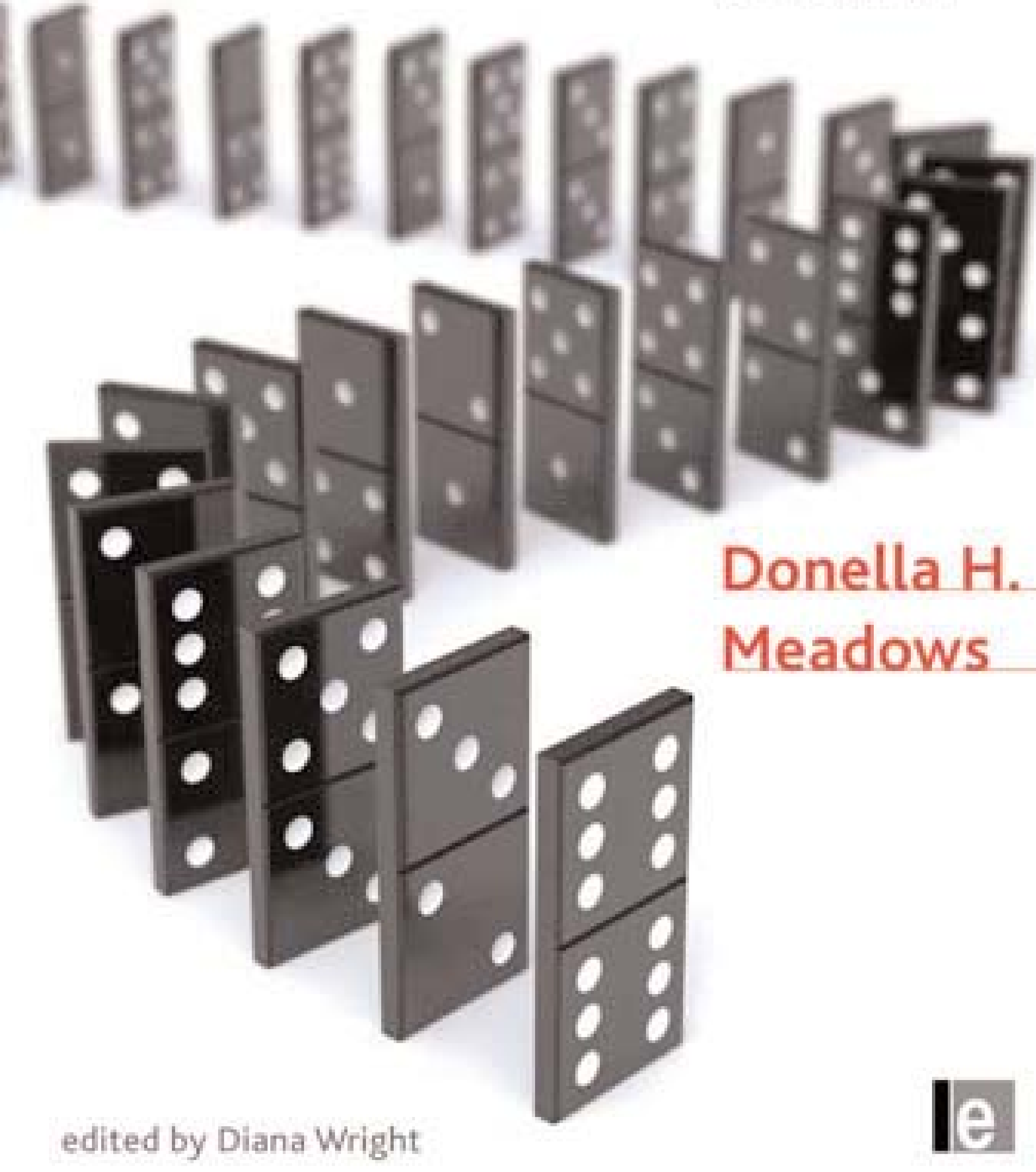
From the lead author of the international bestseller *Limits to Growth*

Thinking in Systems

A Primer



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Introduction: The System Lens

> Managers are not confronted with problems that are independent of each other, but with dynamic situations that consist of complex systems of changing problems that interact with each other. I call such situations messes. . . . Managers do not solve problems, they manage messes.
>
> —Russell Ackoff,[1] operations theorist

Early on in teaching about systems, I often bring out a Slinky. In case you grew up without one, a Slinky is a toy—a long, loose spring that can be made to bounce up and down, or pour back and forth from hand to hand, or walk itself downstairs.

I perch the Slinky on one upturned palm. With the fingers of the other hand, I grasp it from the top, partway down its coils. Then I pull the bottom hand away. The lower end of the Slinky drops, bounces back up again, yo-yos up and down, suspended from my fingers above.

"What made the Slinky bounce up and down like that?" I ask students.

"Your hand. You took away your hand," they say.

So I pick up the box the Slinky came in and hold it the same way, poised on a flattened palm, held from above by the fingers of the other hand. With as much dramatic flourish as I can muster, I pull the lower hand away.

Nothing happens. The box just hangs there, of course.

"Now once again. What made the Slinky bounce up and down?"

The answer clearly lies within the Slinky itself. The hands that manipulate it suppress or release some behavior that is latent within the structure of the spring.

That is a central insight of systems theory.

Once we see the relationship between structure and behavior, we can begin to understand how systems work, what makes them produce poor results, and how to shift them into better behavior patterns. As our world continues to change rapidly and become more complex, systems thinking will help us manage, adapt, and see the wide range of choices we have before us. It is a way of thinking that gives us the freedom to identify root causes of problems and see new opportunities.

So, what is a system? A system is a set of things—people, cells, molecules, or whatever—interconnected in such a way that they produce their own pattern of behavior over time. The system may be buffeted, constricted, triggered, or driven by outside forces. But the system's response to these forces is characteristic of itself, and that response is seldom simple in the real world.

When it comes to Slinkies, this idea is easy enough to understand. When it comes to individuals, companies, cities, or economies, it can be heretical. The system, to a large extent, causes its own behavior! An outside event may unleash that behavior, but the same outside event applied to a different system is likely to produce a different result.

Think for a moment about the implications of that idea:

- Political leaders don't cause recessions or economic booms. Ups and downs are inherent in the structure of the market economy.
- Competitors rarely cause a company to lose market share. They may be there to scoop up the advantage, but the losing company creates its losses at least in part through its own business policies.
- The oil-exporting nations are not solely responsible for oil-price rises. Their actions alone could not trigger global price rises and economic chaos if the oil consumption, pricing, and investment policies of the oil-importing nations had not built economies that are vulnerable to supply interruptions.
- The flu virus does not attack you; you set up the conditions for it to flourish within you.
- Drug addiction is not the failing of an individual and no one person, no matter how tough, no matter how loving, can cure a drug addict—not even the addict. It is only through understanding addiction as part of a larger set of influences and societal issues that one can begin to address it.

Something about statements like these is deeply unsettling. Something else is purest common sense. I submit that those two somethings—a resistance to and a recognition of systems principles—come from two kinds of human experience, both of which are familiar to everyone.

On the one hand, we have been taught to analyze, to use our rational ability, to trace direct paths from cause to effect, to look at things in small and understandable pieces, to solve problems by acting on or controlling the world around us. That training, the source of much personal and societal power, leads us to see presidents and competitors, OPEC and the flu and drugs as the causes of our problems.

On the other hand, long before we were educated in rational analysis, we all dealt with complex systems. We are complex systems—our own bodies are magnificent examples of integrated, interconnected, self-maintaining complexity. Every person we encounter, every organization, every animal, garden, tree, and forest is a complex system. We have built up intuitively, without analysis, often without words, a practical understanding of how these systems work, and how to work with them.

Modern systems theory, bound up with computers and equations, hides the fact that it traffics in truths known at some level by everyone. It is often possible, therefore, to make a direct translation from systems jargon to traditional wisdom.

> Because of feedback delays within complex systems, by the time a problem becomes apparent it may be unnecessarily difficult to solve.
> — *A stitch in time saves nine.*
>
> According to the competitive exclusion principle, if a reinforcing feedback loop rewards the winner of a competition with the means to win further competitions, the result will be the elimination of all but a few competitors.
> — *For he that hath, to him shall be given; and he that hath not, from him shall be taken even that which he hath (Mark 4:25)*
> or
> —*The rich get richer and the poor get poorer.*
>
> A diverse system with multiple pathways and redundancies is

> more stable and less vulnerable to external shock than a uniform system with little diversity.
> — *Don't put all your eggs in one basket.*

Ever since the Industrial Revolution, Western society has benefited from science, logic, and reductionism over intuition and holism. Psychologically and politically we would much rather assume that the cause of a problem is "out there," rather than "in here." It's almost irresistible to blame something or someone else, to shift responsibility away from ourselves, and to look for the control knob, the product, the pill, the technical fix that will make a problem go away.

Serious problems have been solved by focusing on external agents—preventing smallpox, increasing food production, moving large weights and many people rapidly over long distances. Because they are embedded in larger systems, however, some of our "solutions" have created further problems. And some problems, those most rooted in the internal structure of complex systems, the real messes, have refused to go away.

Hunger, poverty, environmental degradation, economic instability, unemployment, chronic disease, drug addiction, and war, for example, persist in spite of the analytical ability and technical brilliance that have been directed toward eradicating them. No one deliberately creates those problems, no one wants them to persist, but they persist nonetheless. That is because they are intrinsically systems problems—undesirable behaviors characteristic of the system structures that produce them. They will yield only as we reclaim our intuition, stop casting blame, see the system as the source of its own problems, and find the courage and wisdom to *restructure* it.

Obvious. Yet subversive. An old way of seeing. Yet somehow new. Comforting, in that the solutions are in our hands. Disturbing, because we must *do things*, or at least *see things* and *think about things*, in a different way.

This book is about that different way of seeing and thinking. It is intended for people who may be wary of the word "systems" and the field of systems analysis, even though they may have been doing systems thinking all their lives. I have kept the discussion nontechnical because I want to show what a long way you can go toward understanding systems without turning to mathematics or computers.

I have made liberal use of diagrams and time graphs in this book because there is a problem in discussing systems only with words. Words and sentences must, by necessity, come only one at a time in linear, logical order. Systems happen all at once. They are connected not just in one direction, but in many directions simultaneously. To discuss them properly, it is necessary somehow to use a language that shares some of the same properties as the phenomena under discussion.

Pictures work for this language better than words, because you can see all the parts of a picture at once. I will build up systems pictures gradually, starting with very simple ones. I think you'll find that you can understand this graphical language easily.

I start with the basics: the definition of a system and a dissection of its parts (in a reductionist, unholistic way). Then I put the parts back together to show how they interconnect to make the basic operating unit of a system: the feedback loop.

Next I will introduce you to a systems zoo—a collection of some common and interesting types of systems. You'll see how a few of these creatures behave and why and where they can be found. You'll recognize them; they're all around you and even within you.

With a few of the zoo "animals"—a set of specific examples—as a foundation, I'll step back and talk about how and why systems work so beautifully and the reasons why they so often surprise and confound us. I'll talk about why everyone or everything in a system can act dutifully and rationally, yet all these well-meaning actions too often add up to a perfectly terrible result. And why things so often happen much faster or slower than everyone thinks they will. And why you can be doing something that has always worked and suddenly discover, to your great disappointment, that your action no longer works. And why a system might suddenly, and without warning, jump into a kind of behavior you've never seen before.

That discussion will lead to us to look at the common problems that the systems-thinking community has stumbled upon over and over again through working in corporations and governments, economies and ecosystems, physiology and psychology. "There's another case of the tragedy of the commons," we find ourselves saying as we look at an allocation system for sharing water resource among communities or financial resources among schools. Or we identify "eroding goals" as we study the business rules and incentives that help or hinder the development of new technologies. Or we see "policy resistance" as we examine decision-making power and the nature of relationships in a family, a community, or a nation. Or we witness "addiction"—which can be caused by many more agents than caffeine, alcohol, nicotine, and narcotics.

Systems thinkers call these common structures that produce characteristic behaviors "archetypes." When I first planned this book, I called them "system traps." Then I added the words "and opportunities," because these archetypes, which are responsible for some of the most intransigent and potentially dangerous problems, also can be transformed, with a little systems understanding, to produce much more desirable behaviors.

From this understanding I move into what you and I can do about restructuring the systems we live within. We can learn how to look for leverage points for change.

I conclude with the largest lessons of all, the ones derived from the wisdom shared by most systems thinkers I know. For those who want to explore systems thinking further, the Appendix provides ways to dig deeper into the subject with a glossary, a bibliography of systems thinking resources, a summary list of systems principles, and equations for the models described in Part One.

When our small research group moved from MIT to Dartmouth College years ago, one of the Dartmouth engineering professors watched us in seminars for a while, and then dropped by our offices. "You people are different," he said. "You ask different kinds of questions. You see things I don't see. Somehow you come at the world in a different way. How? Why?"

That's what I hope to get across throughout this book, but especially in its conclusion. I don't think the systems way of seeing is better than the reductionist way of thinking. I think it's complementary, and therefore revealing. You can see some things through the lens of the human eye, other things through the lens of a microscope, others through the lens of a telescope, and still others through the lens of systems theory. Everything seen through each kind of lens is actually there. Each way of seeing allows our knowledge of the wondrous world in which we live to become a little more complete.

At a time when the world is more messy, more crowded, more interconnected, more interdependent, and more rapidly changing than ever before, the more ways of seeing, the better. The systems-thinking lens allows us to reclaim our intuition about whole systems and

- hone our abilities to understand parts,

- see interconnections,
- ask “what-if” questions about possible future behaviors, and
- be creative and courageous about system redesign.

Then we can use our insights to make a difference in ourselves and our world.

INTERLUDE • *The Blind Men and the Matter of the Elephant*

Beyond Ghor, there was a city. All its inhabitants were blind. A king with his entourage arrived nearby; he brought his army and camped in the desert. He had a mighty elephant, which he used to increase the people’s awe.

The populace became anxious to see the elephant, and some sightless from among this blind community ran like fools to find it.

As they did not even know the form or shape of the elephant, they groped sightlessly, gathering information by touching some part of it.

Each thought that he knew something, because he could feel a part. . . .

The man whose hand had reached an ear . . . said: “It is a large, rough thing, wide and broad, like a rug.”

And the one who had felt the trunk said: “I have the real facts about it. It is like a straight and hollow pipe, awful and destructive.”

The one who had felt its feet and legs said: “It is mighty and firm, like a pillar.”

Each had felt one part out of many. Each had perceived it wrongly. . . .[2]

This ancient Sufi story was told to teach a simple lesson but one that we often ignore: The behavior of a system cannot be known just by knowing the elements of which the system is made.

— ONE —

The Basics

> I have yet to see any problem, however complicated, which, when looked at in the right way, did not become still more complicated.
>
> —Poul Anderson[1]

More Than the Sum of Its Parts

A system isn't just any old collection of things. A **system**[*] is an interconnected set of elements that is coherently organized in a way that achieves something. If you look at that definition closely for a minute, you can see that a system must consist of three kinds of things: *elements*, *interconnections*, and a *function* or *purpose*.

For example, the elements of your digestive system include teeth, enzymes, stomach, and intestines. They are interrelated through the physical flow of food, and through an elegant set of regulating chemical signals. The function of this system is to break down food into its basic nutrients and to transfer those nutrients into the bloodstream (another system), while discarding unusable wastes.

A football team is a system with elements such as players, coach, field, and ball. Its interconnections are the rules of the game, the coach's strategy, the players' communications, and the laws of physics that govern the motions of ball and players. The purpose of the team is to win games, or have fun, or get exercise, or make millions of dollars, or all of the above.

A school is a system. So is a city, and a factory, and a corporation, and a national economy. An animal is a system. A tree is a system, and a forest is a larger system that encompasses subsystems of trees and animals. The earth

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[*] Definitions of words in bold face can be found in the Glossary.

is a system. So is the solar system; so is a galaxy. Systems can be embedded in systems, which are embedded in yet other systems.

Is there anything that is not a system? Yes—a conglomeration without any particular interconnections or function. Sand scattered on a road by happenstance is not, itself, a system. You can add sand or take away sand and you still have just sand on the road. Arbitrarily add or take away football players, or pieces of your digestive system, and you quickly no longer have the same system.

When a living creature dies, it loses its "system-ness." The multiple interrelations that held it together no longer function, and it dissipates, although its material remains part of a larger food-web system. Some people say that an old city neighborhood where people know each other and communicate regularly is a social system, and that a new apartment block full of strangers is not—not until new relationships arise and a system forms.

A system is more than the sum of its parts. It may exhibit adaptive, dynamic, goal-seeking, self-preserving, and sometimes evolutionary behavior.

You can see from these examples that there is an integrity or wholeness about a system and an active set of mechanisms to maintain that integrity. Systems can change, adapt, respond to events, seek goals, mend injuries, and attend to their own survival in lifelike ways, although they may contain or consist of nonliving things. Systems can be self-organizing, and often are self-repairing over at least some range of disruptions. They are resilient, and many of them are evolutionary. Out of one system other completely new, never-before-imagined systems can arise.

Look Beyond the Players to the Rules of the Game

> You think that because you understand "one" that you must therefore understand "two" because one and one make two. But you forget that you must also understand "and."
>
> —Sufi teaching story

The elements of a system are often the easiest parts to notice, because many of them are visible, tangible things. The elements that make up a tree are roots, trunk, branches, and leaves. If you look more closely, you

THINK ABOUT THIS

How to know whether you are looking at a system or just a bunch of stuff:

A) Can you identify parts? . . . and
B) Do the parts affect each other? . . . and
C) Do the parts together produce an effect that is different from the effect of each part on its own? . . . and perhaps
D) Does the effect, the behavior over time, persist in a variety of circumstances?

see specialized cells: vessels carrying fluids up and down, chloroplasts, and so on. The system called a university is made up of buildings, students, professors, administrators, libraries, books, computers—and I could go on and say what all those things are made up of. Elements do not have to be physical things. Intangibles are also elements of a system. In a university, school pride and academic prowess are two intangibles that can be very important elements of the system. Once you start listing the elements of a system, there is almost no end to the process. You can divide elements into sub-elements and then sub-sub-elements. Pretty soon you lose sight of the system. As the saying goes, you can't see the forest for the trees.

Before going too far in that direction, it's a good idea to stop dissecting out elements and to start looking for the *interconnections*, the relationships that hold the elements together.

The interconnections in the tree system are the physical flows and chemical reactions that govern the tree's metabolic processes—the signals that allow one part to respond to what is happening in another part. For example, as the leaves lose water on a sunny day, a drop in pressure in the water-carrying vessels allows the roots to take in more water. Conversely, if the roots experience dry soil, the loss of water pressure signals the leaves to close their pores, so as not to lose even more precious water.

As the days get shorter in the temperate zones, a deciduous tree puts forth chemical messages that cause nutrients to migrate out of the leaves into the trunk and roots and that weaken the stems, allowing the leaves to fall. There even seem to be messages that cause some trees to make repellent chemicals or harder cell walls if just one part of the plant is attacked by insects. No one understands all the relationships that allow a tree to do what it does. That lack of knowledge is not surprising. It's easier to learn about a system's elements than about its interconnections.

In the university system, interconnections include the standards for admission, the requirements for degrees, the examinations and grades, the budgets and money flows, the gossip, and most important, the communication of knowledge that is, presumably, the purpose of the whole system.

Some interconnections in systems are actual physical flows, such as the water in the tree's trunk or the students progressing through a university. Many interconnections are flows of information—signals that go to decision points or action points within a system. These kinds of interconnections are often harder to see, but the system reveals them to those who look. Students may use informal information about the probability of getting a good grade to decide what courses to take. A consumer decides what to buy using information about his or her income, savings, credit rating, stock of goods at home, prices, and availability of goods for purchase. Governments need information about kinds and quantities of water pollution before they can create sensible regulations to reduce that pollution. (Note that information about the existence of a problem may be necessary but not sufficient to trigger action—information about resources, incentives, and consequences is necessary too.)

Many of the interconnections in systems operate through the flow of information. Information holds systems together and plays a great role in determining how they operate.

If information-based relationships are hard to see, *functions* or *purposes* are even harder. A system's function or purpose is not necessarily spoken, written, or expressed explicitly, except through the operation of the system. The best way to deduce the system's purpose is to watch for a while to see how the system behaves.

If a frog turns right and catches a fly, and then turns left and catches a fly, and then turns around backward and catches a fly, the purpose of the frog has to do not with turning left or right or backward but with catching flies. If a government proclaims its interest in protecting the environment but allocates little money or effort toward that goal, environmental protection is not, in fact, the government's purpose. Purposes are deduced from behavior, not from rhetoric or stated goals.

A NOTE ON LANGUAGE

The word *function* is generally used for a nonhuman system, the word *purpose* for a human one, but the distinction is not absolute, since so many systems have both human and nonhuman elements.

The function of a thermostat-furnace system is to keep a building at a given temperature. One function of a plant is to bear seeds and create more plants. One purpose of a national economy is, judging from its behavior, to keep growing larger. An important function of almost every system is to ensure its own perpetuation.

System purposes need not be human purposes and are not necessarily those intended by any single actor within the system. In fact, one of the most frustrating aspects of systems is that the purposes of subunits may add up to an overall behavior that no one wants. No one intends to produce a society with rampant drug addiction and crime, but consider the combined purposes and consequent actions of the actors involved:

- desperate people who want quick relief from psychological pain
- farmers, dealers, and bankers who want to earn money
- pushers who are less bound by civil law than are the police who oppose them
- governments that make harmful substances illegal and use police power to interdict them
- wealthy people living in close proximity to poor people
- nonaddicts who are more interested in protecting themselves than in encouraging recovery of addicts

Altogether, these make up a system from which it is extremely difficult to eradicate drug addiction and crime.

Systems can be nested within systems. Therefore, there can be purposes within purposes. The purpose of a university is to discover and preserve knowledge and pass it on to new generations. Within the university, the purpose of a student may be to get good grades, the purpose of a professor may be to get tenure, the purpose of an administrator may be to balance the budget. Any of those sub-purposes could come into conflict with the overall purpose—the student could cheat, the professor could ignore the students in order to publish papers, the administrator could balance the budget by firing professors. Keeping sub-purposes and overall system purposes in harmony is an essential function of successful systems. I'll get back to this point later when we come to hierarchies.

You can understand the relative importance of a system's elements, interconnections, and purposes by imagining them changed one by one. Changing elements usually has the least effect on the system. If you change all the players on a football team, it is still recognizably a football team. (It may play much better or much worse—particular elements in a system can indeed be important.) A tree changes its cells constantly, its leaves every year or so, but it is still essentially the same tree. Your body replaces most of its cells every few weeks, but it goes on being your body. The university has a constant flow of students and a slower flow of professors and administrators, but it is still a university. In fact it is still the same university, distinct in subtle ways from others, just as General Motors and the U.S. Congress somehow maintain their identities even though all their members change. A system generally goes on being itself, changing only slowly if at all, even with complete substitutions of its elements—as long as its interconnections and purposes remain intact.

The least obvious part of the system, its function or purpose, is often the most crucial determinant of the system's behavior.

If the interconnections change, the system may be greatly altered. It may even become unrecognizable, even though the same players are on the team. Change the rules from those of football to those of basketball, and you've got, as they say, a whole new ball game. If you change the interconnections in the tree—say that instead of taking in carbon dioxide and emitting oxygen, it does the reverse—it would no longer be a tree. (It would be an animal.) If in a university the students graded the professors, or if arguments were won by force instead of reason, the place would need a different name. It might be an interesting organization, but it would not be a university. Changing interconnections in a system can change it dramatically.

Changes in function or purpose also can be drastic. What if you keep the players and the rules but change the purpose—from winning to losing, for example? What if the function of a tree were not to survive and reproduce but to capture all the nutrients in the soil and grow to unlimited size? People have imagined many purposes for a university besides disseminating knowledge—making money, indoctrinating people, winning football games. A change in purpose changes a system profoundly, even if every element and interconnection remains the same.

To ask whether elements, interconnections, or purposes are most important in a system is to ask an unsystemic question. All are essential. All interact. All have their roles. But the least obvious part of the system, its function or purpose, is often the most crucial determinant of the system's behavior. Interconnections are also critically important. Changing relationships usually changes system behavior. The elements, the parts of systems we are most likely to notice, are often (not always) least important in defining the unique characteristics of the system—*unless changing an element also results in changing relationships or purpose.*

Changing just one leader at the top—from a Brezhnev to a Gorbachev, or from a Carter to a Reagan—may or may not turn an entire nation in a new direction, though its land, factories, and hundreds of millions of people remain exactly the same. A leader can make that land and those factories and people play a different game with new rules, or can direct the play toward a new purpose.

And conversely, because land, factories, and people are long-lived, slowly changing, physical elements of the system, there is a limit to the rate at which any leader can turn the direction of a nation.

Bathtubs 101—Understanding System Behavior over Time

> Information contained in nature . . . allows us a partial reconstruction of the past. . . . The development of the meanders in a river, the increasing complexity of the earth's crust . . . are information-storing devices in the same manner that genetic systems are. . . . Storing information means increasing the complexity of the mechanism.
>
> —Ramon Margalef[2]

A **stock** is the foundation of any system. Stocks are the elements of the system that you can see, feel, count, or measure at any given time. A system stock is just what it sounds like: a store, a quantity, an accumulation of