available information (on the macrostate) to assign probabilities to possible outcomes (microstates), making the weakest or minimally prejudiced assumption possible in view of the available information, i.e., take the maximum uncertainty position. We can then incorporate these probabilities as constraints in the decision-making process and choose the microstate which can be achieved in the maximum number of ways and therefore is the most probable. The principle of

maximum entropy is thus restated by Cesario as the "principle of maximum uncertainty" and essentially means minimizing your chance of error given what information you have. (It does not mean we try to maximize the disorder in the system; we try to minimize that!).⁶⁰

Wilson and others have used this statistical idea in their models of transportation systems.⁶¹ This author, however, finds the arguments rather complex and only marginally interpretable in any behavioral or physical sense that is useful to planners. It is interesting to note that the art historian, Robert Arnheim, has used the same ideas, though very nonmathematically, to argue for the simplest and most elementary structure available at any given level of complex structural theme.⁶²

In other words, micro-forms should be the simplest possible with respect to the function to be performed in the same sense that theoretically complex but structurally simple mathematical formulas are "elegant." We might think of this as the most homogenous distribution of parts possible; such a structure or microstate, however, would also be the most probable, and this is, therefore, an analogous argument.

The reason why this probabilistic interpretation of entropy has been dwelt on here is because it suggests other more applicable planning principles. In an early paper using this probability concept, Leopold and Langbein argued that a river system is in dynamic equilibrium with its environment (steady state),⁶³ its most probable condition, when the energy in the system is as uniformly distributed as may be permitted by the physical constraints.⁶⁴ In the case of rivers, Leopold and Langbein show that this means that the downstream rate of production of entropy per unit mass is everywhere constant. Hence the most probable river profiles and hydraulic conditions should exist. They derive from this

conclusion river profile and hydraulic equations which produce results that agree closely with actual field observations. More importantly, however, they demonstrate that the profiles and drainage networks so derived also follow the principle of least effort. This means that not only is the downstream rate of entropy production everywhere constant (the most probable condition), within that condition it is also at a minimum. The river channel makes interval adjustments among its hydraulic variables to meet the requirement for maximum probability; within the constraints of this system, these adjustments tend also to achieve minimization of work.

The principle of least effort was formulated by Zipf.⁶⁵ This principle states that a system will minimize its average rate of work expenditure over time. However, because the time sequence of events is never known, a system can only minimize the probable average rate of work, i.e., it is guessed by the principle of the least average rate of probable work.⁶⁶ Thus a river system in steady state will achieve maximum entropy by establishing a distribution of entropy production which is uniform (everywhere constant). This distribution is maximally probable from the entropy distribution point of view because all energy gradients (per unit mass) are equal. Then, within this probability distribution, the rate of work is minimized. This principle of least work is graphically expressed by the rank size rule.

The rank size rule relates the level (e.g., quantity) and order (rank) of the characteristics of a phenomenon. In the case of streams, it says that the relation between (the log of) stream length and the stream order is linear (see Figure 4). Further work by Leopold and also by McMahon has demonstrated that tree branching patterns follow

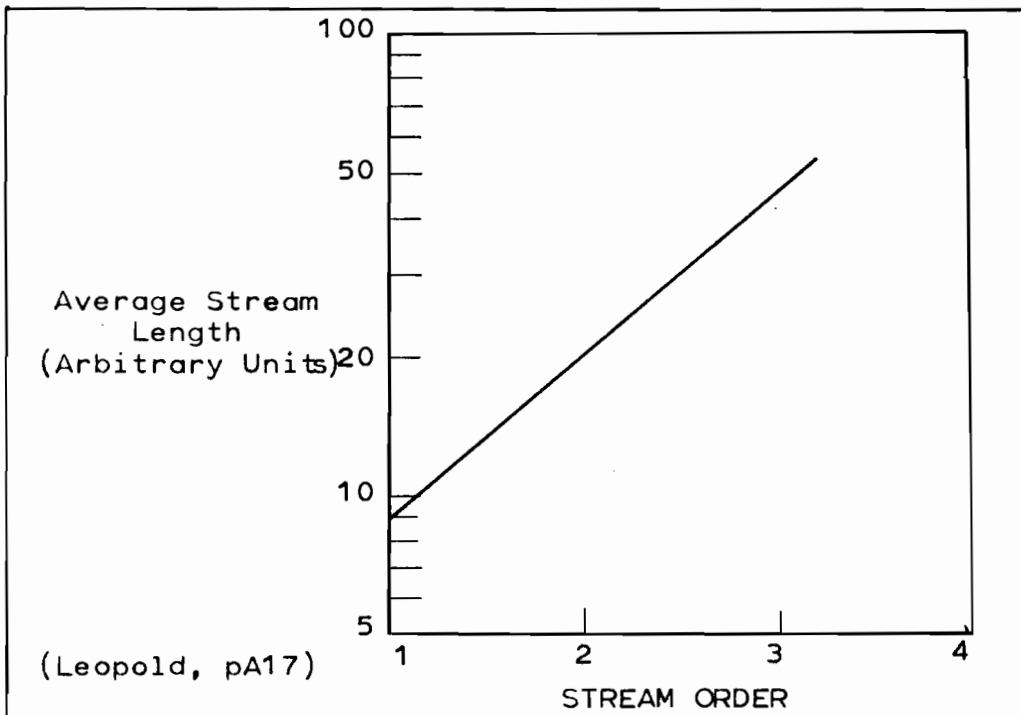


Figure 4. Relation of Length of Streams to Order

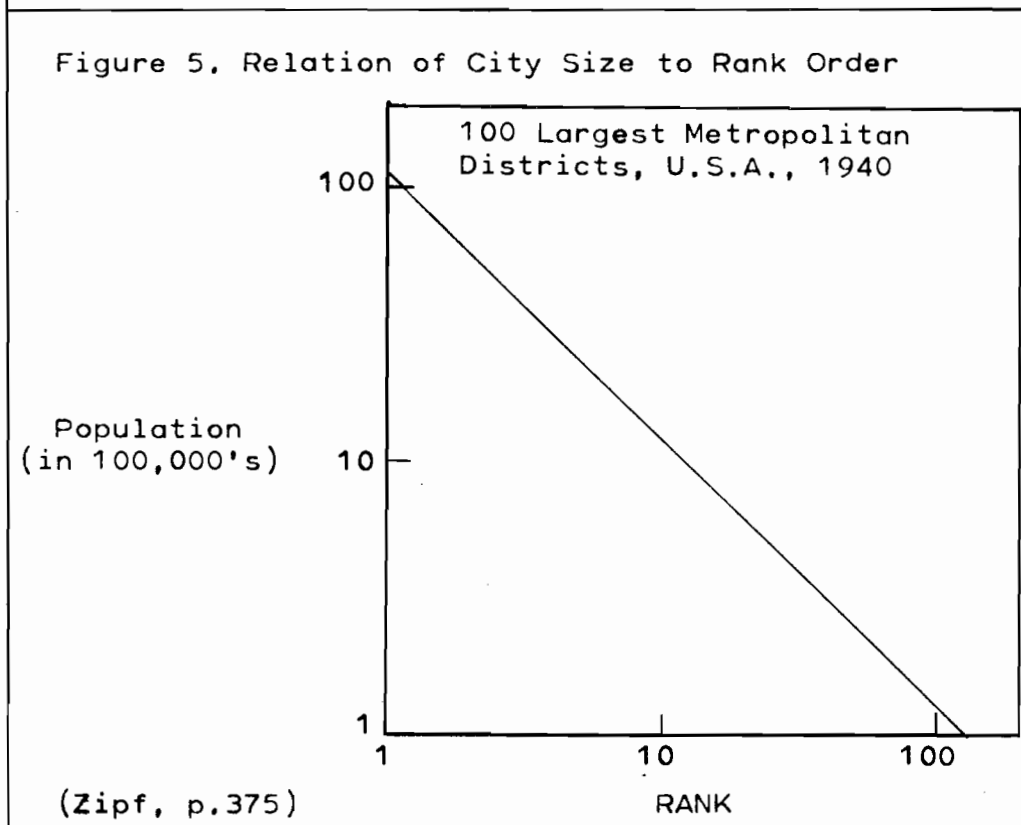


Figure 5. Relation of City Size to Rank Order

similar efficiency criteria and that the rank size rule describes the relation between branch order and lengths and numbers.⁶⁷

However, the rank size rule is not limited to trees and streams; it is applicable across a wide variety of fields, including, for example, city size (see Figure 5).⁶⁸ The immediate implication is that this curious rule is indeed a general result flowing from thermodynamics as was the case for trees and streams. A rigorous proof of such a proposition would offer considerable intellectual economy to investigators and constitute a significant advance in systems theory. Woldenberg and Berry summarize the work of several investigators who have shown with analyses similar to Leopold's that the rank size rule as applied to cities is the "least effort" and most probable solution to the (allometric) growth equations used for systems of cities.⁶⁹ The rank size rule thus represents achievement of thermodynamic equilibrium (a "graded urban system") under certain conditions of growth (allometric) in an open (to materials and energy) urban system. Similar work has also been done for central place hierarchies.⁷⁰ While there are qualitative differences in application between the above investigators and Leopold and Langbein (e.g., in the spatial geometry adapted by the networks), Woldenberg and Berry generalize that:

Rank size is an expression of the conservation of matter for the steady state: it implies achievement of a steady state. Orders [rank] and levels [quantity] reflect organization demanded by continuing energy inputs, and are expressed in that system geometry that performs work with least effort efficiency.⁷¹

This is a powerful generalization. It suggests that the principles of thermodynamics may be the fundamental underpinnings for many of our successful social science models. Woldenberg and Barry say:

General systems theory can be thought of as an outgrowth of thermodynamic theory. The second law of thermodynamics states

that, on the scale of the universe, energy becomes randomly distributed in the universal closed system and unavailable for work. For more limited or open systems this second law may be stayed or reversed. In river systems, continued energy inputs stay the process; such systems achieve that maximally probable steady state permitted within the energy input context. In urban systems there is at least a staying of the second law, and at increasing scale, there is evidence that economies of agglomeration lead to self-sustaining positive feedback embodying increasing differentiation, specialization, interdependence, and order. Nonetheless, both river and urban systems achieve analogous equilibria with analogous order properties, although with different geometric forms. Are there not lessons to be learned as we attempt to formulate more general regional theory?⁷²

The intellectual ramifications of such a conclusion are truly wideranging, although this author is not aware of more recent work to develop and apply this theme in a more detailed, policy-oriented manner. Such an exploration is also beyond the scope of this paper. However, some additional interpretation is worthwhile within this context to indicate the possibilities and potential areas of fruitful research.

First, if we reconsider our energy slide drawing of earlier discussions, we see that it is a similar diagram to that for the rank size rule for cities (see Figure 6a). The effects of more efficient energy use on city systems are shown in Figures 6b and c.

Second, core-periphery or heartland-hinterland models of regional growth also carry an added interpretation. As we move up the energy slide or rank size line, we move up in order, information, city size, and do work. The periphery or hinterland has traditionally provided much of the low entropy material to accomplish this ordering and work. Work is done locally, disorder created (e.g., for extractive industries), and the resulting products sent on upward. Similarly, work is done at the top of the slide as well and so dissipated energy or pollution slides down to the hinterland (e.g., air pollutants will diffuse out

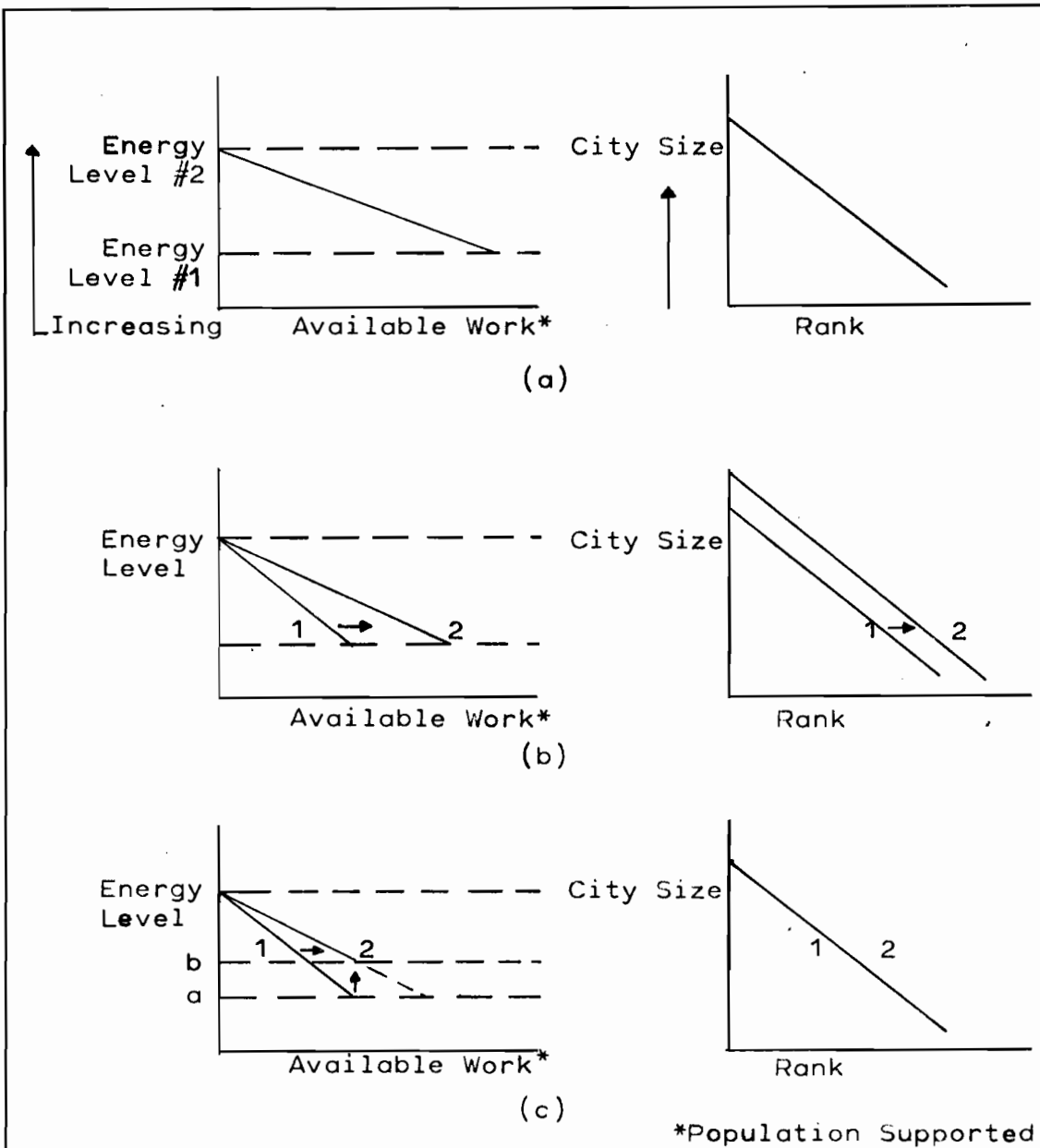


Figure 6. The Effect of Energy Efficiency on City Systems

A country can improve the efficiency of its material and energy usage by lengthening the run on its energy slide: (a) for a country with the optimal size distribution this would mean (b) supporting a greater population with the same level of resource consumption, or if ZPG existed, either providing more goods and services to the existing population (no graph) or (c) curtailing existing resource use (from 'a' to 'b').

from their source) as well as left over "bits" of energy.

These left over "bits" are ordered energies such as new information (perhaps in the form of new processes) which the next lower level city adds to its other energy and entropy inputs to do work. It in turn creates left over flows for the next lower city, etc. This offers a new model for the technology diffusion process. Because innovation represents a new knowledge, it is most likely to occur in the most ordered environment (big cities); later, when the process is more standardized (e.g., run by automata), the host environment even more ordered than is necessary for the new process, and other environments now ordered enough, it can drop away to a lower level city. This suggested model is quite compatible with the innovation diffusion processes postulated by such workers as Wilbur Thompson and Brian Berry.⁷³ Wilbur Thompson, for example, argues that the extensive social overhead of larger metropolitan areas--large university and research parks, sophisticated engineering firms, financial institutions, flexible transportation networks and utility systems, persuasive public relations firms, excellent medical facilities, etc.--facilitates the institutionalization of entrepreneurship (invention, innovation, promotion) in those areas.⁷⁴

Furthermore, because the rank size line describes the least effort or most energy-conserving city size distribution, i.e., the longest possible run on the energy slide, it provides a planning strategy for countries where such a distribution is absent (as in the LDC's). A country can lengthen its run on the energy slide by changing a differently shaped rank size curve to the optimal shape (see Figure 7).⁷⁵

This also leads us to certain conclusions about future growth in industrial countries: up to a point, big cities have to get bigger,

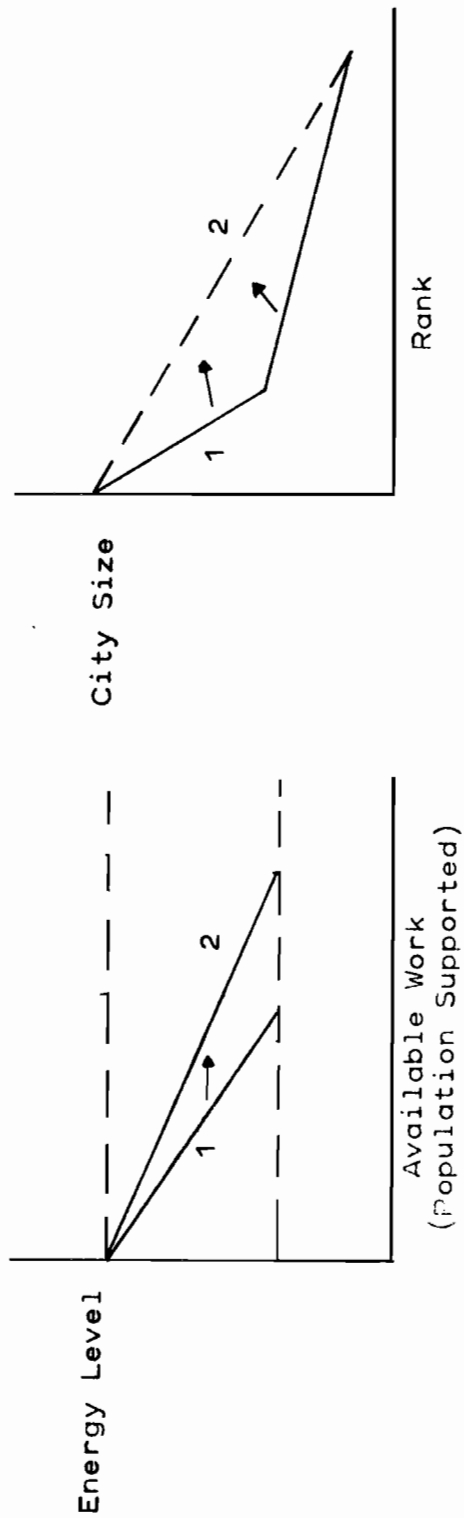


Figure 7. The Least Effort Solution for City Size Distribution in Developing Countries

A developing country can improve the efficiency of its energy and material useage by lengthening the run on its energy slide (from 1 to 2) and adopting the linear rank size relationship shown (from 1 to 2).

(Partially adapted from B. Berry)

i.e., they must get their proportionate share of growth. We can see this by use of Figure 8. If we freeze the size of the largest city (by setting a limit on city size) and force growth elsewhere (undirected), we will end up with a different distribution (there are a number of possibilities, but we could find the maximally probable one under the new system constraints). Such a distribution is imagined in Figure 8a for different points in the future after the "rules" went into effect (say, 1980). However, this new distribution will not be optimal because it will not satisfy the least effort solution for a less constrained system, that is, one without the population distribution rules. Therefore, it will use more resources.

While it may not be possible to limit directly the growth of large cities, it is possible to imagine policies which would somewhat slow down the growth of large cities relative to the small cities and thereby regrade the size distribution (see Figure 8b). However, such policies would have to work on the underlying structural conditions which give big cities their competitive advantage. By changing these structural conditions, a new least effort distribution could result, one which hopefully would look like Figure 6b. At present, however, not enough is known about the factors which affect the shape of the least effort curve to enable us to change them efficiently.⁷⁶ It is possible that redistribution policies would not result in a minimal least effort curve but again only a least effort curve for a more constrained and less efficient system. The least effort solution for given structural conditions is shown in Figure 8c.

It must also be emphasized that the growth of the urban hierarchy can continue only up to a certain limiting level; the least effort policy

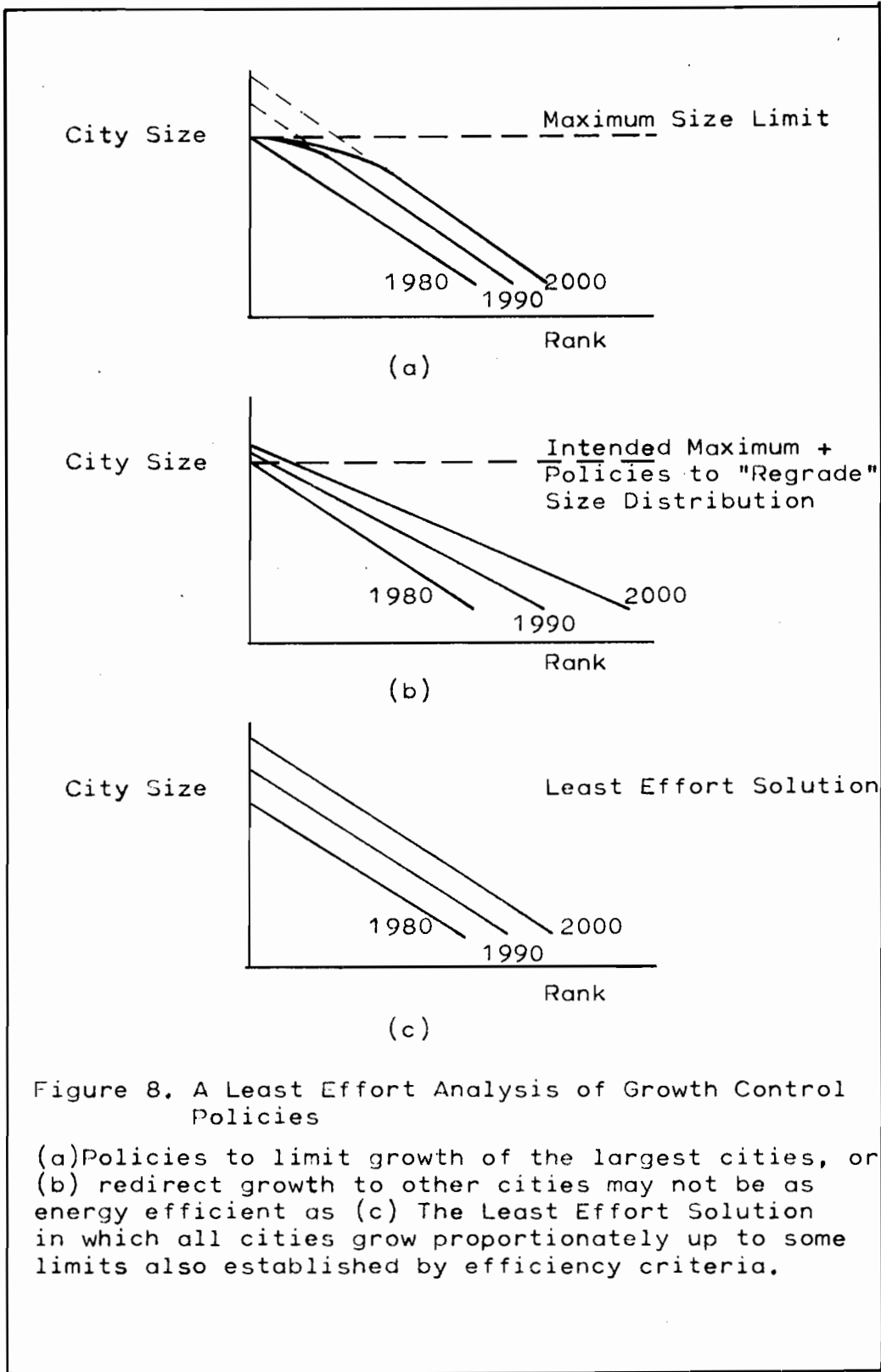


Figure 8. A Least Effort Analysis of Growth Control Policies

(a) Policies to limit growth of the largest cities, or (b) redirect growth to other cities may not be as energy efficient as (c) The Least Effort Solution in which all cities grow proportionately up to some limits also established by efficiency criteria.

rule postulated here only describes the growth of cities up to a point somewhat below that level. There are two fundamental reasons to suggest a limit to both the rank size rule and city size (and hence to national growth): (1) increasing size brings with it increasing social costs and diseconomies and decreasing efficiency which may limit growth, and (2) rank size order assumes simple central places (i.e., a city with a central business district), while with the rise of polycentric urbanism and large multifunctional and multilocational corporations, it is no longer clear that shocks will move through the urban hierarchy in the same manner as formerly postulated. While a thorough discussion of each of these points is again beyond the bounds of this paper, each will be discussed briefly below.

The issue of city size and its associated costs and benefits is vigorously debated today and has generated an enormous literature which has not resolved the issue of what those limits are.⁷⁷ While most authors concede, or argue for, the existence of limits to city size on the basis of an expanded cost-benefit analysis, suggested limits range from 5000 (by Aristotle, based on the number of citizens who could enter a meeting hall to conduct democratic meetings) to unspecified figures beyond the size of any existing city. While it is probably premature to specify the size and shape of a city size-efficiency curve, locate cities on the curve, and perform definite cost-benefit evaluations, the existence of such a curve can be accepted. At some level, the increasing requirements for system maintenance alone will produce a level of diseconomy and require a level of complex organization which will argue against further growth due to the risk of instability and self-destruction.⁷⁸ At such a point the system will have achieved the steady state or maintenance

level characteristic of all mature systems.⁷⁹ Energy flowing through the system will then have as its purpose the maintenance of the order which has been built.

A second limitation on the use of the rank size rule is due to a structural change in the urban hierarchy, i.e., from a simple central place hierarchy to a complex polycentric system dominated by large multifunctional and multilocal corporations. As a result, some argue that the urban structure and organizational interactions of advanced economies such as the United States and Japan can no longer be adequately described by theories based on strictly hierarchical models. According to a model put forth by Allan Pred, private and public multifunctional, multilocal organizations dominate advanced economies and are responsible for the lion's share of growth-inducing innovation adoptions that affect city system development in those economies.⁸⁰ The interurban paths or city-size sequences followed by shocks to the system initiated by these organizations are influenced by the spatial structure of those organizations, which is both hierarchical and asymmetrical in its own right, and the intermetropolitan information circulation relationships which exist. These two subsystems feed back upon one another to channel the diffusion process and influence the city system growth process. The result is that urban hierarchies in advanced economies cease to react in the simple fashion described earlier but develop cross-linkages between all levels of city size, i.e., large to small and large to larger, smaller to larger, smaller to smaller, etc. In such a situation (in advanced economies), the rank size rule as set forth here becomes useful only for historical analysis. However, it should still retain some usefulness in lesser developed countries.

CHAPTER X
CONCLUSIONS AND SUMMARY

In this paper we have talked about energy and entropy, about the opposition of life to the evolution of the universe and the tithe we must pay, about how in every process we create more disorder (somewhere) than the order we build up. We have then further argued that while pollution is inevitable, considerable conservation is possible, that information is related to diversity and stability and is necessary for (and part of) the growth of order, that developing a modern irreversible bioeconomics is essential in the true meaning of that word, and finally that there is a potential applicability of the entropy law through general systems theory to all of our present and future models.

Throughout this discussion, there have been occasional references to the concept of steady state or the achievement of thermodynamic equilibrium. This is a dynamic equilibrium maintained by constant energy inputs. It represents the overall strategy of resource conservation, stability, and long life from which the strategies discussed herein have been deducted (as was obvious in the case of bioeconomics).

According to Prigogine, thermodynamic systems in steady state show several very interesting properties: (1) as they evolve towards this steady state and usually higher state of order, they show a decrease in entropy production, i.e., their processes become more and more efficient; (2) when they achieve dynamic equilibrium, they minimize their production of entropy, i.e., they achieve the least effort condition; and (3) they show high stability and resilience to perturbation.⁸¹

Similarly, Eugene Odum has summarized the biological characteristics

of systems in steady state. Such systems are characterized by low gross production, high efficiency in energy use, high levels of diversity, long complex life cycles, nutrient recycling, selection pressure for quality and feedback control, good stability, low entropy, and high information.⁸²

Both authors neatly summarize the strategies for entropy conservation discussed throughout this paper. If we are to strive for a resource-conserving dynamic equilibrium as all other natural systems do (and indeed we eventually must), then we must utilize all the thermodynamic potential available to us, i.e., get the most output possible from the least input possible (the least effort criterion). A "reward" for achieving this condition will be a stable and probably long-lasting society.⁸³

CHAPTER XI

SOME NOTES ON COSMOLOGY AND THE FUTURE

One set of issues not dealt with in this paper might be termed cosmological: is this model of the universe really correct? What is the source of this order and disorder? Are we really evolving to a point of no return? Thermodynamic order is only one level of order, the simplest; what do other ordering principles have to say? Entropy is sometimes called "time's arrow" because its steady increase marks what we consider to be the "forward" direction for time (because backward things are considered very improbable). However, this pessimistic concept is always under challenge. We have already seen that Georgescu-Roegen takes a straightforward physical interpretation and sees no escape from our entropic doom.

However, others such as Arnhem and Chardin are more optimistic. Arnhem argues that equilibrium is really a very desirable, orderly, balanced state.⁸⁴ Chardin says that "contrary to appearances still admitted by physics, the great stability is not at the bottom of the infra-elementary sphere, but at the top in the ultra-synthetic sphere." "Hominisation" has plunged us into "growing and irreversible unification" and allowed us an escape from entropy. The "grains of thought go on building themselves in the inverse direction of matter" leading Chardin to conclude that "the universe is a collector and conservator, not of mechanical energy, as we supposed, but of persons."⁸⁵ Clearly these arguments talk a metaphysics which is not contained within thermodynamics.

Recently, Layzer has argued in quite physical terms that entropy processes are really quite timeless and have their origin in various cosmological processes of the universe that do not imply a necessary

entropy doom.⁸⁶ Still others argue that states of the system far from the equilibrium point may actually "create" order within the system.⁸⁷

This debate really need not concern us here except to caution those who would adopt a cosmological model which they operationalize to mean that there is nothing to worry about. At this point in space and time, our observations tell us quite strongly that the laws of thermodynamics are laws indeed. Even information theory and use has its limits, though some may not agree. Not even information with its tiny energy flows and great amplification can be a perpetual motion machine. As Georgescu-Roegen says:

We cannot obtain, transmit, or even keep in store information of any kind without an increase in the total entropy of the isolated system in which we act. To determine the speed of a particle we must cast a beam of light on it; this will necessarily produce a dissipation of available energy and, hence increase the total entropy. The same result is produced by the barking of a dog which wants to inform its master that it wants to be let into the house. Also the typesetter increases the total entropy when he sets a sentence in type even if he sets a completely garbled sequence of letters.⁸⁸

While this paper has broken little new ground, its purpose has been to describe and apply the principles of thermodynamics in order to allow interested investigators to pick up leads indicated here. In particular, the field of regional science seems to be ripe for new applications. The idea that "cities are systems within systems of cities" which follow the principle of least work and achieve a dynamic equilibrium needs further analysis within the context of developing and developed countries. In particular, how do the entropy law and principle of least effort translate into considerations which relate to the new urban system evolving in advanced economies? Results could serve to help policy makers develop sound approaches to the problems of city size and resource allocation.

Looking more generally, if we use systems theory to map the concepts of thermodynamics onto other levels of organization or fields of study (see Table 1), we see that we are lacking a developed behavioral interpretation of entropy. Communications theory focuses on transactions, probability theory on choosing the least foolish behavior if one is a rational observer, and the principle of least effort on minimizing one's perceived work over time. However, such concepts are still sketchy and very incomplete in their behavioral interpretations: how does information flow relate to behavior and thence to the entropy of the organism and the entropy of the system? At the more comprehensive behavioral level, why hasn't political science utilized these concepts in its analyses and models (e.g., imperialism is nothing but stealing low entropy and leaving behind high entropy!)?⁸⁹ Further work on the interactions of the entropy law and the economic system on a macro level is also needed.⁹⁰

It is hoped that "time's arrow," no matter what else it accomplishes, reveals a growing and more widespread appreciation of these fundamental ideas in environmental planning, particularly in the areas sketched above.

TABLE 1

ENERGY, ENTROPY, AND LEVELS OF ORGANIZATION

The general systems theorists note that each level away from human scale builds up a unique science and mode of analysis. One cannot profitably employ experimental and observational techniques developed for one level at another scale; ambiguities in interpretation tend to destroy the persuasiveness. Yet energy and entropy appear at all levels under different names! The release of energy or entropy at one level of organizations triggers a burst at the next lower level in all but rare instances. Living systems, in particular, contain these triggers and amplifiers across levels in an ordered sequence through time.

Science	Levels	Scale	Energy (stored)	Energy (flow)	Entropy Content	Entropy Flow
Physics	Particles	10^{-27} to 10^{-30}	Momentum	Neutrino/gamma ray	Energy/temp.	Increase in closed system
Chemistry	Atoms	10^{-24} to 10^{-26}	Excitation levels	Photon (mostly ultraviolet)	Energy/temp.	"
Biochemistry	Molecules	10^{-20} to 10^{-24}	Vibration, excitation	Photon (mostly infrared)	" " + ordering of atoms	" but slow
Microbiology	Cells	10^{-12} to 10^{-19}	Fat, carbohydrate	ATP transfer	DNA codons	Metabolism
Physiology	Organs	10^{-1} to 10^{-11}	Fatty tissue, glycogen	Ion discharge	Structural networks	Defense mechanism
Psychology	Organism (observer)		Stamina	Works, effort	Memory, experience	Communication
Social Psychology	Group (household)	3 to 20	Wealth, status	Consumption	Cohesion	Interaction
Sociology Economics	Organization	10^1 to 10^5	Worth, capital	Turnover	Structure, procedures, traditions	Transactions
Urbanology	Community (metropolis)	10^5 to 10^7	Physical equipment, rank, order	Traffic, utilities	Files knowledge	Reform Reconstruction

Source: Richard Meier, Landscape Architecture 239, December 1975.

EPILOGUE

Thermodynamics II

Necessary to the calculation
of the living process--the energy
available to push the engines of
our selves;
the fuel we need so we can blaze up once
or twice between the night and night--
I say,
necessary to the calculation
is a wee, small, tidy factor that
laughs the limit to us:
entropy.

It stands inside the furnace of the farthest star--
perhaps it is the ash of ash of ash--
and with unerring hands, it
turns the
damper
down.

Fanchon Lewis
This Is Women's Work, 1974

NOTES

¹R. Kern and A. Weisbrod, Thermodynamics for Geologists, p. 34; Wilson Clark, Energy for Survival, p. 9; Bruce Mahan, Elementary Chemical Thermodynamics, p. 2.

²Barry Commoner, The Closing Circle, pp. 39, 45.

³Teilhard de Chardin, The Phenomenon of Man, p. 56.

⁴Kern and Weisbrod, p. 68; Clark, p. 12.

⁵Clark, p. 12; Mahan, p. 3.

⁶F.C. Andrews, Thermodynamics: Principles and Applications, p. 37.

⁷Isaac Asimov, "In the Game of Energy and Thermodynamics You Can't Even Break Even," Smithsonian.

⁸Clark, p. 8.

⁹Chardin, p. 57.

¹⁰See Andrews, pp. 69-70.

¹¹Specifically the maximum possible efficiency for a perfect, reversible heat engine is given by: $T_h - T_c / T_h$, where T_h is the temperature of the steam or hot temperature, and where T_c is the temperature of the coolant or cold temperature of the final output.

¹²The change in free energy (ΔG) of a system during a process with constant temperature (T) and pressure is defined as: $\Delta G = \Delta E - T\Delta S$, where ΔE is the change in internal energy of the system and S is entropy (see Mahan, pp. 23, 85; Lehninger, p. 27).

¹³after David Layzer, "The Arrow of Time," Scientific American, p. 56.

¹⁴Richard L. Meier, A Communications Theory of Urban Growth, pp. 124-125.

¹⁵See John R. Pierce, "Communication," Scientific American.

¹⁶The Boltzmann-Planck formula is $S = K \ln(N)$, where S is entropy, K is a constant, and N is the number of microscopic states available to the system (from statistical mechanics). Thus when $N = 1$, i.e., $T = -273^\circ\text{C}$ or absolute zero, the substance is in a perfect crystal and the entropy is defined as 0. In more general terms, when $N > 1$ and can be described by a probability distribution, p , then: $S = -K \sum_j P_j \ln(P_j)$ which reduces to that above when all states are equally probable, i.e.,

$P_j = 1/N$. This is also the maximum value of S for that system.

Similarly, information can also be defined as the logarithm to the base 2 of the possible combinations of bits. In a signal composed of an infinite number of discrete symbols of R kinds, Shannon's formula defined the information content per symbol in a string of symbols as: $H = - \sum_j P_j \log_2 P_j$, where P_j is the probability of occurrence of the j th kind of symbol. Note that the more improbable, i.e., the higher the surprise value, the greater is the information index. For a comparison of these formulas, see text and note 23 (Mahan, p. 79; Gallucci, pp. 348-349; Howard Odum, 1971, pp. 169-171).

¹⁷Vincent Gallucci, "On the Principles of Thermodynamics in Ecology," Annual Review of Ecology and Systematics, pp. 348-350; Eugene Odum, "The Strategy of Ecosystem Development," Science, p. 228.

The exact form they give is: $-\sum n_i/N \log_2 (n_i/N)$, where n_i is the number of species (N_i/N approximates P_i) (Eugene Odum, p. 228; Gallucci, p. 349).

¹⁸Meier, Communications Theory, pp. 149-150. Layzer argues that entropy and information are opposite sides of the same coin; information means macrostate knowledge while entropy means microstate information. The problem is that random perturbations (noise) prevents us from ever knowing the microstate information and hence prevents us from doing work (Layzer, p. 60).

¹⁹Robert Arnheim, Entropy and Art, p. 14.

²⁰Kenneth Boulding, "Search for Time's Arrow," Science, p. 1099.

²¹Eugene Odum, p. 228; Gallucci, p. 350; Odum further points out that a decrease in variety of species, i.e., a loss of some n_i , can be offset by a more even distribution of the remaining n_i/N , thus leaving the diversity index unchanged (Eugene Odum, p. 228).

²²If we remember that information is the log of the possible combinations, we see that many combinations may not be useful at all.

²³Gallucci, pp. 349-350. For example, in comparing the two equations (see above #3), they have opposite interpretations despite the formal similarity in the math: S is entropy and H is information content or negentropy. When $R = N = 1$, $H = S = 0$, i.e., when $R = 1$, I have only one kind of symbol available and convey no information, while when $N = 1$, the physical system is the most well ordered energy state possible, the perfect crystal. I then have perfect knowledge of that energy state as opposed to when S is at equilibrium in which condition I have little knowledge of the physical system but maximum information in my string of symbols.

Sometimes the formula for H is written with a K in front and the sign reversed so that $H = -.693S$. However, this equality is based on analogy, not a strict proof.

²⁴More precisely, the entropy change of the system of a living organism can be split into 2 parts, $\Delta_e S$, which is the net flow of entropy due to exchanges with the environment, and $\Delta_i S$, which is the entropy production due to irreversible processes within the system: $\Delta S = \Delta_e S + \Delta_i S$. For life to continue, the Second Law says that ΔS and $\Delta_i S > 0$; therefore, $\Delta_e S \leq -\Delta_i S < 0$, i.e., a sufficient amount of negative entropy (food and energy) from outside the system is added to balance the positive entropy changes (degradation) within the system--to allow steady state or growth within the entire system (organism and environment), total entropy (ΔS) increases.

²⁵Howard Odum, Environment, Power and Society, pp. 171-172.

²⁶Eugene Odum, p. 232.

²⁷Clark, p. 25.

²⁸Henry A. Bent, "Haste Makes Waste: Pollution and Entropy," Chemistry, pp. 8-9.

²⁹To be most general and correct, the term thermodynamic potential is reserved for the term E (internal energy) given by: $E = TS - PV + \sum_k u_k m_k$. T is the temperature, S is entropy, P is pressure, V is volume, and the last term is chemical potential. We then define $\phi = E - TS + PV - \sum_k u_k m_k = 0$ for a system in equilibrium. We recognize the Free Energy G as the first three terms of this equality. Thus ϕ , called the null function, is used by Keenan et al. to measure the available useful work because for a system not at equilibrium $\phi > 0$. Its interpretation means that for given energy, volume, and composition of the system, ϕ decreases with increases in entropy; with low entropy it is large and vice versa. As Keenan et al. point out, this is a better formula than Gibbs Free Energy in a system where the constituent substance is free to mix with the atmosphere (as in some fuels) because the chemical potential term becomes important. It is ignored by R.S. Berry et al. in their work on automobiles. When applied to a hydrocarbon fuel, ϕ represents the minimum work necessary to form the fuel in a given state from the water and CO_2 in the atmosphere. Thus this is the maximum useful work which could be obtained in the reverse process, i.e., fuel consumption (Keenan et al., pp. 459-460; Andrews, pp. 76-83).

³⁰J.S. Keenan, E.P. Gyftopoulos, and G.N. Hatsopoulos, "The Fuel Shortage and Thermodynamics--The Entropy Crisis," and R.S. Berry, M.F. Fels, and H. Makino, "A Thermodynamic Valuation of Resource Use," in Energy: Demand, Conservation, and Institutional Problems, ed. M.S. Macrakis; R.S. Berry, "Recycling, Thermodynamics, and Environmental Thrift," Bulletin of the Atomic Scientists.

³¹R.S. Berry et al., p. 506.

³²R.S. Berry, p. 32.

³³R.S. Berry et al., p. 513.

³⁴Howard Odum, Presentation before the Royal Swedish Academy (untitled), Energy Digest, p. 487.

³⁵Ibid.

³⁶Howard Odum, Environment, Power and Society, pp. 125-128. However, the system he reviewed was proposed by A.D. Little several years ago and should not be viewed as the most efficient one possible. Principal energy costs are in stirring and harvesting, and these can be minimized. If anything, Odum's analysis points the way to a net energy yielding system.

³⁷See Clark, pp. 464-465.

³⁸Clark, p. 107; W.W. Kellogg and S.H. Schneider, "Climate Stabilization: For Better or for Worse," Science.

³⁹Meier, Communications Theory, preface and p. 39.

⁴⁰Some of the recent evidence on this point is quite illuminating. Alonso has shown that income per capita is correlated with increasing city size (population), which is a rough measure of the number of opportunities for interaction available in a place and therefore a rough measure of information content. Further, he has shown it is also correlated with the population potential of a city, i.e., the potential access to opportunities for interaction with people in other places and thus may be thought of as an index of borrowed size. Therefore, because of their high population potential, small metropolises in megalopolitan complexes have much higher incomes than independent metropolises of equivalent size which are distant from large population complexes (Alonso, 1973, p. 200).

⁴¹Meier, pp. 150-151.

⁴²Ibid., p. 164.

⁴³Georgescu-Roegen, "Economics and Entropy," The Ecologist; The Entropy Law and the Economic Process; "Energy and Economic Myths," Southern Economic Journal.

⁴⁴Kenneth Arrow, quoted in "Georgescu: A Prophet of Energy Economics," Business Week, p. 114.

⁴⁵Georgescu-Roegen, "Economic Myths," p. 348.

⁴⁶Ibid., p. 353.

⁴⁷Bent, p. 8.

⁴⁸Georgescu-Roegen, "Economic Myths," p. 353.

⁴⁹Georgescu-Roegen, "Economic Myths," p. 369.

⁵⁰Ibid.

⁵¹For a discussion of these asymmetries, see Georgescu-Roegen, "Economic Myths," pp. 369-372. The essential points have been made.

⁵²Georgescu-Roegen, "Economic Myths," p. 374.

⁵³Ibid., p. 370.

⁵⁴Ibid., p. 373.

⁵⁵Ibid., pp. 377-379.

⁵⁶Isaac Asimov, "Natural Changes Create Disorder," Science Digest, p. 55.

⁵⁷Chardin, p. 57.

⁵⁸from Mahan, p. 58.

⁵⁹from F.J. Cesario, "A Primer on Entropy Modeling," AIP Journal, pp. 41-42.

⁶⁰Ibid., p. 46

⁶¹See Cesario for applications; essentially the constraints are set as the marginals for a matrix whose exact set of values are then chosen on the basis of that which is most probable, i.e., can be arrived at in the greatest number of ways.

⁶²Arnheim, see especially p. 52.

⁶³Dynamic equilibrium is the concept of steady state where the system does enough work to just maintain itself. Systems in steady state are in their most probable condition and are characterized by choosing a condition which accomplishes the least work necessary to maintain the steady state. This is different from the concept of final equilibrium referred to throughout, where all processes are finished and tensions reduced to the irreducible minimum, i.e., all energy gradients are flat. For a discussion of the thermodynamics of steady state, see this paper below and I. Prigogine, An Introduction to the Thermodynamics of Irreversible Processes, pp. 75-92.

⁶⁴Luna Leopold and W.B. Langbein, The Concept of Entropy in Landscape Evolution.

⁶⁵G.K. Zipf, Human Behavior and the Principle of Least Effort.

⁶⁶Zipf states that the principles of least effort and least work differ because the latter does not consider work minimization over time, or more precisely, in view of a probability distribution of system

variables, while the former does. Because Leopold and Langbein contain their achievement of least work within the achievement of a maximally probable distribution of system properties, they are actually describing the principle of least effort as formulated by Zipf (Zipf, pp. 5-6; Leopold and Langbein, pp. A17, A13).

⁶⁷Luna Leopold, "Trees and Streams: The Efficiency of Branching Pattern," Journal of Theoretical Biology; Thomas McMahon, "The Mechanical Design of Trees," Scientific American.

⁶⁸See Zipf for many other applications.

In the case of cities, the rank size rule describes the size relations in a group of cities, usually greater than a particular size, as follows:

$$(1) P_r = P_1 / r^q$$

where P_r is the population of the city of rank r and P_1 is the population of the city of rank 1. Therefore, (1) becomes:

$$\log P_r = \log P_1 - q \log r$$

which will graph as a straight line with slope of $-q$ on log-log paper ((1) will also graph as a straight line on log normal paper). According to Zipf (see Figure 5), q equaled 1 for the U.S. in 1940 (B.J.L. Berry, 1962, p. 148; Zipf, pp. 374-375).

⁶⁹Michael J. Woldenberg and Brian J.L. Berry, "Rivers and Central Places: Analogous Systems?" Journal of Regional Science. Allometric growth is a general growth principle which states most generally that some law of proportionate effects operates among the components of a growing system. One example of an allometric growth equation states that the rate of growth of a system's components is a constant fraction of the rate of growth of the whole system, or $dY/Y = b dX/X$. Integrating and taking antilogs, we find that $Y_i = ax_i^b$, which defines a probability distribution for the system. There are a number of variants or relationships possible depending on the growth process. A probabilistic version is used for cities: the growth probability of an entity is a random proportion of the previous value of the entity, hence entities have the same probabilities for a given percent increase. While this choice of models seems restrictive, it appears to fit the data. Alternatively, Zipf uses the least effort approach to arrive at the same result. At any rate, in general, the conclusion is simply that for any regular growth process there is a maximally probable steady state within the constraints of the process which results in a certain distribution of the characteristics of the system. As Leopold points out for river systems, there are several ways to achieve this most probable state; the way actually chosen results in satisfying the least work criteria. This is irreversible, nonequilibrium thermodynamics (Leopold, p. A7; Woldenberg and Berry, p. 130-132).

⁷⁰For a summary, see Woldenberg and Berry, pp. 133-136; see also M. Beckmann, "City Hierarchies and the Distribution of City Size," Economic Development and Cultural Change, pp. 243-248; and Michael Woldenberg, Energy Flow and Spatial Order. In this latter work, Woldenberg concludes

that for market area hierarchies the rank size rule is only a relatively crude indicator of equilibrium (i.e., least work and maximum entropy) and that for fine discrimination of disequilibrium a convergent mean model is more appropriate. Nevertheless, for general purposes it is adequate (Woldenberg, p. 33).

⁷¹Woldenberg and Berry, p. 136.

⁷²Ibid., p. 137.

⁷³For a traditional model, see, for example, Wilbur Thompson, "Internal and External Factors in Urban Economics," in Regional Policy, eds. John Freidman and William Alonso.

Allan Pred, however, takes a somewhat different approach; see below.

⁷⁴Thompson, pp. 210-215.

⁷⁵Brian J.L. Berry, "City Size Distributions and Economic Development," Economic Development and Cultural Change, pp. 582-583; and "Cities as Systems within Systems of Cities," Regional Science Association Papers, pp. 147-164. Berry notes that the rank size rule generally applies throughout the world for developed countries and for those developing countries with long urban traditions, such as India and China. In the developing countries with dual economies or which exhibit primacy, the relationship does not hold but develops as natural development occurs.

⁷⁶According to Zipf, the "least work" solution would probably involve a parallel shift of lines as shown in Figure 8c but also a possible change in slope. This is because he found that the slope of the rank size line was related to the diversity index m , i.e., a measure of the levels and diversity of available goods and services. The measure m was causally related to city size: m increased with city size and vice versa. Hence an increase in resource use or efficiency of resource use could either be translated into an increase in total population, supported as shown in Figure 8c and/or could be used to increase the diversity index m . An increase in m would proportionately increase the growth of large cities at the expense of the growth in the small cities, while a decrease in m (not discussed by Zipf) would achieve the reverse. Thus, "least effort policies" could be designed which would regrade the size distribution as shown in Figure 8b by restricting the relative growth of goods and services in large cities when compared with small cities. The implication is that if we decrease the advantages of living in a large city relative to small cities, the latter would develop more quickly than the former. It has been suggested by some that such a process is occurring in the U.S. because of the inability of city governments to keep up with service demands. See, for example, Jack Patterson, "The Prospect of a Nation with No Cities," Business Week. See the text discussion for reservations about such policies.

For historical curves of city system growth in the U.S. and Germany, see Zipf, pp. 420, 427. The U.S. pattern is very similar to Figure 8c, while the German pattern showed a change in slope during the

period of German unification, due to an increase in the diversity index m , i.e., the X axis intercept increased at a slower rate than the Y axis intercept (a shift in the opposite of the direction shown in Figure 8b).

⁷⁷The two best summary articles, though from opposite points of view, are: William Alonso, "The Economics of Urban Size," Papers of the Regional Science Association; and Alan Gilbert, "The Arguments For Very Large Cities Reconsidered," Urban Studies.

⁷⁸For a thorough discussion, see D.H. Meadows, D.L. Meadows, J. Randers, and W.W. Behrens III, The Limits to Growth.

For a well written scenario of what will happen when the system becomes unstable, see Roberto Vacca, The Coming Dark Age.

⁷⁹Eugene Odum, "The Strategy of Ecosystem Development," Science; see especially p. 230.

⁸⁰Allan Pred, "Diffusion, Organizational Spatial Structure, and City System Development," Economic Geography.

⁸¹I. Prigogine, Introduction to the Thermodynamics of Irreversible Processes, pp. 75-92. See also note 63.

⁸²Eugene Odum, p. 230.

⁸³For a blueprint of the implications for planning from an urban transition to steady state, see Richard Meier, Planning for an Urban World: The Design of Resource Conserving Cities. See Chapter 12, especially p. 442.

⁸⁴Arnheim, p. 25.

⁸⁵Chardin, pp. 298-299.

⁸⁶Layzer, especially pp. 68-69.

⁸⁷I. Prigogine, G. Nicolis, and A. Babloyantz, "Thermodynamics of Evolution," Physics Today. See also Isaac Asimov, "Can Decreasing Entropy Exist in the Universe?" Science Digest.

⁸⁸Georgescu-Roegen, The Entropy Law, p. 392.

⁸⁹Karl Deutch has made some partial, but uncompleted, efforts in this connection. See also the forthcoming paper by R.G. Ramke, Q.A.L. Jenkins, and P.H. Templet, "Energy, Entropy, and Social Order."

⁹⁰See the very recent work by Barry Commoner, The Poverty of Power. This volume was published too late to be reviewed in this paper.

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