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UNDERSTANDING LONG-TERM CONSEQUENCES OF ENERGY DEVELOPMENT PROGRAMS IN THE THIRD WORLD

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INTRODUCTION

During 1981 analysts within the Dartmouth College Resource Policy Center have worked to develop a set of tools useful for energy planning and energy education in the Third World. The work has been supported by the United States' Agency for International Development (AID); this is the final report to AID on the project. This introduction summarizes the Agency's principal energy policy goals, describes the nature of the major product from the Center's research, the Total Resource Base model (TRB), describes several ways the TRB can assist the day-to-day activities of energy development planners, and indicates the purpose of this report.

AID's Energy Goals:

AID's 1981 "Energy Assistance Policy Paper" describes the urgent and complex problems engendered for the Third World by the tremendous increase in oil prices during the past decade. The paper spells out three objectives for use in identifying projects that might qualify for AID financing:

- assure adequate energy supplies at reasonable prices to support continued world economic growth;

- encourage developing countries to expand their own energy resources, both non-renewable and renewable, without increasing the risk of nuclear proliferation; and

- assist developing countries in overcoming energy-related constraints to their development.

To guide AID investment towards energy-related projects with greatest potential to attain those objectives, the Agency has identified four areas that should receive special emphasis:

- energy analysis and planning,
- energy training and institutional development,
- site testing, demonstration, and evaluation of new energy technologies, and
- increasing energy supplies.

Important though those activities may be, AID officials and others recognize that energy problems cannot usefully be isolated from concerns for overall development.

> the world cannot and should not see the role of these alternative energy sources outside of the global concept of development. It would be a tremendously misleading policy to divert attention from the real and most essential element - development. Integral development has been the philosophy of the United Nations for years. Alternative sources of energy are only tools for achieving that concept.
>
> - Secretary-General Iglesias
> UNCNRSE Conference News #9

"Integral development" is an intricately-phased evolution in which a region's energy resources, capital plant, institutions, physical resources, financial stocks, labor force, and population grow in concert - on average producing sufficient output to satisfy the rising demands of the population and still finance investment in the growing capital stock. When development proceeds successfully these seven different factors

accumulate year by year so that resources are used more efficiently, energy is substituted for human labor, and the spectrum of goods and services produced by the economy grows steadily, at all times sufficient to finance necessary imports and to sustain development of the region's human resources.

This intricate process has operated successfully within many nations during the past century. But it has not yet taken place anywhere in the presence of high-cost fossil energy. Industrial development still remains a realistic option for Third World nations, despite tremendous increases in energy cost and capital requirements. But integral development will now require patterns of material growth and change very much different than thosed observed among the nations that industrialized during periods of relatively cheap fossil fuels.

The four energy program areas identified by AID can encompass activities that will help poorer nations achieve integral development in an era of costly fossil fuels, but identification of appropriate energy initiatives can no longer be based on the historical experience of the West. It will require a new, comprehensive theory of the ways energy interacts with other sectors of a developing economy.

Currently, the personnel responsible for implementing AID's energy programs do not have available any theory or image of development that depicts the long-term features of an economy able to sustain material growth and promote social equity while it is dependent on expensive oil and on locally available, renewable, energy resources. We have developed the TRB as an important step in developing that theory and in conveying it to people actually involved in the daily decisions governing development of energy resources.

The Nature of TRB;

TRB is a portrait of the physical features that operate in every region, irrespective of its political and economic system, to determine the long-term effects of alternative energy development efforts. It contains the principal stocks and flows that govern growth and decline in fossil fuel deposits, productive land, forests, water resources, mineral reserves, population, and productive capital stocks. It depicts the aggregated flows of labor, capital, and energy required to sustain industrial development.

The model is set of dynamic theories that describe the ways these physical entities interact in an economy over time as it responds to shifts in its sources of energy. In TRB the myriad social, psychological, and political factors that differentiate one region from another are implicit in the policies governing physical flows. And we have developed our report so that planners in many different cultures will gain insights about the energy policy options and the constraints made relevant for them by the physical characteristics of their region.

The Role of TRB;

TRB has been deliberately designed for use in activities that fall within the first two of AID's priority areas - energy analysis and planning; energy training and institutional development. Thus we have designed it for use by those without special expertise in computers and modeling. Until those at the local level have practical mastery of concepts like those elaborated by our report, their responses to energy shortages may simply transfer pressures originally engendered by oil depletion over to other sectors of each region's resource base.

The AID report chronicles many examples of this:

- diminished access to kerosene for cooking has lead to spiraling demands on the forests. The poor countries face a 40 percent loss of tropical forest resources between 1978 and 2000,

- declining fuelwood availability forces a switch to use of dung and crop residues for fuel, depriving agricultural lands of essential nutrients. Erosion and declining yields are the result. This will in lead in Nepal, for example, to direct loss of one million tons of grain production potential by the year 2000.

- reduced soil fertility presses the poor into use of marginal lands with thin soils and steep slopes. The resulting erosion rapidly causes flooding and reduced hydroelectric potential downstream.

TRB can also assist international energy analysts. Without the insights afforded by a generic theory of total resource interactions, it is very difficult to relate results from a detailed energy study in one country to problems faced in other regions. AID has invested substantial sums in energy plans for specific countries, for example Thailand. The enormous detail involved in such studies may be necessary for detailed policy planning in one country, but it obscures the relevance of the study's results to the energy problems confronting policy makers in other countries. TRB is no replacement for detailed empirical work. But it does provide a common conceptual foundation that permits basic insights from one regional study to be extended to other countries.

The Purpose of this Report;

This is not a learned dissertation; it is a self-teaching manual to provide its readers with new and powerful ways of thinking about areas many of them already know in detail, areas whose long-term behavior is expecially important in identifying appropriate energy development strategies. The material in this report is written for readers who know the specifics of their region well, but who have trouble contemplating the whole -- for those who know current conditions, have a good idea of what the short-term future may bring, but are not skilled at seeing the long-term possibilities. After working through the material presented here, such readers will be able to integrate their knowledge and that of others, to use it to form a dynamic picture of the developing resource base and economy, and, if they like, to begin a formal quantitative, long-term total resource management plan that can be the basis for energy planning.

What is presented here is a way of thinking that will be new to most readers -- hardly anyone has been trained to think this way -- but it will also call upon the intuitions and the experiences most development planners have known for a long time. This way of thinking is:

unusual - - but intuitive
easy - - - - but profound
abstract - - but practical

Many of its points are well-known in other arenas, but they are rarely applied to problems of economic development. Much of what will be said here is second nature to workers of the land and dwellers of the forests everywhere, but they rarely can express what they know so that others of us, more removed from direct contact

with the complex natural cycles that affect resources, can learn it.

The only difficult part of reading and understanding this report will be to remain patient with deliberately simple explanations of things that seem well known. The text purposely uses simple examples and moves forward in small steps. Underneath everything that looks familiar will be a new discovery and a point that is worth pondering. The reader's job is to maintain what Zen Buddhists call "beginner's mind," the ability to see old things as if they were new, so that, in fact, new aspects of them become clear for the first time.

In the body of this report "I" denotes Donella H. Meadows, the principal author. "We" denotes planners, analysts, policymakers, intellectuals, and development specialists, in both the industrialized and nonindustrialized worlds, who have the privilege and the responsibility to think about and to control the development processes of whole nations and regions. "You" denotes the reader of this report, who is presumed to be one of the above sorts of people.

This report was written by Donella H. Meadows with the assistance of Dennis Meadows, James Kirchner, Beth Russell, Wendy Walsh, and Jean Graf.

THE BIG PICTURE: WHAT IS DEVELOPMENT?

At the outset of our work for USAID, I was discussing this project with the program officer who originally suggested it. "What questions bother you most?" I asked. "If we could work on the answer to just one question for you, what question would you most like to have answered?" He thought a moment, and sighed, and gave me the question "What is development?"

his paper begins ith a philosophical igression about evelopment, to set he stage for the etailed analysis f resources that ollows.

Of course that is the question that must be answered before all others by any development agency, and it is the question whose answer, usually implicit and unexamined, guides everyone who ever presumes to intervene in the long-term evolution of any society. This paper is not an answer to that question. But it is built upon an implicit answer, which should be made explicit, so that you know why I am writing this, what I am trying to accomplish, how I think reading it will be useful to you, and what degree of authority and certainty I feel behind what I write. Anyone who is not interested in learning these things can skip this section (which is a bit of a digression) and go on to the next part, which begins on page 6 .

e know what the sence of develop- ent is, but we e less clear out what velopment is.

Those of us who are concerned with the problem of economic development know very clearly what the source of our concern is. It is the intolerable deprivation and suffering of the world's poor. We are clear that that condition must be changed and that our work involves changing it. We are sure of the direction we want to move away from. We are less clear what direction we want to move toward.

If there is any agreed-upon definition of what development is, I have not come across it in ten years of searching. The most commonly-understood measure of development, of course, is the overall size of the economy, the aggregate flow of all the goods and

e measure of velopment is IP,

ch is probably ll the center most institu- nal attention

services generated by the society in the course of a year--the GNP (or GNP per capita). Although the concept of GNP as a measure of development is being challenged and revised almost everywhere, it still is obviously correlated somehow with some sort of human welfare, and it still is the center of thinking, with some qualifications, of most of the major investors in and spokesmen for the development process:

> While there is now increasing recognition that growth does not obviate the need for human development and other steps to reduce poverty, it must be stressed that the converse is true as well---direct steps to reduce poverty do not obviate the need for growth....The direct attack on poverty, if it is ultimately to be successful, must be combined with measures to ensure that the economies of the developing countries continue to expand.
>
> Robert S. McNamara
> World Development Report, 1980
> The World Bank

> Development never will be, and never can be, defined to universal satisfaction. It refers, broadly speaking, to desirable social and economic progress, and people will always have different views about what is desirable. Certainly, development must mean improvement in living conditions, for which economic growth and industrialization are essential. But if there is no attention to the quality of growth and to social change one cannot speak of development.
>
> It is now widely recognized that development involves a profound transformation of the entire economic and social structure. This embraces changes in production and demand as well as improvements in income distribution and employment. It means creating a more diversified economy, whose main sectors become more interdependent for supplying inputs and for expanding markets for output.
>
> North-South
> Report of the Brandt Commission
> Pan Books, London, 1980, p. 48

Those who question GNP as a useful measure prefer to look at the plight of the poorest, the provision of basic human needs, income distribution, and local

empowerment as more appropriate indices of development. They have invented other measures, such as the PQLI (physical quality of life index, derived from life expectancy, infant mortality, and literacy). While they are also focusing on material adequacy, these analysts are at least as much concerned about the conditions of human existence under which that adequacy is obtained.

other measure PQLI,

Development is the unfolding of people's individual and social imagination in defining goals and inventing ways to approach them. Development is the continuing process of the liberation of peoples and societies. There is development when they are able to assert their autonomy and, in self-reliance, to carry out activities of interest to them. To develop is to be or become. Not only to have.

K.K. Dadzie
"Economic Development"
Scientific American
September, 1980

d other indices neern self-steem and rsonal and cial powerment.

Our view of development is a process by which one's overall personality is enhanced. This is so for society as well as for an individual. For society the identity is a collective. Thus development for society means development of the collective personality of society....Personality stands for a distinct identity, self-confidence, creative ability, and ability to face the world with poise, purpose, and pride.

Wahidul Haque, Niranjan Mehta, Anisur Rahman, and Ponna Wignaraja
Development Dialogue, 1977:2, p. 15

While these and other notions of development are part of the picture, close to what we are trying to produce for ourselves and others, none of them is quite complete or adequate. Most of them are our best guesses about the means to the end of development, not the end itself. No society has worked out fully a vision of what it will be like when it is "developed", much less what it will take to become so developed.

ese measures of velopment are l useful, but ne is fully tisfactory. st are guesses out means to e end of velopment

There is little agreement about why non-development persists so stubbornly in some places and not others. We do not know for sure how to make development, by any definition, happen where it has not happened. When the development process, whatever it is, begins, we are not very good at controlling it. We do not know how to measure its progress. And we have only the vaguest ideas where it might end, or even if it needs to end.

e cannot be very ure about what e are doing

In short, we are proceeding toward "development" with general good will, hope, considerable energy, partial insight, and deep ignorance--all of which are probably appropriate for the long-term social change we are working toward.

even about ether or to at extent velopment is oceeding.

In assessing the record of what our attention to development has produced in the world, one can, depending on one's inclination to pessimism or optimism, either be overwhelmed at the progress that has been made in a few decades, or be aghast at the massive and fruitless interventions that have been made in the planet's resources and in human cultures and lives.

ere are signs at things are ing very well.

On the optimistic side, since 1950 income per person in the developing world has doubled. The proportion of adults in those countries who are literate has increased from 30% to more than 50%. Average life expectancy has increased by 9-15 years in nearly every poor country. A number of nations have grown so fast that they are now properly classified as "middle-income"---Argentina, Mexico, Brazil, South Korea, Taiwan, Malaysia, Singapore, Cuba, and, of course, the Middle-Eastern oil countries. Some areas that we think of as masses of poverty, such as India, have built up, alongside their ongoing poverty, fully modern production systems and large pools of trained technical manpower. Food production in the developing

countries has nearly doubled over the past twenty years. These are tremendous achievements.

nd there are igns of failure.

And on the pessimistic side, about 750 million people still live in dire poverty. In more than half of the developing countries less than 50% of the population has access to safe drinking water. Some 600 million adults are illiterate, and in the developing countries still 1/3 of the primary school age children are not in school. 550 million people live in countries where the life expectancy is less than 50 years. 15-20 million die every year of hunger. Mature forest is being consumed in the poor countries at the rate of 20 million hectares per year, and arable land is lost to desertification at 6 million hectares per year. The real price of oil in the world market has quadrupled and is likely to go higher. And in the last decade in the oil-importing developing countries, real GNP per capita growth rates dropped by more than half, inflation rates more than tripled, and the real balance of payments deficit tripled. The achievements of the past seem to be threatened from many sides.

ur guesses, efinitions, and ssessments of rogress are mportant---they ive continuous eal impact on assive programs f intervention.

Our theories of development, the indices we choose to measure it, and our perceptions of progress are not just academic matters. The central variables in our theories define what we pay attention to, what programs we implement, what lessons we learn, and whether we go on trying, change course, or give up in despair. Our theories determine whether and where we intervene in the lives of people, the structures of society, and the cycles of nature. Under the influence of different successively-fashionable theories, we have focused on contraceptive availability, on grain seed varieties, on technology transfer, on infrastructure investments, on appropriate technology, on village organization for self-help, and on renew-

able energy sources. In every case substantial, irreversible changes have occurred, some intended and some unexpected, some good and some bad, most probably beyond our capacity to judge, and many as yet unnoticed.

need to evaluate nstantly not only r development ograms, but the eories that nerate them.

We who have the interest, the profession, and the institutional responsibility to promote development do not have the option of not intervening, nor do we have the hope of intervening with complete truth, wisdom, and knowledge. We will always be working with incomplete, distorting theories, learning as we go. We have, therefore, a heavy responsibility to keep questioning our theories and honestly evaluating the real-world results flowing from them. We have to be careful and flexible about our choices of indicators, and above all we have to be alert for signals that something might be going wrong, that some area we are not monitoring is in fact important, that there might be another index that adds to our information about what we really want to know. We have to be especially open to bad news, corrective signals that can teach us something, and to new ways of looking that direct our attention to things we didn't notice before. It is from the bad-news signals, and the new theories, synthesized with the good news and the old theories, that we can slowly align our knowledge and our actions with the full complexity of the world. We can learn what is truly important, which constraints are really present and which are not, so that our interventions do lead away from poverty and toward whatever forms of development can be envisioned.

e reason for ying all this to remind us all the real state uncertainty in ich we operate, our minds will nain open to new ncepts and ways looking--- cluding the one esented here.

WHY RESOURCES? WHY DYNAMICS?

The macroeconomic view of development is accepted, rather well worked out, never likely to be

acroeconomics nd personal mpowerment are oth important arts of the icture. But nother important art, too often gnored, is the tate of the esource base.

lost from view. The state of basic human needs, the lives of individuals underneath the macroeconomic numbers, is finally, rightfully, coming to our attention. But at least one other critical factor in the development process is glaringly absent from most official consideration; the condition of the resource base from which the development process is built and fueled. Major growth paths for entire economies are being charted. Villages are being taught how to create methane generators and political clout. But no one is looking very hard at which growth paths are consistent with the world's supply and relative abundances of resources, or which indigenous resources can be used, in what combinations, for how long, to support grass-roots ventures.

ne absence of esources in ost development neories is already eading to oblems.

The lack of attention to the resource part of the development equation is becoming apparent in some of the problems now encountered, from balance-of-payments deficits to deforestation, erosion, and receding groundwater tables. Resources are not the only thing to monitor about development. But if they are not in the picture, the picture is clearly incomplete. When we ignore them, we engender development that is probably, in the long run, unsustainable.

esources are ard to deal ith conceptually,

Resources have played a small role in development thinking not because anyone believes them unimportant, but primarily because we have not had the tools, conceptual or analytical, to deal with them or to integrate information about them with economic, political, and demographic information.

ecause they hange very owly,

Everyone knows that the resources of any region are interconnected, both physically and economically. But the interconnections are hard to keep track of, especially since they are often manifested only over decades. A forest may take 50 years to grow, a groundwater table may be overutilized for a century

before it becomes noticeably inaccessible or polluted. A major factory or electrical generating plant or dam may take 5 to 10 years to build and then be on the scene for thirty years or more. Resource availabilities are rooted in physical, long-term, interdependent dynamic changes, which are just about impossible to envision totally and simultaneously.

cause they are naged by separate tities

In order to deal with the complexity of resource systems, most countries, no matter what their form of government, manage resources separately, usually through non-interacting government agencies (agriculture, fisheries, mines, energy, forests) or through non-interacting economic enterprises (forest products companies, mining companies, oil companies, farmers) or both. Each kind of resource is understood in some detail by someone, but no one has an overview of the entire picture. It can happen that plans for developing the minerals sector require trained manpower that the energy sector has already sequestered; that the forestry sector's activities alter runoff patterns needed for an irrigation system; that the plan for importing petroleum requires the production of crops for export at rates that are not sustainable; or that the industrial sector is investing in electricity-using capital considerably faster or slower than the electricity sector is investing in the generating facilities.

though in fact ey are inter- lated,

l because the erful unfolding their dynamics ems unstoppable e it gets rted.

Even within a single resource sector, the dynamics of long-term resource management are not straightforward. In New England, for example, there have been three great waves of forest harvesting. Each time the forest-products capital base was built up far beyond the capacity of the forest resource to supply it; each time the forest was harvested beyond its sustainable limit long before the capital had served its useful lifetime. Bankruptcies, unemploy-

ment, and emigration followed---three times. The management of a groundwater resource so that water is not depleted and soils are not salted is notoriously difficult. In many poor countries, forests and soils are being exhausted at a frighteningly rapid rate to provide basic fuels and food for truly needy people, and no one is quite sure how to stop the resource loss while still supplying the continuous vital human needs.

need a new way integrating e whole resource cture, which, course, is at this report about.

More study, more data, more detail about single resources are surely necessary. But also necessary is a view of the resource base as a total interacting system, a broad, integrated, long-term view to supplement our deep, short-term views of the individual resources.

is about source dynamics--- ising, transition er time, sustain- ility,

This report is about a theory and a set of tools to produce that broad, long-term view. The concepts and tools presented here focus on the resource base (defined broadly to include capital, human resources, minerals, soils, forests, fuels, and water) from which development occurs, on the dynamic path over time and the phasing of resource utilization, on the sustainability of any particular development path, and on the transitions, smooth or turbulent, from dependence on one resource base (such as petroleum) to another (such as solar or nuclear power). The discipline of economics has already developed tools to focus on capital and labor wealth, its productivity, and its rate of return. What is presented here is a supplementary tool to look at all forms of resource wealth, their productivities, and their rates of return.

responding to definition of elopment involv- a society's lity to manage resource base.

Thus the definition of development underlying this report centers on a society's ability to draw from the resources it can command the goods and services it needs in a wise, balanced, and secure way; on its ability to develop those resources in phase

with one another, so that each one enhances rather than drains others; and on its ability to utilize abundant resources cleverly to make up for and to husband scarce resources.

EVENTS, BEHAVIOR, STRUCTURE

To build up a picture of a total resource system, one that incorporates many interconnections and one that leads to useful statements about the future, I will be drawing from some powerful theories of system structure. By structure I mean the timeless, essential relationships that hold a system together and that determine its behavior over time.

RUCTURE
↓
HAVIOR
↓
ENTS

Most of us, most of the time, see the world in terms of the events that happen around us moment by moment. Newspapers primarily report events--specific happenings at particular moments. To take a simple example, it is an event (not a very newsworthy one) that at the moment the temperature in the room where I am writing is 65°, while the outside temperature is 23°.

Over time strings of events trace out dynamic patterns of behavior. The behavior of the temperature in this room has been a slow fluctuation between 63° and 68°, while the outside temperature over the past week has been undergoing a random-looking variation from -11° to +34°.

The structure giving rise to the room temperature behavior, which looks at any given moment like an event, is, of course, a furnace delivering heat to the room, and a thermostat set at 66°, which turns on the furnace whenever the temperature falls too low. (I won't presume to describe the structure causing the outside temperature!) This is a system whose structure is familiar to almost everyone, so it is diffi-

derstanding at e level of events less useful an understanding the level of havior. Under-nding at the el of behavior much less eful than derstanding at e level of ucture.

cult to imagine how confused we would be if we were trying to predict tomorrow's temperature, or to make the room warmer, knowing only the most recent stream of events---the temperature over the last few hours. If we knew the history of the system sufficiently to know its generally constant behavior, we would be better at predicting, but still poor at controlling the system. If the room temperature suddenly started going down, it would be only by knowing the structure that we would think to reset the thermostat or renew the oil supply or repair the furnace.

s report esent a theory understanding the level of ucture.

This example is very simple, but when it comes to development, to resource management, and to social change, we know much more at the level of events than at the level of behavior, and we know very little at the level of structure. For example, world oil price changes are mostly experienced as sudden, disconnected, and unpredictable events. We have a vague sense of the underlying behavior patterns--exponentially rising demand, price rising relative to other commodities, geographic concentration of remaining reserves, shifts in stocks of money and debt. But we have only glimpses of the structural understanding that would allow anyone to predict or control the system as confidently as we do a thermostat system.

This document will not reveal all the structural secrets of the world oil pricing system. But it will present basic structural principles, from which such an understanding can begin to be worked out.

THE TOTAL RESOURCE BASE

t the TRB gram is good

The Total Resource Base Diagram (which I will call the TRB diagram for short) is a first rough sketch of the structure of a resource system. As you will see, it is simultaneously complicated and incomplete. It is a way to picture and begin to talk about a resource endowment and to visualize some of the

interconnections among resources. It is useful for guiding discussions across disciplines and areas of expertise, for making one's thoughts about resources more organized and precise, and, ultimately, for developing a more complete and quantitative picture consistent with the special resource characteristics of any particular region.

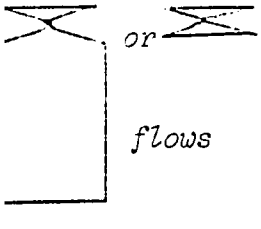
I will go through the diagram piece by piece, stopping occasionally to explain, as I run into them, all the classic structural elements that make up any system and describing the behaviors they produce. The discussion will proceed on two levels simultaneously. First I will be talking about specific resources, their structural configurations, their typical behaviors, and their responses to different policy interventions. Second, I will be describing and demonstrating basic techniques of diagramming and analyzing systems that can be applied to any sort of system at all.

ix categories f resources, easured in hysical units:
soil
water
fossil fuels
minerals
capital
human resources

First notice that the TRB diagram represents six basic kinds of resources. Starting from the upper left-hand corner and proceeding clockwise, they are soil, water, fossil fuels, minerals, and, in the center, capital, and human resources. In all cases the symbols are meant to indicate physical quantities of resource---tons of minerals, cubic meters of water, numbers of people, and for capital the actual physical factories and machines that produce manufactured goods, not money or credit. (Money and credit, by the way, are also resources, as are information, technology, and many other things. They could be added to the diagram, but for now we will concentrate on physical resources.)

tock

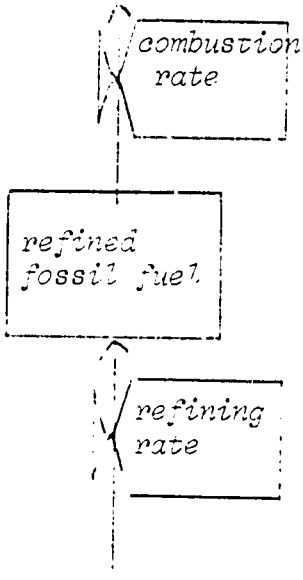
THE DYNAMICS OF SIMPLE STOCKS



There are two kinds of symbols on the diagram, stocks shown by boxes and flows shown by valves. I find it helpful to think of the stocks as bathtubs

filled with water and the flows as faucets through which water is pouring in or draining out, at varying rates determined by the degree to which the valves are open or closed.

SIMPLE STRUCTURE:



The bathtub analogy makes it easy to understand the intrinsic dynamics of stock-flow resource systems. As an example, look at just one stock from the diagram and its related flows---the stock of refined fossil fuel. Refined fossil fuel is essentially oil ready to burn, stored in tanks. Actually there are many such tanks, centralized ones in refineries or ports, the tanks of delivery trucks and trains, distributors' storage tanks in stores and gas stations, and consumers' storage in vehicles and furnaces and such. There are also many grades and types of refined fuel, each with its own storage network. For a detailed study the dyanamics of all the intermediate stocks and flows might be of interest, and the diagram could be expanded to illustrate them. Here they have been aggregated together.

In fact, each stock in the TRB diagram is a gross aggregate of many actual stocks. It is easy enough to think of the detailed complexity implied by each box in the diagram, because our human experience is made up of such details. It is also natural to become uneasy with the diagram and even to reject it because it does not show such details. The purpose of this exercise is to focus on the forest, not the trees. It is in fact a harder exercise than adding in all the detail one can think of, and at least as valuable. Please tolerate the simplicity here and appreciate it; things will get complicated all too soon.

digression to elate the simple iagram to the omplexity you ow in the world...

nd a polemic on he virtues of implicity.

Think of a fuel storage tank for a moment as completely full, with all the flows in and out shut off. Now imagine turning on the combustion rate, the flow out of the tank and into the motors or furnaces that burn oil. Obviously the level in the tank will begin to go down, at a constant and linear rate. It

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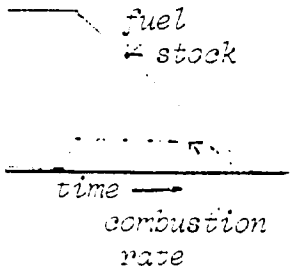
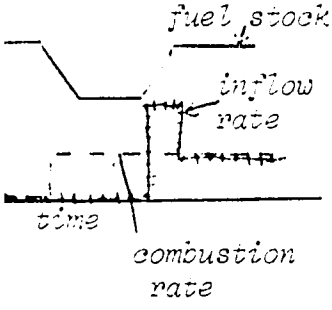


will continue to go down until eventually the tank is emptied. At that point, of course, the combustion rate will be zero, even if the valve is still open.

Now start again with a full tank, and after the combustion rate has run for just a short while, turn on an inflow rate from the refinery that is just equal to the outflow rate. At that point the stock of fuel levels off and stays constant at a new, lower level. To bring it back to full, one would have to raise the inflow rate higher than the outflow rate for a short time (or turn on another inflow rate, such as the import rate, for awhile) and then bring it back down to equal the outflow rate.

ANOTHER POSSIBLE BEHAVIOR:



This example is very simple. Anyone with practical experience of bathtubs can readily deduce all the dynamics of a single resource stock with any combination of inflow and outflow rates. The fundamental points, which you know well but may never have bothered to generalize, are:

As long as the sum of inflows exceeds the sum of outflows, the stock level will rise.
As long as the sum of outflows exceeds the sum of inflows, the stock level will fall.
If the sum of outflows equals the sum of inflows, the stock will hold steady at whatever level it happened to be at when the two flows became equal.

No great secrets here.

But when the subject changes from bathtubs to a social system one is personally involved in, even these simple points are not always obvious. For example, development clearly involves building up a nation's stock of productive capital. One usually hears the reasonable suggestion that capital can be increased by increasing the inflow rate of investment, but one rarely hears that capital can be accumulated equally well (usually more easily) by decreasing the outflow rate of depreciation.

point often ignored: stocks can be built up by slowing their outflows as well as by increasing their inflows.

Outflow rates tend not to be noticed. It is easier to see that known fossil fuel reserves can be increased by new discoveries than by reducing combustion through conservation. It is easier to see that a workforce can be built up through hiring than through reducing the turnover or quitting rate. These points are obvious when you see them, but it is amazing how hard it is sometimes to see them.

Stock levels change only slowly, never suddenly.

You can't drain a bathtub instantly, or fill it instantly. Flows may jump up and down, turn on and off, very suddenly. But stocks just slowly accumulate all those variations. A stock is a lag, a buffer, a ballast, a delay, a stabilizer in a system. It is an accumulation of the total history of all its past flows.

ocks capture a stem's history d slow its rate change. The ger the stock, lative to its ws, the slower change.

Picture a medium-size bathtub with normal-size inflow and outflow pipes, and imagine the slow rate by which the level of the water in the tub can rise or fall. Now picture the tub four times as big but with the same inflow and outflow pipes. Obviously the water level will now change much more slowly. Large stocks, relative to flows, provide much more stability than small ones. That is a principle by which all sorts of storage systems, from store inventories to irrigation tanks, are designed.

The inherent momentum of population aging, of capital turnover, of the accumulation of wood in a forest or water in a dam, is usually underestimated. A classic example is the Nixon Administration's study leading to the goal of U.S. independence from oil imports by 1980. That plan simply did not take into account the immense stock of oil-burning capital in the country.

he sluggishness f stocks allows ystems to develop atterns of resource veruse,

Slow change of stocks is the main reason for the frequency of overuse of resources. If the stock of oil or water, for example, is large, the drain rate can be higher than the input rate for a long time. During that time, stocks of capital and population using that resource build up. Then those stocks cannot adapt quickly to the resource scarcity that inevitably follows.

lows development,

nd provides the pportunity for ction and for orrection.

Slow stock changes also set an inherent slow pace to the process of development as a whole. They also provide time, however, for corrective action when it is determined that a set of policies is not working. The stability that stocks create in a system allow room for maneuvering, for experimenting, and for building.

If you have an accurate sense of the possible rates of change of stocks, you don't expect things to happen too fast, you don't give up too soon, and you use the opportunities presented by the system's own momentum to guide the system toward your goals---much as a judo expert uses the momentum of his opponent to produce the results he wants.

The presence of stocks allows flows to be independent and decoupled.

ocks allow me certainty d stability, en when flows e uncertain and riable

It would be extremely difficult to run an economy if gasoline had to be refined at exactly the rate at which all the cars were burning it. It would be hard to manage a store if deliveries had to come in the back door just as customers placed orders through the front door. It would be impossible to harvest a forest just at the rate the trees grow. Stocks allow life to proceed with some certainty, continuity, predictability, and security, even as flows vary and fluctuate. Societies create stocks at all levels to mediate between flows. The more complicated and

interconnected a society is, the more crucial is the maintenance and integration of critical stocks. There are hundreds of mechanisms in any society to keep important stocks within acceptable levels; a vast number of individual and institutional decisions and actions are designed to regulate stocks.

society can be en as a conglom- ation of stocks d of mechanisms adjust stocks

Because of their importance in providing security and continuity, stocks are safeguarded by many individual and societal mechanisms to keep them at reasonable levels. People monitor stocks constantly, and their decisions are based on information about stock levels. Those decisions add up to the macroeconomic ebbs and flows of society. Inventory overruns or inadequacies lead to price changes or new orders or cancellation of orders. Household food stocks influence purchasing. Standing biomass in the fields, as it develops, leads to decisions ranging from farmers' loan applications to bookings of grain-transport ships to bids on commodity markets. Water levels in reservoirs and wells cause all sorts of anxious corrective actions when they rise too high or fall too low. The same can be said for levels of credit, of cash in your pocket, of known reserves of an oil company, and of the pile of wood chips feeding a paper mill.

An important key to understanding why social systems do what they do is an awareness of how stocks are protected. A key to development is to strengthen those protective mechanisms so stocks can stabilize, flourish, and grow.

FEEDBACK REGULATION OF STOCKS

Since stock-control mechanisms are so important, we will need some ways of picturing them and of

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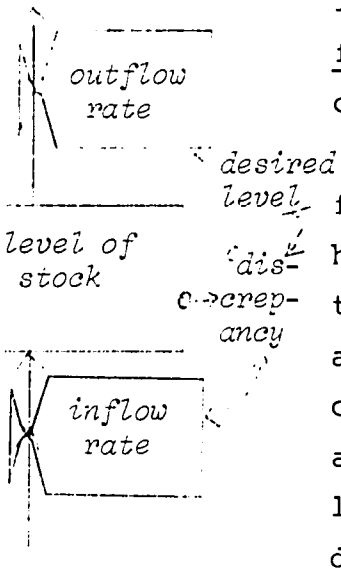
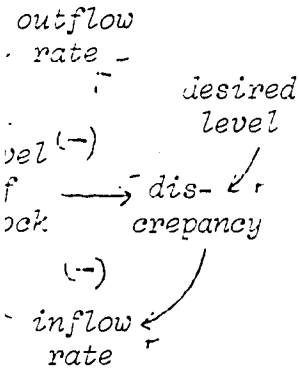


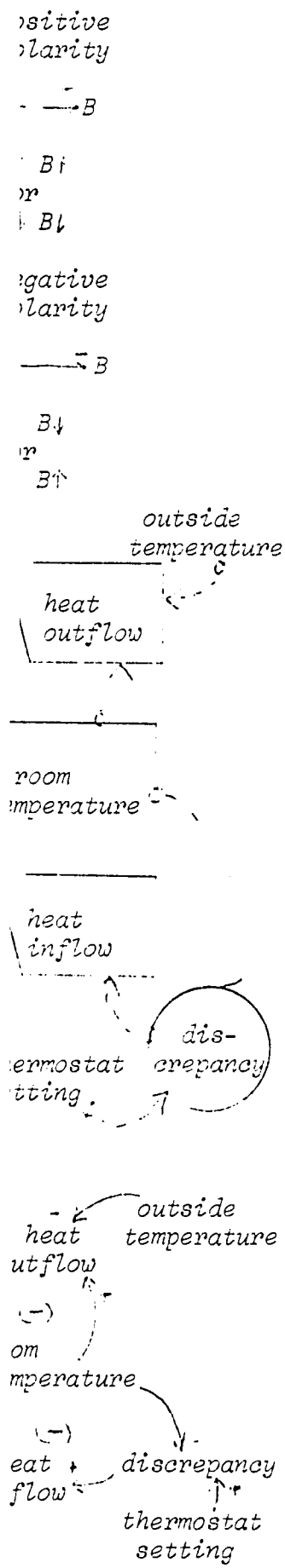
d LOOP DIAGRAMS:



thinking through their behavioral implications. A stock that is held within a stipulated range by a control mechanism is contained structurally in a feedback process. Whenever the stock starts moving out of bounds, whoever or whatever is monitoring it, begins a corrective mechanism (adjusts the rates of inflow or outflow). The stock's own level provides a signal that is compared against some goal or acceptable level. When there is a discrepancy, an action is initiated to reduce the discrepancy. The stock level feeds back through a chain of signals and actions to control itself.

There are two ways of picturing this kind of feedback system. One is the box-and-valve diagram you have already seen. Dashed information arrows depict the series of signals, the information, taken into account in the decision to regulate the flows into or out of the stock. Corrective feedback of this sort always proceeds through information about the stock level (and perhaps about other stocks as well) to determine the flows affecting the stock level. The information may not be timely and it may not be accurate---later on we will see what happens when it is not. The desired stock level may or may not be set at a point that actually meets the goals of the system---again, the behavioral implications are important, and we will come back to them.

The other way of representing a stock-control feedback is with a loop diagram. This is an abbreviated version of the box-and-valve diagram. It does not explicitly show the stocks and flows, but it does emphasize the feedback structure of the system. I will be using both types of diagrams here, depending on whether I want to accent the stocks and material flows in a system or the feedbacks and information flows.



Whereas in the box-and-valve diagram we emphasize the direction of material flow in a system, in the loop diagram, we emphasize the direction of influence of interacting entities. The arrows point from cause to effect, from one element to another element that changes as a result of changes in the first element. A small + sign by the arrowhead indicates that the two elements change in the <u>same direction</u>: when A increases, B also increases; when A decreases, B decreases. A - sign indicates change in the <u>opposite direction</u>: when A increases, B decreases, and when A decreases, B increases.

For practice, think about a stock-control system that is familiar to you---the thermostat system I have already mentioned. In this case the critical stock is the amount of heat in the room, which is measured by the temperature. If it is colder outside than inside, heat slowly leaks from the room and the temperature goes down. The colder the outside temperature, the faster the heat drain, and the warmer the inside temperature, the faster the heat drain. When the temperature in the room gets too low, the thermostat detects a discrepancy between the actual temperature and the desired one. The heat flow into the room is turned on. Eventually enough heat accumulates in the room to eliminate the discrepancy, and the heat is turned off again.

You should take the time to be clear about how the words in the paragraph above have been translated into the two kinds of diagrams. They are diagrams of system <u>structure</u>. As you work through this paper you will see many more of both kinds of diagrams, and your ability to understand and eventually to create such diagrams will grow. You will become more aware of the structure of increasingly complex systems, more able to communicate that awareness to others, and to

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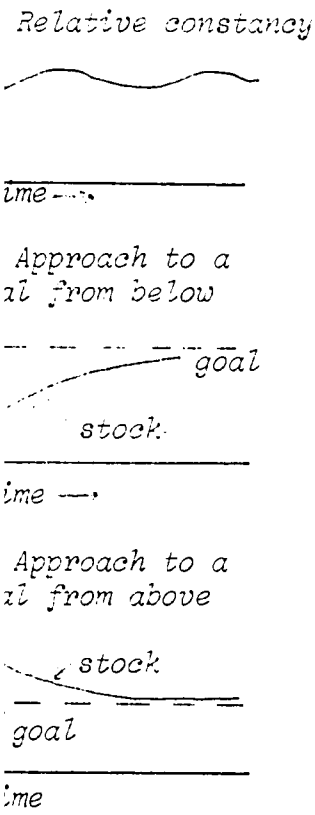
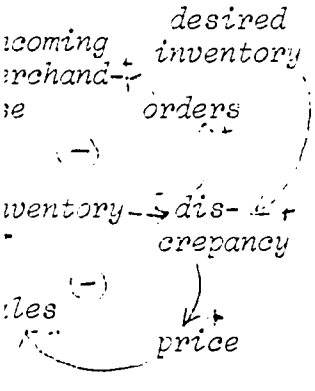




deduce from the structure the leverage points through which the system's behavior can be changed.

The behavior associated with the thermostat structure, and of any stock-regulating structure that works well, is a nearly constant stock (room temperature), with just enough small oscillations to trigger the mechanism that maintains the constancy. The outflow rate in this case will vary with the outside temperature, which could be quite random. The inflow rate will be either off or full on.

If a stock for some reason gets far out of its acceptable range, either too high or too low, the feedback processes will pull it back. Usually the pull is harder, the farther the stock is from its desired value.

The thermostat system is an example of a stock regulated only by its inflow rate. Stocks can also be regulated through their outflow rates, as, for example, the level of water in a flood-control dam, or through both their inflow and outflow rates, as the level of merchandise in a store's inventory.

All the feedback mechanisms pictured here are corrective, regulatory systems designed to keep stocks within a desired range. This particular type of feedback is called negative feedback. (No value judgement is implied by the word negative. Negative feedback processes can be either bad or good in terms of social values, and we will encounter examples here of both). The presence of a negative feedback process is indicated by a (-) sign in the loop on the loop diagram.

Negative feedback is always goal-seeking, acting to pull a system's stocks back to some range whenever they deviate. There are thousands of negative feedback processes regulating the operation of your body, a forest ecosystem, a national economy, the U.S. State Department. We will come back later to all the intricacies of interlinked negative feedback loops pulling

with different strengths toward different goals. For now it is sufficient to remember that:

Negative feedback loops are goal-seeking. They are the source of stability and control in systems. They are also the source of resistance to change.

There is also such a thing as positive feedback, which we will get to very soon.

u already know e basic dynamics stocks, flows, d negative edback. Now you ve a way of eturing it.

Nothing I have said so far about the operation of systems in unknown to you, although the language and diagram formats I have used are probably unfamiliar, and you may never have consciously linked your knowledge of bathtubs and thermostats to your instinctive sense of the dynamics of forests, store inventories, or national economies. Of course there is a point where the simple analogies break down, and understanding forests and national economies requires more rigorous analysis. Let's move another step toward that point by looking at stocks controlled by positive feedback, by multiple feedback, and by interlinkages with other stocks. We can find plenty of examples by proceeding through the six sectors of the TRB diagram.

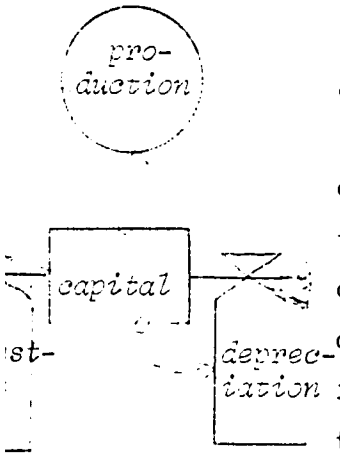
CAPITAL RESOURCES AND ENERGY DEMAND

ital is the sical stock of ductive assets--- ngs that make ngs.

Capital is the stock of manufactured items that are used to produce other manufactured items. Factories, machines, trucks, tools, looms, anything that helps to produce something else, is capital. Capital increases through the inflow of investment, which is the deliberate production of something that will allow further production, rather than something that is immediately useful in itself. Capital decreases through the outflow of depreciation, the physical wearing-out and loss of productivity of the capital plant. Most forms of capital have a long lifetime, so the outflow rate is relatively slow. The

capital stock nges very wly.

capital configuration of an economy therefore shifts only slowly, over decades, not years.



Associated with each stock of capital is the amount of production it permits. Production is a flow, not a stock. It is the stream of output each capital plant produces; the electricity coming out of the nuclear power plant, the cars coming out of the car-assembly plant. The size of the capital plant is one determinant of the actual production stream, as indicated by the information arrow connecting capital to production. But capital only defines the upper bound of production. The degree to which capital is actually utilized is affected by the availability of other factors of production---labor, energy, materials, finance, etc.---some of which will be discussed later.

There are five kinds of capital:

In the TRB diagram five basic types of capital are distinguished. The most important type for our purposes here is resource-producing capital. Within each resource sector are the capital stocks associated with producing that resource: pumps and dams for water, drilling rigs and supertankers for petroleum, saws and lumber trucks for wood products. Since this diagram focuses on resources, the category of primary-resource-producing capital has been disaggregated--you will find pieces of it in all four corners of the diagram.

resource-producing

In the center of the diagram are four sorts of capital associated not with producing primary resources, but with producing services and manufactured goods. These four types of capital are:

capital-producing

1. Capital-producing capital---that which produces all other types of capital. The machines and factories that make drilling rigs for the fossil-fuel sector, hospital buildings and X-ray machines for the service sector, tractors for the agriculture sector, and paper-making machines for the consumer goods sector.

consumer goods-producing

2. Consumer-goods-producing capital--that which produces durable and nondurable consumer goods. Shoe factories, refrigerator factories, paper factories, food processors.

service-producing

3. Service-producing capital---that which produces human and institutional services. Hospitals, schools, banks, barbershops, government buildings and equipment.

and household (which might be called utility-producing)

4. Household capital---that with which private consumers produce goods and services they use directly without entering the market. Stoves, private automobiles, home sewing machines, cooking dishes, brooms, houses.

re are many ways draw arbitrary es through the plexity of social duction systems. one used here as arbitrary as ,

These five categories are inclusive. They cover all types of capital in an economy. They are, of course, highly aggregated, and they are not the only possible categories or ways of dividing reality. In fact, they are a bit unusual, cutting across common accounting categories, and often cutting across single firms or factories. For example, there is no one place where transportation capital appears. It is spread through households (private automobiles), service capital (ambulances, mass transit systems), agricultural capital (farm trucks), capital-producing capital (heavy freight haulers), etc. Similarly, electrical generators could appear in the household sector (private generators), the capital sector (cogenerators), or the consumer-goods sector (most public utilities).

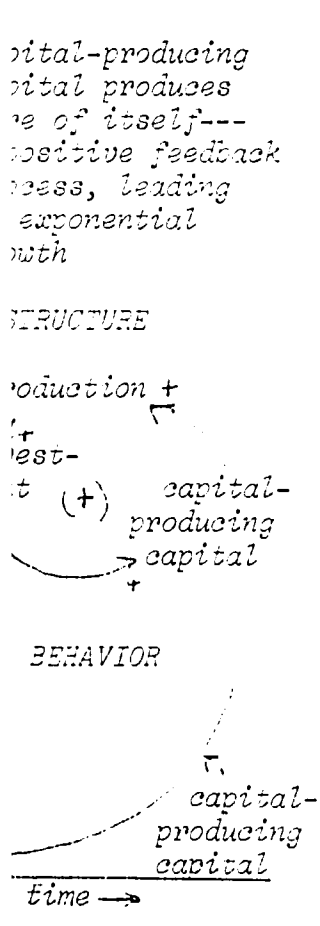
it unusual,

particularly ful for erating g-term amic insights.

No way of categorizing anything is better or worse than any other, except with reference to a particular purpose. For general purposes, and especially for thinking about the long-term dynamics of an economy, the five basic divisions presented here are very useful. There are fundamental dynamic and functional differences in the five categories. They serve very distinct purposes, use different combinations of inputs, and produce products with different lifetimes.

Resource-producing capital plays a central role in providing the materials and energy needed to keep the other types of capital (and itself) going. It sits directly at the interface between the economy and the ecosystem. Service-producing capital produces a product that is ephemeral, cannot be stored in inventories, and yet is vital for the continued functioning of labor and of the other types of capital. Household capital, often ignored in national accounts, is important in itself and also in the changing role it plays during the process of development. In traditional societies household capital is the main productive force. It generates consumer goods, resources, services, and even its own replacement. As development proceeds, more and more household functions are taken up by the other capital sectors, but the utility provided by household capital remains important, even in the richest countries.

Capital-producing capital is an especially important category, because as development proceeds, it is increasingly the engine of economic growth. Capital-producing capital is the source of all capital (with the exception of imports and some household capital production), including itself. The regenerative nature of the capital-producing capital sector is shown by the link from its production to its own investment inflow. This closed loop---more capital allows more production, which allows more investment, which results in more capital---is, of course, a feedback loop. The level of the stock is itself a determinant of what will happen next to the stock. But this is <u>positive</u> feedback. Rather than pulling a stock level toward a goal, this loop generates more stock the more stock is already there. It takes factories to produce more factories, and the more factories you have, the more you can produce.



Positive feedback loops are self-enhancing. They lead to exponential growth (or decline) over time. They are the structural sources of growth in systems. Capital-producing capital is contained within a positive loop that is the source of self-generating growth of an economy.

he outflow of apital to all ectors of the conomy is rucially mportant, and sually determined by very essy political nd economic rocesses--- ore feedback oops

In Figure I is shown the flow of capital from its production in the capital-producing capital sector to all the other economic sectors. The processes by which the stream of capital production is divided and allocated to the different parts of the economy are not shown explicitly, because they are very different in different sorts of economic systems. The capital allocation process may be centrally determined by the government. It may be decided by free bidding in a capital market. It usually is some mixture of the above two mechanisms, combined with a good deal of speculation, political maneuvering, bold risk-taking, conservatism, serendipity, resistance to change, and other messy human characteristics.

Whatever the allocation process, it is governed by thousands of feedback loops, mostly negative and goal-seeking, with different goals, delays, strengths, and accuracy of information. The result of the pulls and tugs of all these loops determines the balance of capital endowment among the various sectors, their shifting ability to serve each other adequately, and the rate and nature of the development process. The allocation of capital to the various sectors of the economy is one of the major leverage points of the development process.

The capital configuration of an economy also is the major determinant of energy demand, as illustrated in Figure II. Capital nearly always requires some form of energy to make it work. By its very design it determines the rate at which energy must be used for

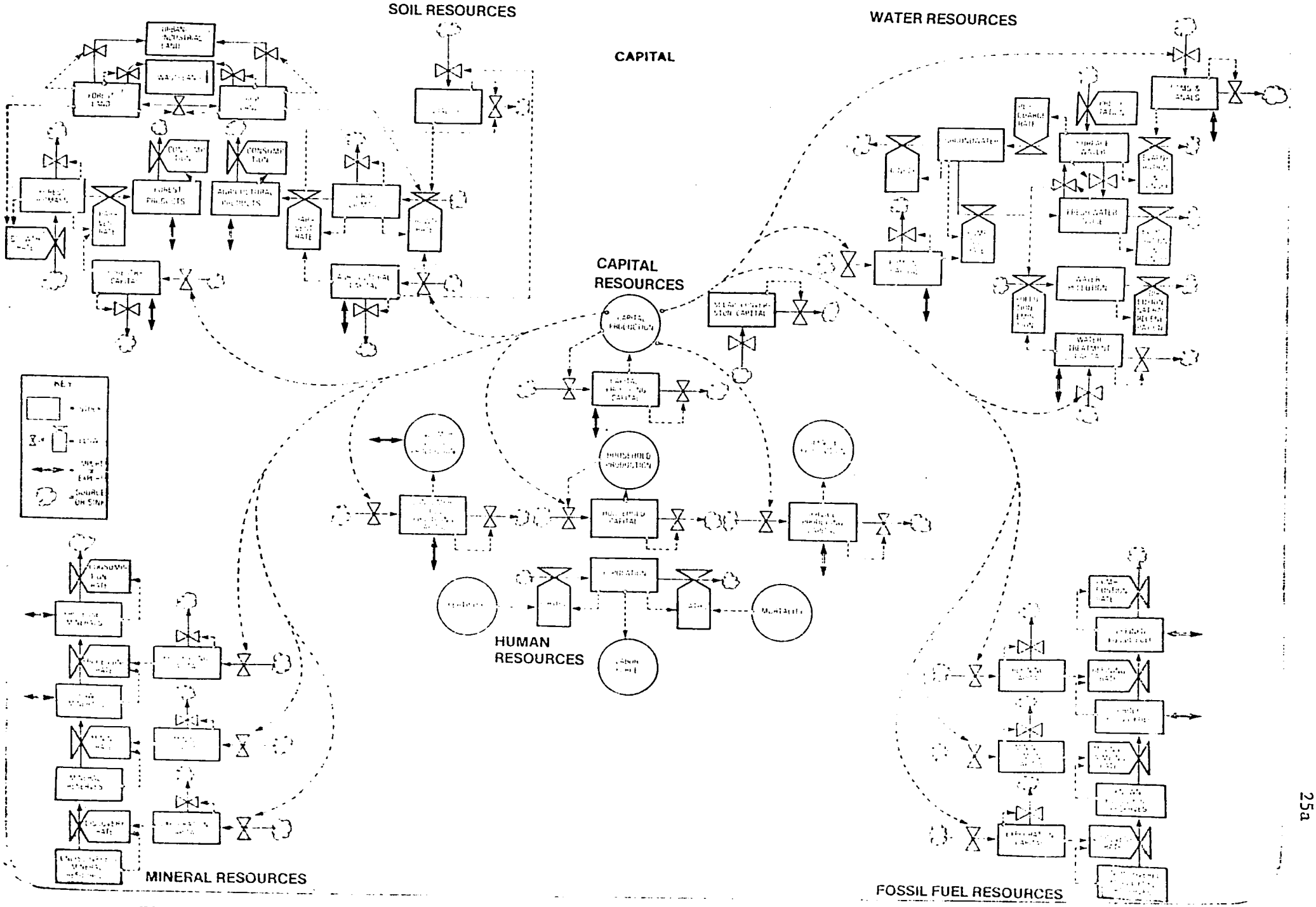


Figure I: Capital flows connecting the TRB stocks

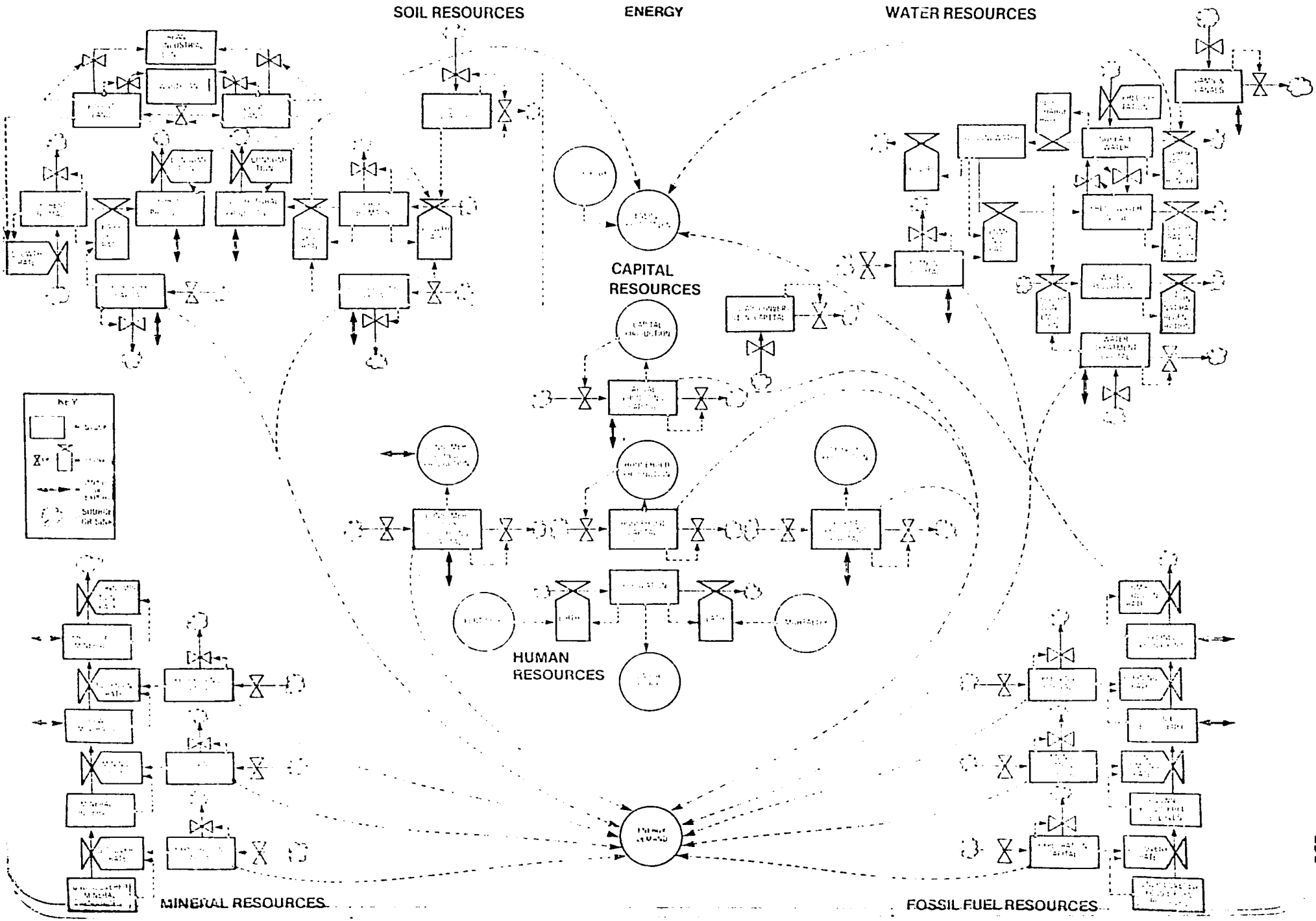


Figure II: Energy flows connecting the TRB stocks

Capital is the main determinant of energy demand...

every hour of its operation and for every unit of output it produces (and it also determines the kind of energy that is necessary). A hoe requires about 400 kilocalories of human energy per hour when it is operating; a household furnace requires about 1 gallon of oil per hour; the 500 MW generator in Bow, New Hampshire requires 200 tons of coal per hour. Just as the nature of the capital plant fixes the upper bound to the flow of production in an economy, it also fixes the upper bound on the flow of energy consumption.

The actual energy consumption depends on the extent to which the capital plant is actually run---the capacity utilization---which, like production, depends on the availability of the other factors of production, including energy. Because capital is the prime determinant of energy demand, and because capital changes very slowly, the basic energy demand pattern of a society cannot change very fast. (Short-term changes in energy demand can only come from changes in the extent of utilization of capital.)

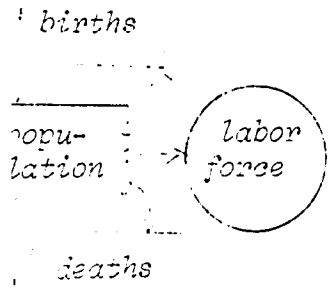
The size and nature of the capital plant determines the upper bound of the rate of energy consumption in an economy. The turnover rate of capital determines the rate at which the amount and nature of energy demand can be fundamentally changed.

and of the demand for all other resources.

In fact the same could be said not only for energy, but for all resources. Any standing piece of capital carries with it a "recipe" for the amounts of water, materials, energy, land, and skilled and unskilled human labor needed to make that capital productive. It is for that reason that capital is in the center of the TRB diagram and that we will not be able to talk about resource management without keeping the development of the capital base clearly in the picture.

Human Resources

In the demographic sector of the TRB diagram the population stock is increased by the flow of births and decreased by the flow of deaths. The labor force is a direct function of the size of the population.



Of course all sorts of complications could be added. The population stock is hardly uniform; it is distinguished by social class, abilities, health, location, and, very important for long-term dynamics, age. The fraction of the population participating in the labor force varies. Laborers have varying skill and productivities. In some places migration, either in or out, is a major factor. All this could be added to the diagram, and some of it will be later. For the moment I want to concentrate on the dynamics of the two simple feedback loops controlling population growth, the loops through births and deaths.

Population growth results from a positive feedback loop.

The number of babies born depends on two things: the number of people there are to have babies, and the fertility or rate at which the average person decides to have babies. Holding the fertility constant (for a moment), we can say that the more people there are, the more babies will be born, and the more babies are born, the more people there will be to have still more babies. This is clearly a positive feedback loop, which would lead to exponential growth of the population, if it were the only thing operating in the system. The positive loop of population and births is the structural source of exponential population growth.

The rate of growth depends on the fertility of the population.

The actual rate of growth depends on the long delay between the time a baby is born and the time it starts having its own babies, and on the number of babies each person ultimately produces. Both of these factors are variable, and they change in interesting and significant ways during the development process (more on that coming). For the moment, it is suffi-

cient to know that the birth loop generates growth that is always exponential, but the exponential growth rate is highly variable.

Human deaths are determined by a negative feedback loop, with an implicit goal of zero.

The more people there are, the more people will die. The more people die, the fewer people there are. This is obviously not a self-reinforcing positive loop. It is also not clearly a self-regulating negative loop pulling a stock to some desired value. It is, however, a negative loop. It is pulling the stock of human population toward the implicit goal of zero. The goal is not a human-motivated one (quite the contrary), but one resulting from natural processes. If there were no births, the behavior of this loop would be to bring the population gradually to zero.

Again the basic dynamic, approach to zero, is built into the structure, but the rate of approach is variable, depending on the age structure of the population and on the mortality schedule, the probability of a person dying at each age. The universal human policy is to keep mortality as low as possible, and again, a society's ability to do that depends greatly on its level of development. So mortality also varies greatly, which affects the timing, but not the general pattern of behavior, of the negative death-rate loop.

Death or depreciation loops with goals of zero are very common in social and ecological systems.

This sort of negative loop with an implicit goal of zero is a very common one. You might think of it as the system dynamics version of the Second Law of Thermodynamics. Things left to themselves naturally wear out, disperse, grind down. The depreciation rate of capital is contained in an exactly analogous loop. Without continuous new investment, the stock of capital will gradually approach zero.

A negative feedback loop with an implicit goal of zero can cause a system to run down or deplete. One such loop determines the death rate of population; another involves the depreciation rate of capital.

What happens when both the birth and death loops are operating at once? Now things begin to get complicated. A structure consisting of one positive loop linked with one negative one can produce many different behaviors--as a human population can. To start, let's assume that all the variable factors--fertility, mortality, and age structure--are held constant. That is, the two loops do not vary in strength.

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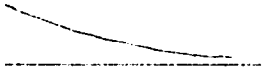
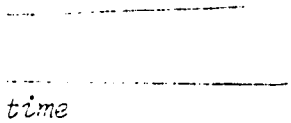
EGATIVE LOOP OMINANT:



time

OTH LOOPS EQUAL:



time

Then only three behaviors are possible. If the birth loop is stronger, it dominates the system, and the population grows exponentially. (With a faster rate of growth, the greater the difference between fertility and mortality.) If the mortality is higher than the fertility, the death rate dominates, and the population gradually approaches zero. If the two loops happen to be exactly the same strength, the population will hold steady at whatever level it was when the two rates became equal.

It is usually the case in a complex system that the structure (the configuration of feedback loops) has inherent within it several possible behaviors. The positive-negative linked loop system can produce only three possible behaviors. More complex systems have more possible behaviors latent within them. Which behavior is actually released and exhibited at any time may depend on both the internal conditions (levels of the stocks, strengths of the relationships within the system) and on conditions impinging from outside. A pendulum has the structural potential to hang straight, to swing back and forth in damped oscillations, or to go around in circles, depending on outside influences. A dangling spring has a structure that permits all of those behaviors and also up-and-down oscillations. Full structural understanding of a system allows one to know all the possible behaviors

sually one tructure con- ains within it everal different atent behavior odes, which are eleased under ifferent ircumstances.

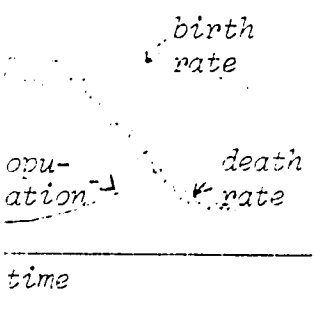
latent in a structure and what circumstances will allow what behaviors to occur.

The structure of a system is its pattern of stocks linked in feedback loops. Structure is timeless and nonquantitative. It determines the sorts of behavior that can and cannot be exhibited by a system. What behavior is actually exhibited at any time depends on quantities such as the levels in the stocks, the strengths of relationships between system elements, and the outside influences imposing on the system.

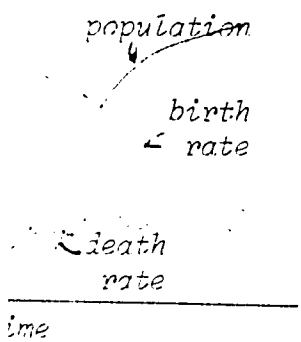
If the strength of linked feedback loops relative to each other changes over time, sequences of different behavior modes can be exhibited.

Until now in this discussion I have held fertility and mortality constant. But usually both fertility and mortality are slowly changing relative to each other, making possible more complicated population behavior modes. That is, the positive and negative loops have not a constant relationship to each other, but a shifting dominance.

HE DEMOGRAPHIC RANSITION:

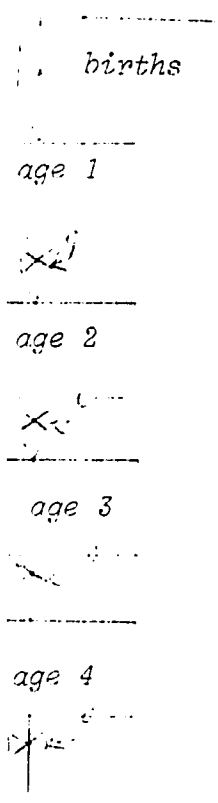


An example of this shifting dominance is the demographic transition. In many nonindustrialized countries both birth and death rates used to be high, with population growing only very slowly (sometimes declining during times of famine). The positive and negative loops were almost in balance. In the last few decades death rates have fallen significantly. The negative death loop weakened relative to the positive birth loop, creating a faster and faster rate of population growth. The exponential growth behavior of the system has been released.



In the long-industrialized nations, death rates have been relatively low for a long time, and birth rates have been slowly falling, thereby gradually bringing the positive loop once again into balance with the negative one. The exponential growth associated with positive-loop dominance has gradually shifted toward a near-equilibrium, as both loops have become equal in strength. This entire behavior

pattern, from high birth and death rates, through an intermediate release of the growth loop, to low birth and death rates (with a large increase in the population stock) is called the demographic transition. It has occurred in every population that has become highly industrialized, and in no population that has not. Behavioral changes in complex systems result from the shifting dominance of linked feedback loops. The "demographic transition" is one example of shifting dominance, in which a behavior of population equilibrium changes to one of rapid growth and then back into near-equilibrium.



A human population can be thought of as a chain of interconnected stocks of different ages, with flow rates of maturation between them. The stock of one-year-olds flows into two-year-olds and then three-year-olds and so forth. Births flow into the first stock, deaths flow out of all of them but particularly out of the later ones, and the cohorts from roughly 15 to 45 years of age produce the stream of births.

e age structure a population ts as a delay lag in the stem

The effect of this chain of stocks is to insert delays into both the positive feedback loop of births and the negative loop of deaths. You already know that any stock acts as a lag in a system, allowing whatever material is flowing to accumulate for some delay time between its flow into the stock and its flow out. In the case of population, the age structure means a 15-45 year maturation delay between the birth of a child and the time when that child produces another child; that is, a 15-45 year **lag in the positive** birth loop. Increasing the age at marriage (if it delays the time of childbearing) effectively increases the delay, let's say to 25-40 years. Increasing the delay in a loop is equivalent to decreasing the relative strength of the loop temporarily.

So, for example, if a population is just at equilibrium and its marriage age increases with no other change, the population will decline to a new equilibrium.

The delay in the death rate loop depends on the mortality schedule (age-dependent death rate) of the population. Aside from a high rate of infant mortality, for most populations death rates do not become significant until 60-90 years of age, so the death loop has a long built-in delay.

The age-structure delay causes populations to shift from one behavior to another through transitions that are not smooth, but that over- or under-shoot the eventual equilibrium

What is the effect of these delays on the behavior of the linked positive-negative loop system? If we go back for a moment to holding the strengths of the loops constant, the system still produces only the three basic behaviors--exponential growth, decay to zero, or equilibrium. If the loop strengths are shifting, the same succession of behavior modes takes place--from growth to equilibrium, say, or from equilibrium to decline. But the transition path from one mode to another now contains a delay and overshoot. For instance, a linked positive-negative loop system without delays will make a quick, smooth transition from growth to equilibrium if the positive loop changes from dominant to equal-strength. A delayed system, however, such as a population with an age structure, will respond to the same shift 1) after a delay, 2) by going beyond its ultimate equilibrium value, and 3) with a higher ultimate equilibrium.

WITHOUT DELAY:

time →

WITH DELAY:

time →

There are two important principles underlying this discussion of population aging. One is applicable to systems in general:

The presence of delays in feedback loops adds momentum to any growth or delay process and a tendency to overshoot or undershoot or oscillate around equilibria.

The dynamic response of a system with major delays like that of a heavy ocean liner. It takes a lot of push for a long time to get it moving. And it takes a

It can be tricky to manage a system that contains long delays.

long time to get it to turn around or stop. The policy implications of trying to control a stock through delayed feedback processes like this are fairly obvious--as with the ocean liner, one has to look far ahead, to be patient, and to apply just the right amount of thrust--not too little to have an effect, and not so much that the system shoots beyond the target.

The second principle is relevant to human populations in particular:

The very long delays in demographic processes create an especially strong momentum in the behavior of human populations. Growing populations tend to go on growing, declining ones to go on declining; age-structure adjustment to new fertility on mortality patterns take decades.

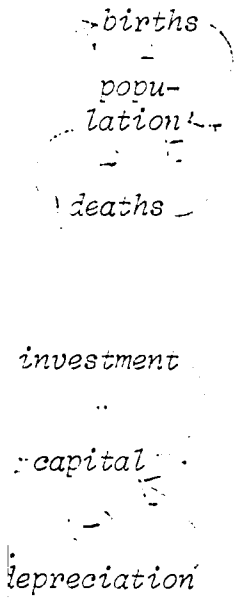
A population that has been growing rapidly will go on growing for at least 70 years, even after its fertility reaches replacement level, and during that time it will more than double in size. If a human population is relying on direct feedback signals to adjust its size to some equilibrium point such as a carrying capacity, it is likely to overshoot the equilibrium and to take decades to reach a final adjustment.

All that I have just said about the structure and behavior of population systems is also applicable to capital systems. One of the most powerful principles of systems theory is:

Similar feedback structures result in similar behavior, even in systems that appear on the surface to be very different.

Therefore when one has bothered to learn about one system, one can often use that knowledge immediately somewhere else. We can apply that principle here, because the essential feedback structure of population

The structure of the capital system is the same as that of the population system,



and so is its behavior.

is almost identical to that of capital. Both are driven by a positive growth loop and a negative death or depreciation loop. Both undergo a gradual aging process. Capital begins to reproduce itself more quickly than people do and has a somewhat shorter lifetime on the average. Much less is known about the age structure and mortality rates of capital than about the same rates for people. But the dynamics of growth, depletion, and momentum are basically the same.

Capital and population systems have the same basic structures and the same behavioral tendencies: exponential growth, decay or depreciation, and a momentum or lag induced by the age structure.

One other similarity is that, like capital, each person in a population is a standing demand for a constant stream of resources necessary for proper functioning. Some of the resources are shared with capital---water, housing, energy, materials, and others are unique to population---food, education, health care and other services. The amount demanded depends, of course on the age, location, income, and other characteristics of each particular person. But population is as central to the diagram and to the resource management process as is capital, both as a source of production and growth and as a demand for resources, goods, and services.

The quality of the labor force is linked to the level of service capital.

Some fraction of the human population makes up the labor force, which can be categorized by skill, location, and other characteristics. The skill level of the labor force is strongly determined by the past history of the adequacy of the service capital level relative to the population level---that is, of the ability of the society to make its children healthy and educated. The interlinking of labor as a factor of production with all the other sectors of the TRB

diagram is shown in Figure . . Each dashed arrow connects the labor force to one of the production functions in the economy. Like capital, labor allocation is important to the balanced development of the various sectors of production. In most countries, however, especially most nonindustrialized countries, labor is in relative excess to capital, so its deployment in the economy is not so critical (the same cannot be said for skilled labor). This brings up another basic systems principle:

abor is not lways a limiting actor in devel- pment...

nd at any given moment, the limiting factor is the only one that counts.

Any process with multiple inputs (the growth of a crop, the production of steel, the development of an economy) is limited at any time by its least sufficient factors only. Increasing factors other than the limiting one will do virtually no good. Increasing the limiting factor will allow output to increase, up to the point where some other factor becomes limiting.

Like most systems principles, this one is firmly planted already in your intuition, sounds simple when you say it, and has ramifications that are surprisingly far-reaching. In the ideal development process the various sectors of the economy will grow in balance, so that none of them becomes seriously limiting to any others. The perfect control system for this process would be a set of monitoring feedback processes that would be strengthening whatever sector is limiting, and detecting continuously what sector is likely to become next limiting, with the understanding that the limiting sector will change over time.

systems dream...

Instead what happens in most complicated growing systems, from corporations to economies, is that those in control learn to deal with one limiting factor, develop theories and practices around it, and go on using those theories and practices long after that factor has stopped being limiting. Specialists in

nd an institu- ional reality.

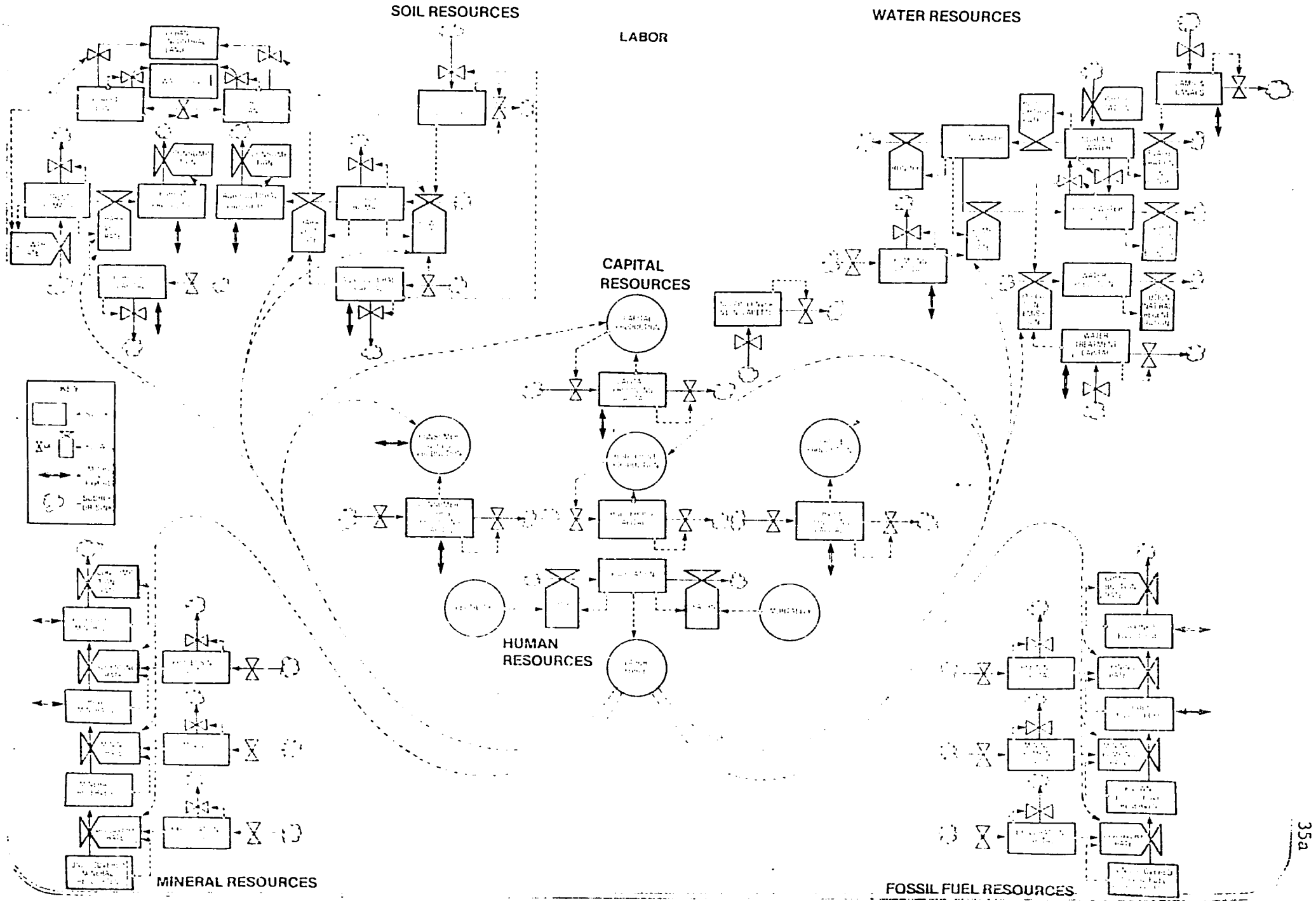
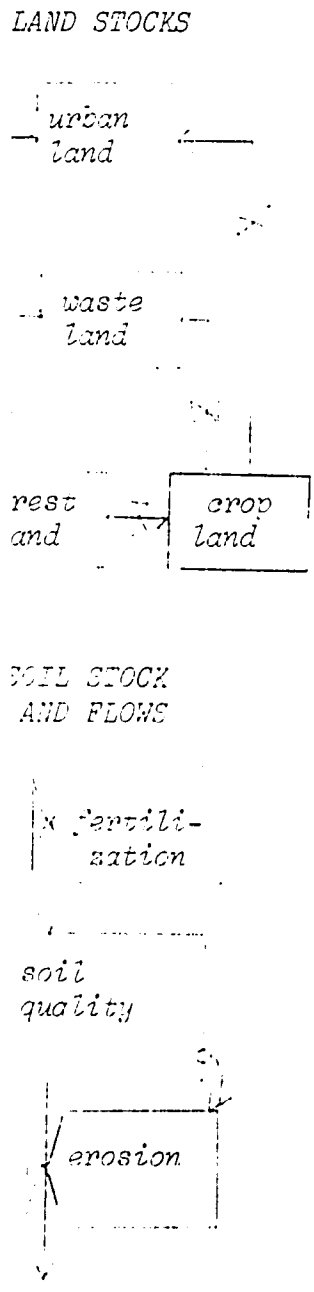


Figure III: Labor Flows connecting the TRB stocks

that particular input factor downplay the importance of any other input factor. The focus of attention stays on labor or capital, although for decades energy or education or land or water has been the key to unlocking the next phase of growth.

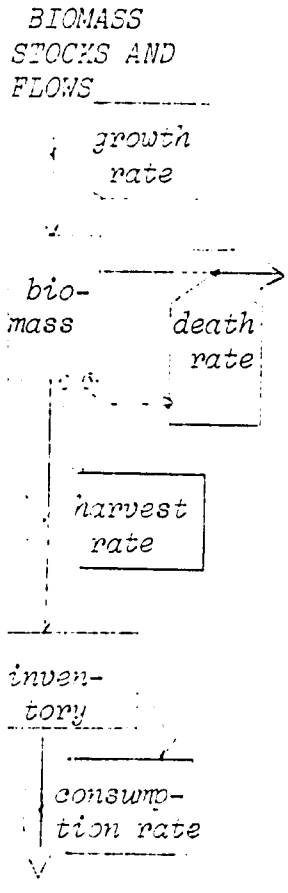
SOIL RESOURCES



In the upper left-hand corner of the TRB diagram is the soil resource sector. It contains five generic kinds of stocks: land, capital, biomass, soil quality and harvested products. Land has been disaggregated into forest, crop, urban-industrial, and waste land. There are no inflows to the overall land stock system, but forest land can be cleared for crops, crop land can grow up into forest, and both these types of productive land can flow, irreversibly, into urban use or wasteland (eroded, salted, desertified, or in some other way made unusable). These land stocks are measured in hectares.

Associated with each of them is a stock of soil quality (only the cropland quality is shown on the diagram). Soil quality is a complicated mix of nutrients, particle size, humus content, slope, and depth. Probably the best way to measure it is in the amount of biomass production it can support (just as capital is measured in the rate of production it permits---as in a 1000 megawatt power plant). Soil quality is increased by an inflow rate of fertilization and depleted by an outflow rate of harvest, erosion, leaching, and natural chemical breakdown.

The amount and quality of the land, together with human inputs of capital, labor, energy, and chemicals, determine the growth rates of crops and trees. Growth inflows accumulate in stocks of standing biomass, which are depleted by harvest and by natural death. Harvested crops or trees go into inventory



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stocks, which are depleted by consumption, and which can also be augmented or diminished by imports and exports.

Agricultural capital, consisting of farm machinery and buildings, tools, trucks, etc, can enhance both the growth rate and the harvest rate of crops and also the quality of the soil. Forestry capital, saws, trucks, chippers, mills, typically affects only the harvest rate, rarely the growth rate of the forest biomass.

Let's discharge our urge to expand and complicate this part of the diagram to include more aspects of reality. Other land types can be distinguished, especially grazing land. Soil quality can be separated into various nutrients. There are different types of capital with very different productivities and lifetimes. Livestock should be added, as well as stocks of pests and weeds. You and I know enough about this system to produce a mind-boggling diagram if we want to. Some day we may need to, but for now let's keep it simple enough so that we can understand the structure and its related behavior.

The stock of standing trees is drained by two flows. One is the natural rate of tree death, a standard negative depreciation loop. The second is the harvest rate. A high harvest rate reduces the natural death rate, because trees are taken before they reach the ages of great mortality risk. (Trees have an age structure like population and capital, not shown here). The harvest rate is primarily determined by the levels of forest product inventory and forestry capital and labor, only secondarily by the stock of trees. That, of course, can be the source of problems.

Mentally hold the outflow rates constant and look at the inflow rate, the growth of trees. There is a basic positive growth loop. The more wood is already

present in the forest, the more can be added each year. It takes trees to make more trees. Trees seed themselves, and once started, wood adds on more wood, twigs form more twigs. So there is a structure producing exponential growth of forests.

forest biomass

But you know that left to themselves, forests do not grow forever. They reach a climax level of standing biomass that maintains itself indefinitely, usually in a slowly fluctuating equilibrium. There must be a time in the growth of a forest when the positive loop overbalances the negative death loop and produces net biomass growth, and there also must be a time when some sort of self-limiting process either decreases the strength of the growth loop or increases the strength of the death loop (or both) to bring about a high-level equilibrium.

ction led

growth rate

wth rate = mass times ction added

two central s in biomass th are a positive th loop and a tive loop slowing th as the biomass hes its sustain- limit.

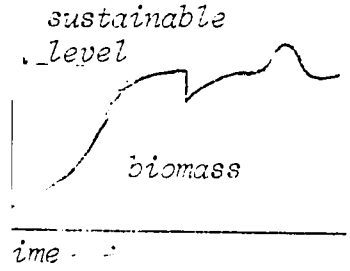
When the forest is young, there is plenty of space and sunlight and soil nutrient for each small tree. Growing conditions are optimal, and the <u>fraction of itself</u> each tree can add each year is maximal. But as the biomass increases, there is increasing competition for light, water, and nutrient There is more biomass present to add more biomass, but the <u>fraction added</u> gradually decreases. At some point characteristic for each climate, soil type, and slope, the land is supporting all the biomass it can. At that point the growth rate equals the death rate and net addition to biomass becomes zero--it could even be negative.

d

biomass

Note that if soil quality is the limiting factor, increasing it not only increases the rate of tree growth, but also the equilibrium level of biomass that can be supported.

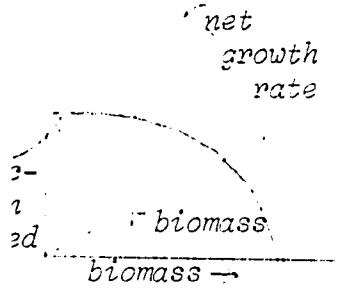
The two feedback loops around the forest growth rate, one positive and one negative, produce an initial exponential growth rate that gradually slows



as the biological limit is approached. If a harvest or storm brings the climax biomass below its sustainable level, there is again an asymptotic approach to the limit. If a few good years allow growth beyond the limit, return of normal weather produces a die-off.

The negative feedback loop controlling the approach of the biomass to its limit acts to change the strength of the positive growth loop. Its strength shifts with the level of biomass. When biomass is low, the fraction added is high, and the positive growth loop dominates the system. When biomass is high, fraction added becomes lower, and the positive loop becomes weak--eventually dominated by the negative loops of tree death or harvest. The relationship between forest biomass and fraction of biomass added is nonlinear. If 100 tons of biomass per hectare produce 10 more tons each year, it does not follow that 1000 tons produce 100 tons each year. It could be that 1000 tons produce 50 tons or 20 or zero or minus 50, depending on where the biomass is in relation to its sustainable limit.

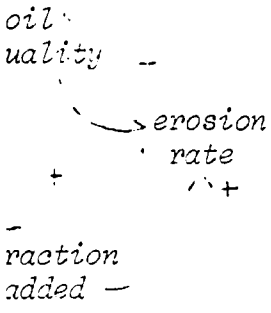
he biomass fraction dded is one xample of a non-inear relationship n a feedback loop.



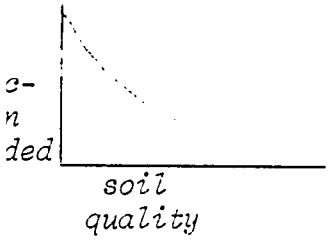
Most feedback loops contain nonlinear relationships. Their strength depends on the state of the system. Nonlinearities are critical in system behavior. They change the relative dominance of feedback loops, which leads to major shifts in behavior.

A slightly different example with the same basic message can be seen in the stock of soil quality. Here let's focus not on the inflow rate, as we did for the forest, but on the outflow rate, the rate of erosion and breakdown in soil quality. This rate is governed by a simple depletion loop; the higher the quality, the more can erode. By itself this loop would slowly bring soil quality down to zero (but of course there are natural and man-made mechanisms to

oil quality s also governed y a positive and negative eedback loop.



restore soil quality constantly). But there is another feedback loop intersecting with this one, and it has an interesting nonlinearity. The higher the soil quality, the slower its natural erosion rate is. Deep topsoil, thick with humus, is more naturally resistant to erosion than is thin, sandy depleted soil. It doesn't blow in the wind, it adheres to itself and is less likely to be moved by running water. It also enhances biomass growth, whose roots hold it still further, but that interaction with the biomass stock is not shown here. It also holds nutrients in bound organic form against leaching. The poorer the soil, the higher fraction of the quality that is there is eroded, given any natural eroding mechanism. The higher the fraction, the more erosion, the poorer the soil.



This is a self-enhancing positive feedback loop that gets worse and worse as it operates. It is a fearsome loop to deal with in the real world. If you can imagine a bathtub that drains faster the emptier it gets, you can imagine the difficulties of dealing with the dynamics of erosion. Fortunately, the loop is not at all strong when soil quality is high, and like all positive loops, it can be run both ways. A deliberate enhancement of soil quality (mulching, composting, fertilization) reduces the fraction eroded. A further increase in quality reduces erosion still further. And then the quality is even better and the erosion rate is even lower, etc.

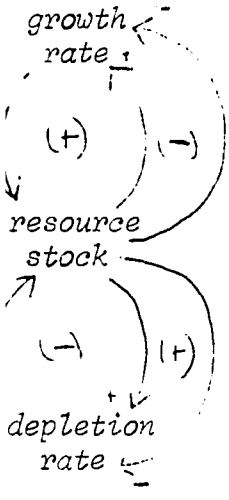
e positive loop f erosion is ifficult to mage when it is rking against ou, but it can be urned around to ork for you.

Positive loops are not only the source of growth in systems, they are also often the source of erosion and collapse. They can be turned around, however, to build up resource quality.

The small pieces of the soil resource sector we have looked at here have illustrated the most fundamental dynamics of renewable resources. The

structures and behaviors just described are found in similar configurations in nearly every renewable resource system, from fish and game populations to cornfields. The exact numerical relationships and time constants of growth and renewability can vary tremendously, of course. The regulating loops may center around the renewal rate or the depletion rate or both. It may be possible to interfere with deliberate policy on only one of the two rates or on both. But the general configuration and the management lessons are ubiquitous. They are:

'he basic structure of renewable resource systems: two positive loops and two negative ones.



Renewable resource stocks are governed by two generic sorts of flows. Inflows through self-regeneration comprise positive feedback and the potential for growth. Depletion outflows constitute a force bringing the stock slowly to zero. In addition, there is nearly always a negative feedback on the growth rate tending to bring the stock up to some maximum level consistent with the availability of resources. There is also nearly always a positive loop, usually associated with depletion that causes increasingly rapid erosion if the system is overstressed.

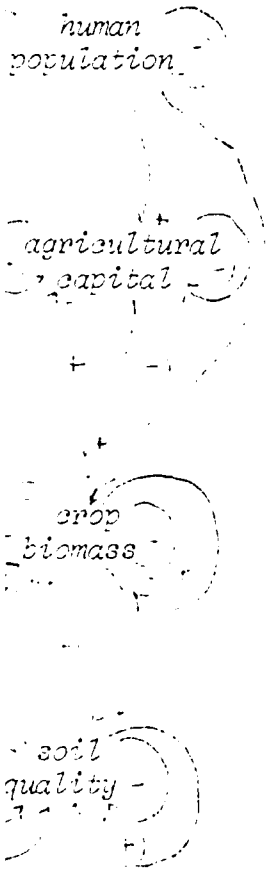
The behavioral result of this structure is that there is usually a wide range of resource stock levels within which the stock maintains itself indefinitely. If the stock becomes larger, it moves toward its climax level and its growth rate slows. If the stock becomes smaller, its growth rate increases to restore it. The stock moves up and down slowly within this range and actively counteracts any tendency to move outside it.

he basic behavior: elf-correcting tability within a ide range, and uick destruction utside that ange.

If, however, some disturbance cuts the stock to a level below the stable range, the stabilizing negative feedback loops are overwhelmed by destructive positive ones. The stock level spirals down to zero, unless heroic measures are taken to restore it.

t's very much easier to work with the forces in ural systems than against them.

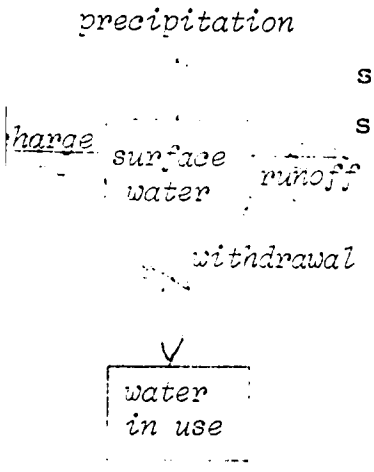
The cost of maintaining a renewable resource stock within its stable range is usually low because the natural structure of the system supports such maintenance. The cost of restoring a system that has gone outside its range of self-maintenance is usually enormous because the natural processes must be opposed rather than enhanced, effectively enough and long enough to bring the stock back into its range of stability.



Imagine one stock such as cropland soil quality, influenced by these four feedback loops. Then enlarge your imagining to include a second level, the crop biomass, also influenced by the same basic loops but all with different time constants. Now add on top of that a stock of agricultural capital, with the basic dynamics of investment and depreciation we have already looked at. Then add one more stock, a growing human population dependent on the harvest from that crop biomass. Typically these interconnected stocks are maintained so that all of them stay within stable and mutually-congruent levels. There are strong forces within both natural and social systems to keep things this way. However, if one of the stocks, particularly the soil stock upon which the whole pyramid rests, goes out of its stable region, the system becomes extremely hard to control.

WATER RESOURCES

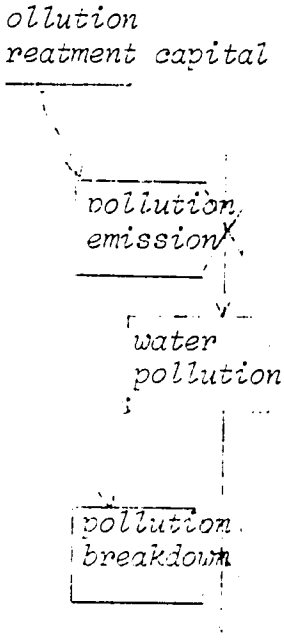
The basic input to the water sector is the precipitation rate of fresh water (and, if the region being analyzed is downstream in a watershed, the inflowing runoff from higher regions). This input is notoriously variable in most parts of the world, usually with a clear seasonal dynamic overlaid with a lot of day-to-day and season-to-season randomness, which systems people call "noise". The incoming fresh water accumulates (usually not for very long) in a



stock of surface water. The outflow rates of this stock are

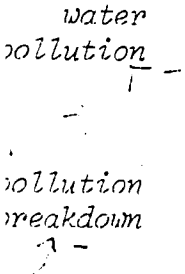
- natural evaporation and runoff (slowed by the presence of dams and canals)
- recharge, or seeping through the soil into stocks of groundwater (a rate also usually changed by the presence of dams and by many human activities, including logging, building, paving, and plowing).
- direct withdrawal into human use

The accumulated groundwater stock can either run off, if it has an underground outflow rate, or it can be pumped up for human use. The stock of water in use (contained in tanks, in human and animal bodies, in boilers, in cooking pots, in pipes, in canals) is usually discharged back to surface water, or it evaporates or runs off. As it is discharged, it usually brings with it a load of some sort of pollutants, which can vary from salts to chemicals to organic wastes. The pollutant emission inflow can be reduced by deliberate treatment, which requires capital. The stock of pollutants is generally reduced naturally by dilution, outflow, and natural waste processing such as bacterial breakdown of organic wastes.



In the structure around the water pollution level is a typical set of erosion loops like the one we encountered in the soil sector.

All else equal, the more water pollution, the more runs off and is processed, a normal depletion loop taking the stock gradually to zero. However, as the level of pollution builds up, it can poison the very microorganisms responsible for cleaning up the pollution. Therefore there is a nonlinear positive loop that can also operate: the more pollution, the slower the rate of pollution cleanup, the more pollution. At the extreme all natural reprocessing mechan-



isms cease and the pollution level simply accumulates inputs with no outputs (this rarely happens because there is usually some outflow and dilution--except in the oceans.)

Many interconnections between the soil resource sector and the water sector are not shown here. The presence of high biomass levels usually slow the rate of runoff of surface water. The rapid runoff of surface water usually enhances the rate of soil erosion. Obviously the presence of surface water in an appropriate range, not too high, not too low, and not too polluted, is essential for biomass growth.

FOSSIL FUEL AND MINERAL RESOURCES

Nonrenewable resources are disaggregated into four stocks: undiscovered reserves

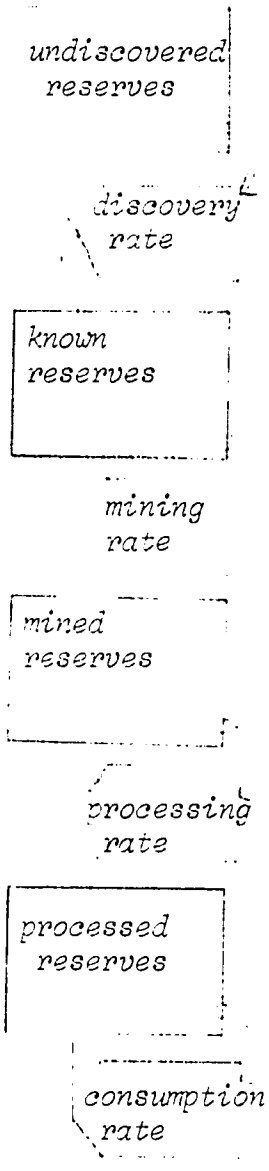
known reserves

mined resources

processed resources

The structures of the fossil-fuel and mineral resource sectors are essentially identical--they are the nonrenewable parts of the TRB diagram--and so I will discuss them together. They consist basically of a chain of four stocks. First there is the stock of undiscovered resource, the size of which no one knows, although geologists can make some very good guesses. (Geologists actually distinguish several categories of undiscovered reserves, depending on the amount known or suspected about their presence, but here they have been lumped together). The classification of reserves also depends on whether they are believed to be economically recoverable--we will take care of that distinction in a minute. The TRB diagram means by any stock of reserves <u>all</u> conceivable deposits of that fuel or mineral <u>and</u> its distribution by grade, including what is not now believed economically recoverable. That is, the stocks in the diagram are physical stocks of materials, regardless of economics.

With investment in discovery capital and the use of labor, energy, and other factors, enough is learned about the undiscovered reserves to move them through



the discovery rate to the category of known reserves. Obviously they don't physically move, they are still underground, but we can think of a discovery as a movement of however many barrels of oil or tons of bauxite from the category of undiscovered to the category of known reserves.

More investment and productive activity then removes the known reserves into the stock of raw minerals or crude recovered fossil fuels--ore or coal or crude oil removed from the ground and ready to be purified or processed into a useful form. After processing, refining, smelting, grading, or whatever, the mineral or fuel moves into the stockpile of material directly ready for use--automobile gasoline or #2 heating oil, iron bars, or aluminum ingots.

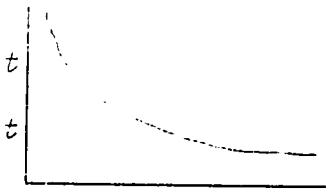
From that stock a consumption rate is the drain. In the case of fossil fuel that is the end of the chain, since consumption here is combustion, with heat, carbon dioxide, and water as the products (and particulates, SO_2, etc. which for some purposes we might want to keep track of--if we are interested in long-term climatic change, we may also want to keep track of the heat and CO_2). In the case of minerals, the consumption rate actually leads to a stock of products in use, some of which may have very long lifetimes. From that stock some recycling may provide an inflow to the processed mineral stock, but that is not shown on the TRB diagram (it can easily be added). More often the outflow rate from the stock of products in use is into a stock of solid waste, which gradually deteriorates, sometimes leading to water pollution.

The dynamics of this chain of processes and stocks is quite straightforward. At each stock, and particularly at the final refined one, are control loops through which human beings maintain the level of stock

Many negative feedback loops (some with long delays) control the flow of resources along the chain of stocks.

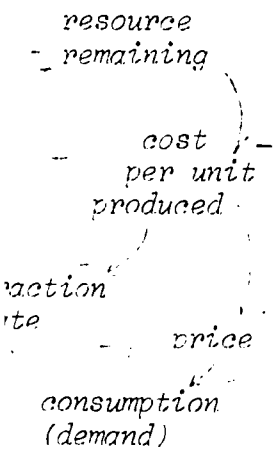
by calling for more inflow from the stock upstream (one of the main control loops involves prices). Longer-term control loops bring about sufficient levels of capital investment all along the chain to keep the material flowing. Even more long-term are research and technology loops that invent new types of capital that can access resources of lower grade, deeper down, or at greater distances. Obviously the timing of these control mechanisms and the proper balance of capital investments are important to keep the stocks filled and the resource flows smooth.

The cost of exploiting a resource rises nonlinearly as the resource is depleted.

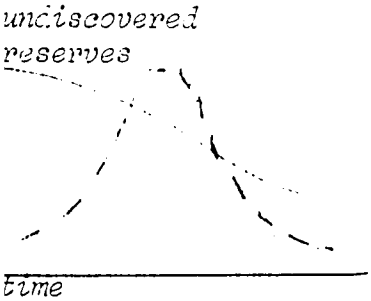


resource remaining

There are no inflows, of course, to the ultimate source of the resource stream, the stock of undiscovered resources. This stock may, in a given region, be very large or quite small, very concentrated and rich, or dispersed and nearly unminable. Sooner or later, depending on the quality and size of the initial resource, the easiest-to-discover and most concentrated resource deposits have all been moved up the chain and into consumption. The result of this is that more capital and effort is required for the next units discovered, and probably more capital is also required for those same less-concentrated units to be mined or pumped into the raw mineral or crude fuel stocks. That is, as each deposit is depleted, more input is required for each additional ton or barrel of output. More pipes are required for deeper wells, more ships for distant deposits, more exploratory drillings, more tailings, more trucks per gallon or ton of processed, usable resource. Depletion is a very long-term negative feedback loop, ultimately countered by another negative feedback: as it becomes more expensive to produce the depleting resource, the price rises, and the consumption rate at the far end of the chain goes down.



THE LIFECYCLE OF NONRENEWABLE RESOURCES:



sumption--dashed curve
entory--wavy curve

The dynamic of utilization of a nonrenewable resource is always the same: the undiscovered reserves gradually diminish. The intermediate stock levels of known reserves and processed resources usually remain about constant relative to consumption, with characteristic inventory cycles around the main trend (due to delays in the negative loops that maintain them). The consumption rate rises at first as the capital and technologies to produce the resource and the capital to consume it are put into place. Finally consumption tails off, as depletion raises cost and price.

Managing nonrenewable resources requires shifting strategies at different points in the resource lifecycle.

The management of a nonrenewable resource over its life cycle is tricky, especially since different strategies are appropriate at different stages. At the beginning the problem is phasing the investment in discovery, processing, and use-capital, so that the flow of resource is smooth and so all parts of the chain grow together. At the peak of the cycle, the problem is finding new technologies and efficiencies all along the chain to offset rising costs. And on the downslope there are two problems. One is phasing out the capital stocks so that they serve their useful lifetimes and depreciate at just the rate that production falls. The other is finding another resource that can serve the function of the depleted one (or that can be traded for such a resource) and to build up the capital plant appropriate to the new resource.

Comprehending the Whole

To see the whole resource base at one time requires a standing-back, intuitive, resonating sort of process.

In Robert Heinlein's science fiction book Stranger in a Strange Land, Martians are endowed with the ability to "grok" situations--to see them fully and wholly, to resonate with everything that is happening as if one were completely immersed and in touch with all of it. Grokking is not done by figuring out complexity bit by bit. It is more of a nonverbal, nonalytical surrender, a plunging-into

sense the everchanging integrity of the whole. Most of us are better at grokking than we realize. And although we can never figure out what all the interconnections and nonlinear relationships are in a total resource system anywhere near as complicated as the one on the TRB diagram, nevertheless we can get a seat-of-the-pants feel for the entire system.

Stocks are constantly changing relative to each other, and causing each other to be built up or drawn down. Negative feedback processes are mediating the stock levels, sometimes successfully and sometimes not.

Stand back from the individual pieces of the diagram now and look at the whole, at all you know about the dynamics of the individual sectors, the slowly changing stocks and more rapidly changing flows. Picture any real region or nation you know, with its many stocks of resources, stocks of all different sizes. The stocks are moving up and down, in interconnected ways, one is built up, one is exploited, one is traded for another. A forest is cut, a watershed is changed, silt washes onto cropland or fills up a dam. Cropland is stripped to provide coal, and some of that coal is used to build up a capital stock of bulldozers and trucks and fertilizers to reclaim that land or to import some grain or to build a school. If the economy is growing, most of the stocks are growing, somewhat in synchronization with one another, but first one, then another getting ahead and being unutilized or getting behind and slowing the growth of others.

This view of the dynamic unfolding of the resource system is a useful one (and not the only useful one) to keep in mind when planning, or assessing, development programs.

This position of overview and dynamic awareness of the whole is not the only place from which to see the process of development, but it is clearly a place one should come to every now and then. And notice that it is not a position that necessarily implies centralized, national development planning. It is useful for looking at a nation, but it is also useful, and equally complicated, to view from this angle a watershed, a village, or a single farm. On the level of village or farm, it is a place many good farmers

are used to seeing from, although they would not describe what they see in formal feedback loops. A computer is not required. But particularly for those of us whose intuition has not been built up by generations of working with a particular farm or village, and for those of us attempting to grok a whole region or nation, a computer can be a useful tool. It is equivalent to a paper and pencil when adding up lots of numbers--it helps us keep our place and not leave out anything.

It is accessible to you without a computer, and a computer can take you the next step...

By working through this paper you have absorbed most of the principles necessary to get a dynamic sense of the parts of a resource system and even of the whole. More accurately, you have gotten in touch with principles you already knew, learned a language and some graphing techniques for expressing them, and perhaps found some ways of applying them you hadn't thought of before. This stage of knowledge of resource systems can already be put to use, both for clarifying discussions with experts in various resource systems and just for strengthening your ability to tune in to your already fairly sophisticated instincts about resource management.

And one can go much farther. This paper is a brief introduction to an active and busy field of analysis in which hundreds of very-detailed computer-aided studies have been done on various real resource sectors in real places with real numbers. The level of knowledge described here is like knowledge of first-aid in a field that is pioneering open-heart surgery. First-aid is handy for everyone to know. I would hope that every planner or development worker everywhere could have an awareness of resource dynamics at least as complete as that described here. Without that I don't think development plans can work. Everyone does not need to do open-heart surgery--but it

From first aid to open-heart surgery.

is good to know how to find it and when it is needed. For that I would hope that every planner could have access to a team of general analysts who can take these dynamic concepts to their next more-detailed and more-quantitative implications and a team of experts who know various sorts of resources in depth, whose knowledge the analysts can integrate.

If you're interested in going further or in seeing the results of going further, here are some publications of interest.

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SUMMARY OF DYNAMIC PRINCIPLES

As long as the sum of inflows exceeds the sum of outflows, the stock level will rise.

As long as the sum of outflows exceeds the sum of inflows, the stock level will fall.

If the sum of outflows equals the sum of inflows, the stock will hold steady at whatever level it happened to be when the two flows became equal.

Stock levels change only slowly, never suddenly.

There are hundreds of mechanisms in any society to keep important stocks within acceptable levels; a vast number of individual and organizational decisions and actions are designed to regulate stocks.

Negative feedback loops are goal-seeking. They are the source of stability and control in systems. They are also the source of resistance to change.

Positive feedback loops are self-enhancing. They lead to exponential growth (or decline) over time. They are the structural sources of growth in systems.

Capital-producing capital is contained within a positive feedback loop that is the source of self-generating internal growth of an economy.

The allocation of capital to the various sectors of the economy is one of the major leverage points in the development process.

The size and nature of the capital plant determines the upper bound of the rate of energy consumption in an economy. The turnover rate of capital determines the rate at which the amount and nature of energy demand can be fundamentally changed.

The positive loop of population and births is the structural source of population growth.

A negative feedback loop with an implicit goal of zero can cause a system to run down or deplete. One such loop determines the death rate of population; another involves the depreciation rate of capital.

The structure of a system is its pattern of stocks linked in feedback loops. Structure is timeless and nonquantitative. It determines the sorts of behavior that can and cannot be exhibited by a system. What behavior is actually exhibited at any time depends on quantities such as the levels in the stocks, the strengths of relationships between system elements, and the outside influences imposing on the system.

Behavioral changes in complex systems result from the shifting dominance of linked feedback loops. The "demographic transition" is one example of shifting dominance, in which a behavior of population equilibrium changes to one of rapid growth and then back into near-equilibrium.

Increasing the delay in a loop is equivalent to decreasing the relative strength of the loop temporarily.

The presence of delays in feedback processes adds momentum to any growth or decay process and a tendency to overshoot or undershoot or oscillate around equilibria.

The very long delays in demographic processes create an especially strong momentum in the behavior of human populations. Growing populations tend to go on growing, declining ones to go on declining; age-structure adjustments to new fertility or mortality patterns take decades.

Similar feedback structures result in similar behavior, even in systems that appear on the surface to be very different.

Capital and population systems have the same basic structures and the same behavioral tendencies: exponential growth, decay and depreciation, and a momentum or lag induced by the age structure.

Any process with multiple inputs is limited at any one time by its least abundant factor only. Increasing factors other than the limiting one will make little difference. Increasing the limiting factor will allow output to increase up to the point where some other factor becomes limiting.

Most feedback loops contain nonlinear relationships. Their strength depends on the state of the system. Nonlinearities are critical in system behavior. They change the relative dominance of feedback loops, which leads to major shifts in behavior.

Positive loops are not only the source of growth in systems, they are also often the source of erosion and collapse. They can be turned around, however, to build up resource quality.

Renewable resource stocks are governed by two generic sorts of flows. Inflows through self-regeneration comprise positive feedback and the potential for growth. Depletion outflows constitute a force bringing the stock slowly to zero. In addition, there is nearly always a negative feedback on the growth rate, tending to bring the stock up to some maximum level consistent with the availability of resources. There is also nearly always a positive loop, usually associated with depletion that causes increasingly rapid erosion if the system is overstressed.