The last subsystem I have identified is the payoff system. In a way all others depend on this. The dynamics of society are the dynamics of the learning process; the learning process depends on the payoff system, and very often the difference between deteriorating or appreciating systems depends on the nature of the payoff system. We see this even in such a simple thing as pollution. The obvious solution of the problem of joint production of goods and bads is to penalize the production of bads and reward the production of goods. The production functions themselves — that is, the input-output relationships which survive — are going to depend on the relative payoffs. The theoretical solution to the pollution problem is very easy: negative commodities should have negative prices. This is hard to do through the market mechanism; we have to have some sort of political mechanism, such as effluent taxes, particularly when the bads are public bads rather than private bads.

I suggest two main conclusions. First, in a great many of these problems the difference between deteriorating and appreciating systems often is quantitatively very small. This is "Engels' Law" — that a sufficient change in quantity produces a change in quality. Sometimes a very slight variation in the parameters of a system either send it from bad to worse or from bad to better.

Second, I do not care how fast we go from bad to better; what I am interested in is that we should go. Direction is more important than speed. The slope of the system should be value-positive, to go back to differential calculus again. We should avoid, as far as possible, any increased efficiency in going from bad to worse. Going from bad to better, however, has to be learned. It involves the growth of knowledge, the growth of self-consciousness, the understanding of learning processes and of political processes. It involves understanding the dynamics of legitimacy, of threats and coercions as well as of market processes and preaching and teaching processes. Difficult as the task is, I know of no theorem that it is impossible.

R. STEPHEN BERRY

Stephen Berry's formula for survival takes a thermodynamic view which holds that "we must recycle wastes while the thermodynamic potential still is moderately high." Otherwise, he warns, they are lost, as helium is lost when it leaves Earth's atmosphere and goes into space. The idea that the Earth is a closed system is a myth, he says. It collapses each time we put our discards into non-recoverable states. The author is a member of the department of chemistry, University of Chicago.

THE OPTION FOR SURVIVAL

We have three options about survival. We might decide that survival is an undesirable goal. Certainly, in this age of institutionalized rancor, I sometimes feel that the healthiest thing for life on earth would be the extinction of the human race. The second choice is to say that it is a matter of indifference whether the species survives or not, that our choice of life style should be made with no explicit consideration of the survival of our descendants. This policy is the alternative we appear to be following now.

The third alternative is to make survival of the species a primary positive goal. I want to explore certain consequences that would follow if we choose the option of survival. As we shall see, these consequences take the form of rejecting certain courses of action, far more than of adopting specific courses; they are "thou shalt nots," rather than "thou shalt." Adopting survival as a goal is not going to deprive us of our freedom of choice or of our confusion over what to do next.

Sometimes people worry about rational examinations of survival, as if this process worked against the process of natural selection. For man, rationality is probably the best Darwinian adaptation he has. It may be inadequate, but logical thinking remains our most useful means to continue and, in one or another way, to improve our existence.

Let us think of our entire human society at this instant of time, now. Conceive of this society as carving a trajectory through time. At every instant, we each face a countless number of alternative courses of action. Without conscious effort, we all go on continuously making these choices. The sum of all the choices that all of us make at one instant determines the next point on our collective time-trajectory. Each individual's different choice would mean a different trajectory for the society. Had I put marmalade on my toast this morning instead of jam, we would all be on a different trajectory than we actually are. Had Hitler taken Stalingrad, our trajectory would have been a different one. Had a mosquito bitten Lee Harvey Oswald (or whoever it was) at the right moment, our trajectory might be a very different one today.

We would like to think it possible to characterize trajectories in the succinct terms of some comprehensive property or function. The economists use utility, for example, or GNP. To a physical scientist, the natural characteristics of a complex system come from the field of thermodynamics, and it is essentially a thermodynamic analysis of society that I want to make for the remainder.
of my discussion. I want to indicate how we can pick a single variable — not necessarily the only useful one, but the most obvious and available one — to give us a criteria for survival and stability, for guidance in our long-range planning and, to a surprising degree, for making policy decisions now.

**Stability and Cataclysm**

Even before we specify the criteria for making our evaluation, we can distinguish different sorts of trajectories for a society. One kind, which we call a stable trajectory, is that of a society whose existence is never seriously threatened by extinction or by a cataclysmic upheaval. The other, in extreme, is the kind of trajectory that corresponds to the pessimistic prophesies of our environmental jeremias. Such a trajectory, leading to extinction or to cataclysm, can obviously be called unstable. If we opt for survival, we want to find criteria to determine whether our own real trajectory is likely to be stable or unstable. We must try to recognize potential instability and to respond by changing our life style from that of an unstable trajectory to a more stable one.

Instabilities may make themselves felt with horrifying speed. The unstable trajectory may remain close, deceptively close, to other more stable trajectories for a very long time. Then, perhaps after centuries or millennia, the society comes close upon the moment of instability. As this time comes nearer, the unstable trajectory moves with increasing velocity away from neighboring trajectories; the way of life along that unstable trajectory becomes more and more different from the other, previously similar life styles, and the other trajectories become less and less accessible. The headlong inflation of 1922-23 in Germany is a miniscule example of an instability restricted primarily to one very limited area and sphere of behavior.

The potential for such instabilities is an inherent property of all non-linear systems — systems in which small causes can feed back to bring about large effects. Most of the time, most of human existence fortunately conforms to a more or less stable system. This, however, does not relieve us of the responsibility of thinking about those rare and devastating events we have the capacity to create.

Nobody knows what happens to a society rushing into the maelstrom of an instability. Extinction is one possibility; another is a cataclysmic change so great that the life style and the trajectory after the awful event bear no resemblance to the previous life style and trajectory. This could well be the situation after the instability we call an all-out nuclear war. One could interpret our post-1945 life style as the adaptation following the society's relatively successful passage through a near-instability. Whatever the new life style would be, the drastic, abrupt change involved in changing to that style would amount to one possible adaptation to living on an unstable trajectory and passing through the instability. Another kind of adaptation would result from recognition of the impending instability before it arrives. If a society manages this, it may adapt by moving consciously and deliberately from one trajectory to another. But to carry it off, the society must have the means to identify the potential instability, to select a more stable path, and to find the will and means to change.

**Making Transitions**

The farther apart are two trajectories, the more their life styles differ. That is what we mean by the distance between the trajectories. Clearly, it is much easier to move to a nearby trajectory than to a farther one. If we want to move from an unstable trajectory to a more stable one, and do it in easy and orderly way as we can, then we had better do it while the two trajectories are close together. The nearer we come to an instability, the greater must be our adjustment to move to stability. Eventually, when the unstable trajectory is far from any stable trajectory, the change required of a society to avoid a cataclysm may cause as much disruption of the society as meeting the cataclysm. Neither is a way of life consistent with opting for survival.

Thus, the survival option carries the imperative that we learn to recognize each potential instability and adapt by changing our trajectory, at a time early enough to make the change in an acceptably smooth way. Whether we can achieve such profound intelligence is entirely unclear. It is also irrelevant. I am not asking whether we will be successful in following the option for survival, but rather, what we should do if we want to try. If we opt for survival, we must develop criteria and institutions to recognize the problems and the requisite changes to achieve increased stability. Here, we can see, is how we encounter those inhibitory guides to which I referred earlier. Our criteria can only tell us which trajectories to avoid; we shall always need other guides to tell us which trajectory to select.

**The Survival Function**

Having looked at time-trajectories and instabilities in very general terms, let me turn now to the property I want to use to characterize a trajectory. Let me introduce the notion of thermodynamic potential. This concept, sometimes called free energy, is a measure of the stored potential of a system to do work, to be useful. It includes not only the chemical energy stored in coal or in food; it also includes the capacity inherent in a system because of its order and organization. A vein of copper ore has a higher thermodynamic potential than the same copper dispersed as dissolved salts in the oceans. Garbage and trash separated into food waste, paper, glass and metal has a higher thermodynamic potential than the same rubbish in a single drum. An organized machine has a higher thermodynamic potential than the same machine wrecked and rusty. I need not assail you here with the scientist's definition of the thermodynamic potential. I believe it is sufficient to say that it has a precise definition and, more important, that we can describe in rather precise and quantitative terms the change in thermodynamic potential associated with virtually any process occurring in our society.

I propose that we use, as our first criterion for survival, the annual consumption of thermodynamic potential. Let us call this quantity the first survival function, or, since I haven't...
found any other as yet, simply the survival function.

In order to use the survival function as a measure of the stability of our way of life, we must examine its rate of change with time. Thus, we must speak of the trajectory of a society as it is characterized by its annual consumption of thermodynamic potential, and the way this consumption changes as the society evolves.

Clearly, the survival function and its evolution in time contain a distillation of the essential information of how a society uses its physical resources. The more primitive the society, the smaller its annual consumption of thermodynamic potential is likely to be. A high state of technological development must imply a high value of the survival function, that is, a high rate of consumption of thermodynamic potential. However any society, primitive or highly developed, may be thrifty or prodigal in its use of thermodynamic potential. There is presumably some minimum rate consistent with a given life style, but I think we have considerable experience in showing that we can far exceed that minimum.

The total thermodynamic potential available to a society is finite. The amount stored in the earth, plus the amount we receive in the form of solar energy each year, constitute our bank balance. If we exceed the amount we receive, we must dip into reserves. If we dip long enough into reserves, we must expect them to disappear. This situation represents the ultimate catastrophe, if we opt for survival; fortunately, we probably have the opportunity to study the behavior of the survival function and confront a few lesser catastrophes before this ultimate problem has anything more than an academic interest.

We can deal with the survival function, and how it provides a framework for making policy decisions, at two levels: We can approach it at the level of sweeping analyses of the whole human society; or we can move to a more specific level, by breaking the society into components and examining the way a specific component consumes thermodynamic potential. I shall first indulge briefly in the heady general problem, and then move to specifics.

I propose that the rate of change with time of the survival function satisfies what economists and scientists call a stationary condition. This means that modest variations in our life style would essentially not affect the annual increase in our consumption of thermodynamic potential; our technology would grow next year at about the same rate it now does, even if we make minor changes in the society. This in itself does not tell the whole story. The time rate of change of the survival function is unaffected by modest change — so long as certain constraints exist. Here, it becomes extremely useful to distinguish various classes of constraints. One set contains the true natural constraints set by nature: conservation of mass and energy, and the natural increase of entropy, for example. A second set is based on technology; some processes are possible in principle but are technologically undeveloped. A third set of constraints would include the social constraints: fiscal, psychological, political.

The reason for distinguishing the constraints is to be able to decide ultimately where technological development or, in principle, social change, would be most likely to accomplish the chosen goals. Some processes are probably working so near their natural limits that no amount of technological development would bring more than a slight benefit, whereas other processes are still far from their limits. Without these considerations, we fall all too readily into the SST syndrome: We try to be technologically cute by solving some relatively easy engineering problem, paying far too little attention to whether that solution has any cogency to the real and difficult problem. If we paid more attention to questioning the contribution that a given so-called technological ad-
rance makes to the larger problem, we would be debating methods of urban surface transportation instead of supersonic cattle boats.

Without going further into detail, I would like to point out that the properties I have proposed for the survival function and its time rate of change have already put us into a position to begin to deal with the evolution of the survival function. Because the rate of change of this function is stationary against small changes in human life style (subject to the various constraints) it follows that we can require this rate to satisfy a well-known equation of physics and economics, and from it, learn very much indeed about the character of the survival function. We do not presume to solve the equation to determine the survival function, but only to characterize it with regard to stability or instability. Instability would display itself as a sharp rise (or conceivably a sharp drop) in the survival function, particularly a sharp rise toward an infinite rate of consumption of thermodynamic potential. Let me hasten to say that I realize that there are other kinds of instabilities in the world, and that I am really not trying to solve all the world’s problems—some, perhaps. We are concentrating modestly on only one that may become tractable.

It would be valuable to study the way the survival function has behaved in the past—both in the recent past, for which we have a lot of detailed information, and in the more distant historical past. By combining history and thermodynamic analysis, we can begin to piece together an idea of what our trajectory has been. Then, with the help of demography, economics and the World Almanac, we can hope to start asking what kind of trajectory we are riding now, by studying the equation for our survival function.

Let me point out that, while I have presented this approach in terms of a variable of physical science, the actual work requires the skills of the humanist and social scientist, as well as of the biologist and physical scientist.

To give you more feeling for the survival function, let me describe some of its natural components. The easiest for scientists to study is probably the area of energy generation, including the extraction and preparation of fuel, the maintenance and operation of equipment and the development of new methods. We learn that far more energy and other thermodynamic potential has been spent on the development of nuclear energy sources than these sources have ever given back to us.

A second area is simply human subsistence. How much thermodynamic potential is consumed in the biological function of human species? This component is the one that reflects most immediately the problems of population and health, but we must recognize immediately that, like all the others, it must interact very strongly with the others, and that the influences of population or “environmental insult” may often be much more subtle than we would guess from examining this component alone.

A third area is the extraction and purification of natural resources. This is a relatively straightforward area to describe in detail, and lends itself to some immediate policy analysis, to which I shall turn later.

A fourth area is in the conversion of purified raw materials into finished goods and then to degraded “used up” goods. This area requires more than conventional thermodynamics for its analysis; it requires that we work with organization and information, with designed structures, as thermodynamic components. In other words we have to extend our tools to include information theory, to describe the change in thermodynamic potential associated with making a new car from raw materials, and then driving it until it is a piece of inoperative junk.

Another area of obviously increasing importance is the management of residuals. This area, I suppose, used to require no consumption of thermodynamic potential in itself. The only contributions wastes used to make to the survival function was in their own increase of the entropy of the world. Now we are building elaborate industries to deal with residuals in more controlled ways, and we are beginning to pay the price in thermodynamic potential.

These areas do not include all the important components in our consumption of thermodynamic potential, but they are possibly enough of a representative sample to give some feeling for the kinds of activity that are important, and a sense of the processes that we should be describing in thermodynamic terms.

Now let us consider the behavior of some of these components, to get away from purely abstract ideas and head toward policy decisions. Instability, as I have been using the term, amounts to a self-catalyzing increasing rate of consumption of thermodynamic potential. It is like a person who, the more he eats, the hungrier he gets. This has a direct analogy in a hypothetical situation that could arise in the interaction of energy production and waste management.

Wastes are obviously produced when energy is generated. At one time, we simply threw these wastes away, without spending any thermodynamic potential for their management. As time has gone on and our demand for energy has increased, the associated wastes have become enough of a problem to require us to spend energy to deal with them. Suppose that we used to produce ten units of energy each year, and required only one unit of energy to handle the associated wastes. At some later time, we could imagine the need for 30 units of energy each year, and that the associated wastes would require not five but 25 units of energy for their disposal, leaving us only 25 units for other purposes. This situation is obviously heading for trouble. At some point, the requirements for energy to handle waste may increase so fast that increasing the total energy production could lead to a decrease in the amount of useful energy for non-waste purposes. It could even be worse than that: suppose we were to reach a state in which the waste from, say, 100 units of generated energy required 101 units of energy for their management.

I present this to illustrate in a vivid way how an instability behaves, not because I believe that our waste disposal problem is quite as monstrous as the situation I just described. Real instabilities are likely to be more subtle and perhaps more insidious. However the general prin-
inciple implied by this scenario is clear: we must develop a life style of thermodynamic thrift. Extravagance with the thermodynamic potential is perhaps the best way to find an unstable trajectory. Whether thermodynamic thrift is a sufficient guide to assure stability probably depends on how far we apply it — that is, on how much we would be willing to change our life style if the situation demanded it. We don't yet have any idea of how great a change we should make, but I think we can expect to make some changes. It is a fairly sound bet that a trajectory on which total energy production, per year, doubles every 10 years, and the per capita energy demands increase more than twice as fast as population, is an unstable trajectory.

Consider the elm tree syndrome: In discussing energy production and waste, I indicated that the cost to manage waste, in thermodynamic potential, increases faster than the cost of energy production. This must be a very general principle: the amount of a primary product increases more or less linearly with the thermodynamic potential consumed in the production, while the requirements for thermodynamic potential to deal with wastes increase at a nonlinear rate, first more slowly and then more rapidly than the primary requirements.

What does this nonlinearity imply? Let us put it in context. Often there are many means to achieve a given end; when we develop a new field, we customarily choose the one means that offers the greatest short-term economic advantage. Consequently we soon find ourselves with a single active, dominant method, and several discarded ones. The original method of choice is fine at first, but, because secondary effects grow in a nonlinear way, the secondary consequences eventually make the initially-selected process far less desirable and more costly in thermodynamic terms than it once seemed. Our reliance on the automobile with an internal combustion engine as the single dominant means for metropolitan transportation springs to mind as an awful example. The once-ubiquitous elm tree, as a single means to provide universal shade, is even more obvious, as the dead stumps are hauled away.

Suppose we were to take cognizance of the nonlinear rate of growth of secondary effects, and of the high probability that the secondary effects of different processes usually interact only weakly. This tells us that it is a far wiser policy to rely, as geographer Gilbert White has advised, on multiple means rather than a single process, to achieve any single sustained end. The short-term economies are deceptive. We know from some of our present dilemmas how massive the difficulties can be in trying to adopt multiple means, once we have locked ourselves and our life style to a single one. It is pathetic to look back and realize that the problems we now have with automobiles — traffic, pollution, disposal — were entirely predictable 20 years ago, and that in every way except one, it would have been much easier to develop multiple means of transportation in 1950 than in 1970. The one exception that might make it easier now is, of course, our own motivation.

In any complex system, we must come to realize the impossibility of trying to live with single means. The complexity of our problems, our limited capabilities to analyze the consequences of any single means, and the need for the flexibility to divert our course to nearby trajectories fairly shout to us of the need for a policy of multiple means.

**Policy: Natural Resources**

Let me now explore the consequences of the principle of thermodynamic thrift in one specific area, the extraction of natural resources. Extractive industries begin by finding minerals in the form of ore veins or gas domes. These are materials in states of moderately low thermodynamic potential, but still in states of potential far higher than if the same substances were dispersed over the whole face of the earth. The industry then raises these materials to a much higher potential by extracting and purifying them, and then putting them in a useful place. Eventually the thermodynamic potential of the materials is raised still higher as they are turned in to finished goods. Then, with use, their potential drops a little. A smashed automobile clearly has less potential than a new one.

Our usual way has been not only to discard the used objects; we have done far, far worse than that. It has been our custom to let the unwanted objects fall from their states of moderately high potential at the moment they are discarded to a state of thermodynamic potential far lower than that of their constituent materials in pristine mineral condition. In short, a thermodynamic view speaks far more forcefully for recycling than any aesthetic argument about the accumulation of debris. It tells us that we must recycle waste while their thermodynamic potential is still moderately high, and not let them fall lower than their starting point. Otherwise we find ourselves spreading out once used resources, putting them into states of such high dispersal and such low thermodynamic potential that the thermodynamic cost of their recovery is beyond measure. Whenever this happens, the resources are lost, to all intents, just as helium is lost when it leaves our atmosphere and goes into space. The myth of the earth as a closed system collapses each time we put our discards into irreversible states.

How do we apply this principle of thermodynamic thrift in the area of natural resources? Let me answer by examining our current policy in light of this principle. Our policy now says that a person owning minerals has a future interest that is depleted every time he extracts some of these minerals. He presumably needs some form of compensation and encouragement to extract his minerals. To provide this incentive, we hand out depletion allowances. This, I assert, is exactly contrary to the principle of thermodynamic thrift. We should discourage any unnecessary extraction of minerals, not encourage it. We need a deple-
tion tax, not a depletion allowance. Furthermore this tax should be highly progressive. I concede that the minimum subsistence requirements of the society could be extracted without tax, but above that minimum, a steeply progressive tax seems to be as direct a means as we have to discourage unnecessary extraction and, thereby, to force the development of recycling methods. Because they begin with materials of high potential, recycling processes must ultimately be cheaper, at least in thermodynamic terms, and probably become cheaper in the short-term economic sense as a consequence.

I propose that we examine what it means to us if we opt for survival as a long-range goal. One thing it means is finding ways to avoid unstable trajectories and to adapt to more stable trajectories while the requisite changes are small, rather than cataclysmic. I propose that one set of guides to the stability of a way of life is its survival function, its annual consumption of thermodynamic potential and the way this consumption changes with time. I believe one can deal with the survival function at several levels, as a mathematical function, as a means to analyze past and current behavior of society and, when it is broken into its components, as a guide to policy. As examples, I have suggested two policies in particular: One is the general adoption of multiple means as a strategy for enhancing stability. The other is the specific device, the adoption of a depletion tax, as one way to practice the principle of thermodynamic thrift.

Last Spring, economist Kenneth Boulding said that he is a short-term pessimist and a long-term optimist. Basically, I am afraid to say that I only half share his opinions. I am, however, just a little bit optimistic about the possibilities of avoiding some kinds of disasters by developing a generalized thermodynamic way of thinking about our society. It will require some scientists and mathematicians to learn economics and history, and some economists and historians to study thermodynamics. In any event, it is perhaps a new kind of challenge — to study the option for survival.

There has been no end of statements recently to the effect that we are going to hell in a handbasket. I feel, however, that this mood has gone farther than the facts warrant, and that such pessimism is not justified either by our present condition or its rate of change. Partly as a corrective to this mood, I will indicate some affirmative possibilities, and how we may deal with them.

In my view, the question is not of survival, but of survival in what form. We are now in a period in which our social institutions are being strenuously questioned, and in which we soon may be able to alter the most fundamental biological and psychological aspects of human life. It may well be that a continuation of the life that mankind has had in the past and has at present is neither possible nor desirable, compared to some of the alternatives that we could construct for ourselves.

I would even extend that notion to the effect of man on his environment. The preservation of the environment in its present form may not be consistent with other things we wish to do, such as to universalize the high living standards of the Western World. However, that is not necessarily a bad thing. The earthly environment was not created for man's benefit, but rather is the result of the random operation of physio-chemical processes. While certain aspects of the environment are desirable for human purposes, there is no reason to believe that the environment we now have or one that existed before human intervention, is the best possible one. Indeed, human history records a series of man-made changes in the environment which have for the most part been for the better. A comparison of the present environment on Manhattan Island, for instance, with that of 300 years ago, or even 100 years ago, suggests very strongly that it is now a much better place to live, air pollution and all. Were any of us set down in the Manhattan environment of 1500 A.D. we would likely find our lives nasty, brutish and short, as did most of those who were in that situation. Of course, we should not allow thoughtless action to produce random changes in the environment. But neither should we, by identifying the natural with the desirable and by abjuring all environmental change, ignore the possibility of improving human life.

We should consider not just the survival of what we have, but rather what kind of world humanity might be able to create for itself if we set our collective minds to it. In this context it is important to realize that most of what we have been able to do through science until now, in the way of improving our common lot, has been to change the external world, that is, the world outside of each individual human being. How-

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