— 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 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 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.

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?

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.

> **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.

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.)

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 material or information that has built up over time. It may be the water in a bathtub, a population, the books in a bookstore, the wood in a tree, the money in a bank, your own self-confidence. A stock does not have to be physical. Your reserve of good will toward others or your supply of hope that the world can be better are both stocks.

A stock is the memory of the history of changing flows within the system.

Stocks change over time through the actions of a **flow**. Flows are filling and draining, births and deaths, purchases and sales, growth and decay, deposits and withdrawals, successes and failures. A stock, then, is the present memory of the history of changing flows within the system.

Figure 1. **How to read stock-and-flow diagrams.** In this book, stocks are shown as boxes, and flows as arrow-headed “pipes” leading into or out of the stocks. The small T on each flow signifies a “faucet;” it can be turned higher or lower, on or off. The “clouds” stand for wherever the flows come from and go to—the sources and sinks that are being ignored for the purposes of the present discussion.

For example, an underground mineral deposit is a stock, out of which comes a flow of ore through mining. The inflow of ore into a mineral deposit is minute in any time period less than eons. So I have chosen to draw (Figure 2) a simplified picture of the system without any inflow. *All* system diagrams and descriptions are simplified versions of the real world.

Figure 2. A stock of minerals depleted by mining.

Water in a reservoir behind a dam is a stock, into which flow rain and river water, and out of which flows evaporation from the reservoir's surface as well as the water discharged through the dam.

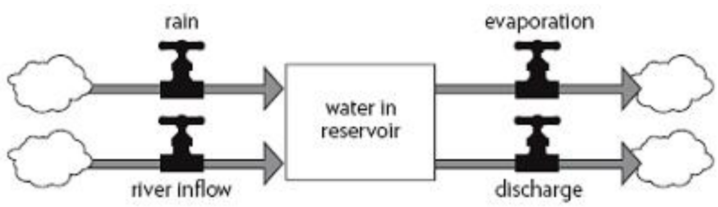


Figure 3. A stock of water in a reservoir with multiple inflows and outflows.

The volume of wood in the living trees in a forest is a stock. Its inflow is the growth of the trees. Its outflows are the natural deaths of trees and the harvest by loggers. The logging harvest flows into another stock, perhaps an inventory of lumber at a mill. Wood flows out of the inventory stock as lumber sold to customers.

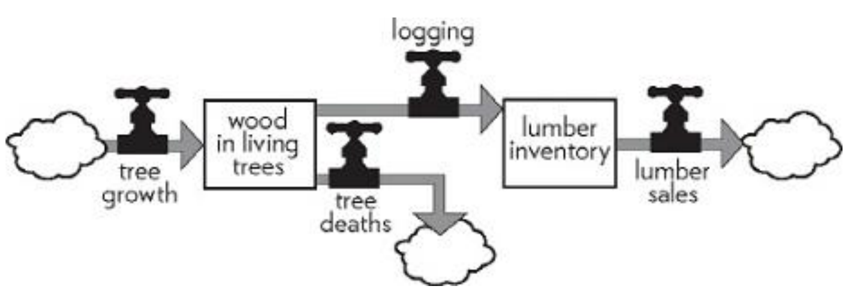


Figure 4. A stock of lumber linked to a stock of trees in a forest.

If you understand the **dynamics** of stocks and flows—their behavior over time—you understand a good deal about the behavior of complex systems.

And if you have had much experience with a bathtub, you understand the dynamics of stocks and flows.

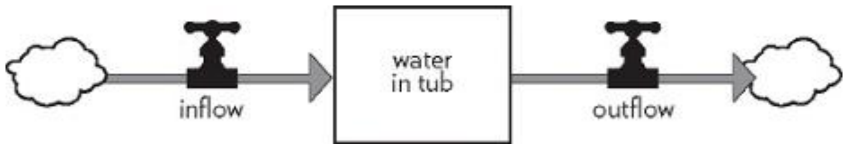


Figure 5. The structure of a bathtub system—one stock with one inflow and one outflow.

Imagine a bathtub filled with water, with its drain plugged up and its faucets turned off—an unchanging, undynamic, boring system. Now mentally pull the plug. The water runs out, of course. The level of water in the tub goes down until the tub is empty.

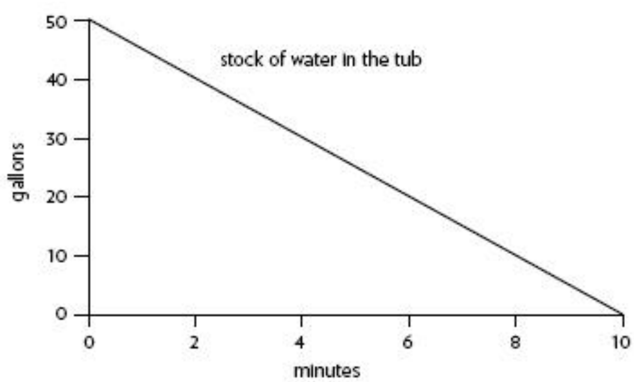


Figure 6. Water level in a tub when the plug is pulled.

A NOTE ON READING GRAPHS OF BEHAVIOR OVER TIME

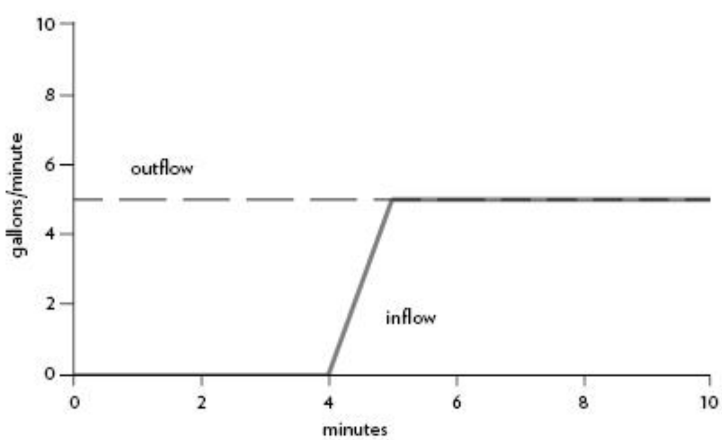
Systems thinkers use graphs of system behavior to understand trends over time, rather than focusing attention on individual events. We also use behavior-over-time graphs to learn whether the system is approaching a goal or a limit, and if so, how quickly.

The variable on the graph may be a stock or a flow. The pattern—the shape of the variable line—is important, as are the points at which that line changes shape or direction. The precise numbers on the axes are often less important.

The horizontal axis of time allows you to ask questions about what came before, and what might happen next. It can help you focus on the time horizon appropriate to the question or problem you are investigating.

Now imagine starting again with a full tub, and again open the drain, but this time, when the tub is about half empty, turn on the inflow faucet so the rate of water flowing in is just equal to that flowing out. What happens?

The amount of water in the tub stays constant at whatever level it had reached when the inflow became equal to the outflow. It is in a state of **dynamic equilibrium**—its level does not change, although water is continuously flowing through it.



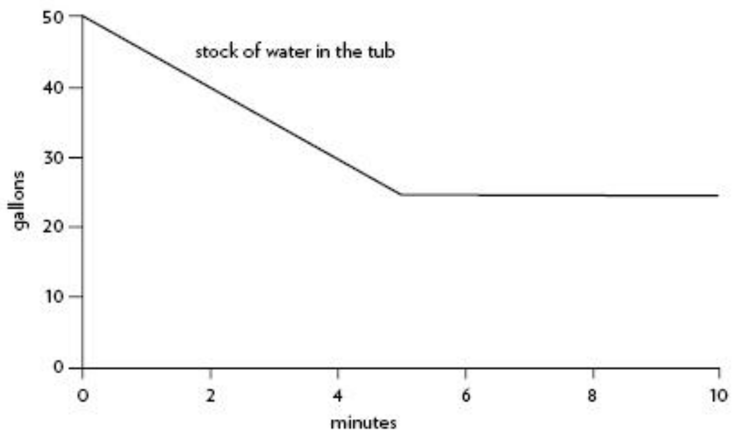


Figure 7. Constant outflow, inflow turned on after 5 minutes, and the resulting changes in the stock of water in the tub.

Imagine turning the inflow on somewhat harder while keeping the outflow constant. The level of water in the tub slowly rises. If you then turn the inflow faucet down again to match the outflow exactly, the water in the tub will stop rising. Turn it down some more, and the water level will fall slowly.

This model of a bathtub is a very simple system with just one stock, one inflow, and one outflow. Over the time period of interest (minutes), I have assumed that evaporation from the tub is insignificant, so I have not included that outflow. All models, whether mental models or mathematical models, are simplifications of the real world. You know all the dynamic possibilities of this bathtub. From it you can deduce several important principles that extend to more complicated systems:

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

- If the sum of all outflows equals the sum of all inflows, the stock level will not change; it will be held in dynamic equilibrium at whatever level it happened to be when the two sets of flows became equal.

The human mind seems to focus more easily on stocks than on flows. On top of that, when we do focus on flows, we tend to focus on *inflows* more easily than on outflows. Therefore, we sometimes miss seeing that we can fill a bathtub not only by increasing the inflow rate, but also by decreasing the outflow rate. Everyone understands that you can prolong the life of an oil-based economy by discovering new oil deposits. It seems to be harder to understand that the same result can be achieved by burning less oil. A breakthrough in energy efficiency is equivalent, in its effect on the stock of available oil, to the discovery of a new oil field—although different people profit from it.

A stock can be increased by decreasing its outflow rate as well as by increasing its inflow rate. There's more than one way to fill a bathtub!

Similarly, a company can build up a larger workforce by more hiring, or it can do the same thing by reducing the rates of quitting and firing. These two strategies may have very different costs. The wealth of a nation can be boosted by investment to build up a larger stock of factories and machines. It also can be boosted, often more cheaply, by decreasing the rate at which factories and machines wear out, break down, or are discarded.

You can adjust the drain or faucet of a bathtub—the flows—abruptly, but it is much more difficult to change the level of water—the stock—quickly. Water can't run out the drain instantly, even if you open the drain all the way. The tub can't fill up immediately, even with the inflow faucet on full blast. *A stock takes time to change, because flows take time to flow*. That's a vital point, a key to understanding why systems behave as they do. Stocks usually change slowly. They can act as delays, lags, buffers, ballast, and sources of momentum in a system. Stocks, especially large ones, respond to change, even sudden change, only by gradual filling or emptying.

> Stocks generally change slowly, even when the flows into or out of them change suddenly. Therefore, **stocks act as delays or buffers or shock absorbers in systems**.

People often underestimate the inherent momentum of a stock. It takes a long time for populations to grow or stop growing, for wood to accumulate in a forest, for a reservoir to fill up, for a mine to be depleted. An economy cannot build up a large stock of functioning factories and highways and electric plants overnight, even if a lot of money is available. Once an economy has a lot of oil-burning furnaces and automobile engines, it cannot change quickly to furnaces and engines that burn a different fuel, even if the price of oil suddenly changes. It has taken decades to accumulate the stratospheric pollutants that destroy the earth's ozone layer; it will take decades for those pollutants to be removed.

Changes in stocks set the pace of the dynamics of systems. Industrialization cannot proceed faster than the rate at which factories and machines can be constructed and the rate at which human beings can be educated to run and maintain them. Forests can't grow overnight. Once contaminants have accumulated in groundwater, they can be washed out only at the rate of groundwater turnover, which may take decades or even centuries.

The time lags that come from slowly changing stocks can cause problems in systems, but they also can be sources of stability. Soil that has accumulated over centuries rarely erodes all at once. A population that has learned many skills doesn't forget them immediately. You can pump groundwater faster than the rate it recharges for a long time before the aquifer is drawn down far enough to be damaged. The time lags imposed by stocks allow room to maneuver, to experiment, and to revise policies that aren't working.

If you have a sense of the rates of change of stocks, you don't expect things to happen faster than they can happen. You don't give up too soon.

You can use the opportunities presented by a system's momentum to guide it toward a good outcome—much as a judo expert uses the momentum of an opponent to achieve his or her own goals.

There is one more important principle about the role of stocks in systems, a principle that will lead us directly to the concept of feedback. The presence of stocks allows inflows and outflows to be independent of each other and temporarily out of balance with each other.

> **Stocks allow inflows and outflows to be decoupled and to be independent** and temporarily out of balance with each other.

It would be hard to run an oil company if gasoline had to be produced at the refinery at exactly the rate the cars were burning it. It isn't feasible to harvest a forest at the precise rate at which the trees are growing. Gasoline in storage tanks and wood in the forest are both stocks that permit life to proceed with some certainty, continuity, and predictability, even though flows vary in the short term.

Human beings have invented hundreds of stock-maintaining mechanisms to make inflows and outflows independent and stable. Reservoirs enable residents and farmers downriver to live without constantly adjusting their lives and work to a river's varying flow, especially its droughts and floods. Banks enable you temporarily to earn money at a rate different from how you spend. Inventories of products along a chain from distributors to wholesalers to retailers allow production to proceed smoothly although customer demand varies, and allow customer demand to be filled even though production rates vary.

Most individual and institutional decisions are designed to regulate the levels in stocks. If inventories rise too high, then prices are cut or advertising budgets are increased, so that sales will go up and inventories will fall. If the stock of food in your kitchen gets low, you go to the store. As the stock of growing grain rises or fails to rise in the fields, farmers decide whether to apply water or pesticide, grain companies decide how many barges to book for the harvest, speculators bid on future values of the harvest, cattle growers build up or cut down their herds. Water levels in reservoirs cause all sorts of corrective actions if they rise too high or fall too low. The same can be said for the stock of money in your wallet, the oil reserves owned by an oil company, the pile of woodchips feeding a paper mill, and the concentration of pollutants in a lake.

People monitor stocks constantly and make decisions and take actions designed to raise or lower stocks or to keep them within acceptable ranges.

Those decisions add up to the ebbs and flows, successes and problems, of all sorts of systems. Systems thinkers see the world as a collection of stocks along with the mechanisms for regulating the levels in the stocks by manipulating flows.

That means system thinkers see the world as a collection of “feedback processes.”

How the System Runs Itself— Feedback

> Systems of information-feedback control are fundamental to all life and human endeavor, from the slow pace of biological evolution to the launching of the latest space satellite. . . . Everything we do as individuals, as an industry, or as a society is done in the context of an information-feedback system.
>
> —Jay W. Forrester[3]

When a stock grows by leaps and bounds or declines swiftly or is held within a certain range no matter what else is going on around it, it is likely that there is a control mechanism at work. In other words, if you see a behavior that persists over time, there is likely a mechanism creating that consistent behavior. That mechanism operates through a **feedback loop**. It is the consistent behavior pattern over a long period of time that is the first hint of the existence of a feedback loop.

A feedback loop is formed when changes in a stock affect the flows into or out of that same stock. A feedback loop can be quite simple and direct. Think of an interest-bearing savings account in a bank. The total amount of money in the account (the stock) affects how much money comes into the account as interest. That is because the bank has a rule that the account earns a certain percent interest each year. The total dollars of interest paid into the account each year (the flow in) is not a fixed amount, but varies with the size of the total in the account.

You experience another fairly direct kind of feedback loop when you get your bank statement for your checking account each month. As your level of available cash in the checking account (a stock) goes down, you may decide to work more hours and earn more money. The money entering your bank account is a flow that you can adjust in order to increase your stock of cash to a more desirable level. If your bank account then grows very large, you may feel free to work less (decreasing the inflow). This kind of feedback loop is keeping your level of cash available within a range that is acceptable to you. You can see that adjusting your earnings is not the only feedback loop that works on your stock of cash. You also may be able to adjust the outflow of money from your account, for example. You can imagine an outflow-adjusting feedback loop for spending.

Feedback loops can cause stocks to maintain their level within a range or grow or decline. In any case, the flows into or out of the stock are adjusted because of changes in the size of the stock itself. Whoever or whatever is monitoring the stock’s level begins a corrective process, adjusting rates of inflow or outflow (or both) and so changing the stock’s level. The stock level feeds back through a chain of signals and actions to control itself.

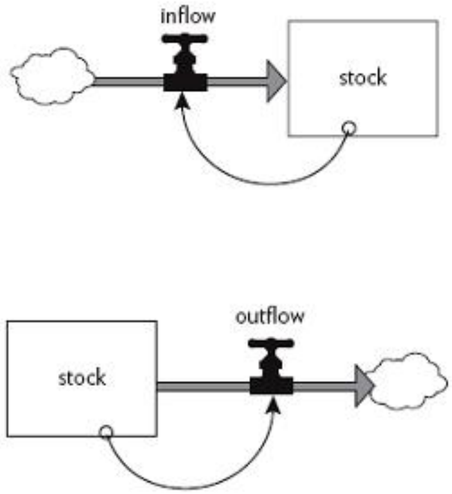


Figure 8. How to read a stock-and-flow diagram with feedback loops. Each diagram distinguishes the stock, the flow that changes the stock, and the information link (shown as a thin, curved arrow) that directs the action. It emphasizes that action or change always proceeds through adjusting flows.

Not all systems have feedback loops. Some systems are relatively simple open-ended chains of stocks and flows. The chain may be affected by outside factors, but the levels of the chain's stocks don't affect its flows. However, those systems that contain feedback loops are common and may be quite elegant or rather surprising, as we shall see.

A feedback loop is a closed chain of causal connections from a stock, through a set of decisions or rules or physical laws or actions that are dependent on the level of the stock, and back again through a flow to change the stock.

Stabilizing Loops— Balancing Feedback

One common kind of feedback loop stabilizes the stock level, as in the checking-account example. The stock level may not remain completely fixed, but it does stay within an acceptable range. What follows are some more stabilizing feedback loops that may be familiar to you. These examples start to detail some of the steps within a feedback loop.

If you’re a coffee drinker, when you feel your energy level run low, you may grab a cup of hot black stuff to perk you up again. You, as the coffee drinker, hold in your mind a desired stock level (energy for work). The purpose of this caffeine-delivery system is to keep your actual stock level near or at your desired level. (You may have other purposes for drinking coffee as well: enjoying the flavor or engaging in a social activity.) It is the gap, the discrepancy, between your actual and desired levels of energy for work that drives your decisions to adjust your daily caffeine intake.

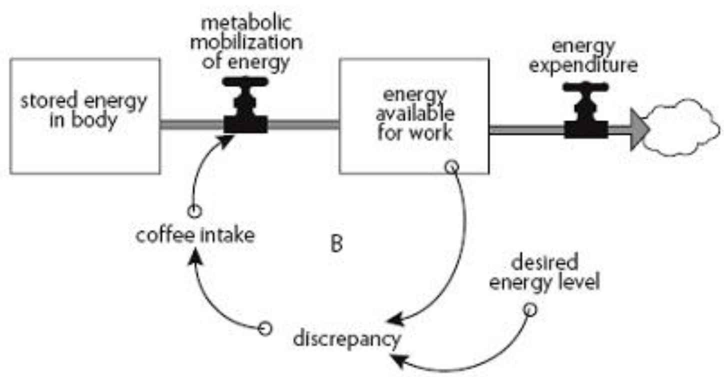


Figure 9. Energy level of a coffee drinker.

Notice that the labels in Figure 9, like all the diagram labels in this book, are direction-free. The label says “stored energy in body” not “*low* energy level,” “coffee intake” not “*more* coffee.” That’s because feedback loops often can operate in two directions. In this case, the feedback loop can correct an oversupply as well as an undersupply. If you drink too much coffee and find yourself bouncing around with extra energy, you’ll lay off the caffeine for a while. High energy creates a discrepancy that says “too much,” which then causes you to reduce your coffee intake until your energy level settles down. The diagram is intended to show that the loop works to drive the stock of energy in either direction.

I could have shown the inflow of energy coming from a cloud, but instead I made the system diagram slightly more complicated. *Remember—all system diagrams are simplifications of the real world*. We each choose how much complexity to look at. In this example, I drew another stock—the stored energy in the body that can be activated by the caffeine. I did that to indicate that there is more to the system than one simple loop. As every coffee drinker knows, caffeine is only a short-term stimulant. It lets you run your motor faster, but it doesn't refill your personal fuel tank. Eventually the caffeine high wears off, leaving the body more energy-deficient than it was before. That drop could reactivate the feedback loop and generate another trip to the coffee pot. (See the discussion of addiction later in this book.) Or it could activate some longer-term and healthier feedback responses: Eat some food, take a walk, get some sleep.

This kind of stabilizing, goal-seeking, regulating loop is called a **balancing feedback loop**, so I put a B inside the loop in the diagram. Balancing feedback loops are *goal-seeking* or *stability-seeking*. Each tries to keep a stock at a given value or within a range of values. A balancing feedback loop opposes whatever direction of change is imposed on the system. If you push a stock too far up, a balancing loop will try to pull it back down. If you shove it too far down, a balancing loop will try to bring it back up.

Here's another balancing feedback loop that involves coffee, but one that works through physical law rather than human decision. A hot cup of coffee will gradually cool down to room temperature. Its rate of cooling depends on the difference between the temperature of the coffee and the temperature of the room. The greater the difference, the faster the coffee will cool. The loop works the other way too—if you make iced coffee on a hot day, it will warm up until it has the same temperature as the room. The function of this system is to bring the discrepancy between coffee's temperature and room's temperature to zero, no matter what the direction of the discrepancy.

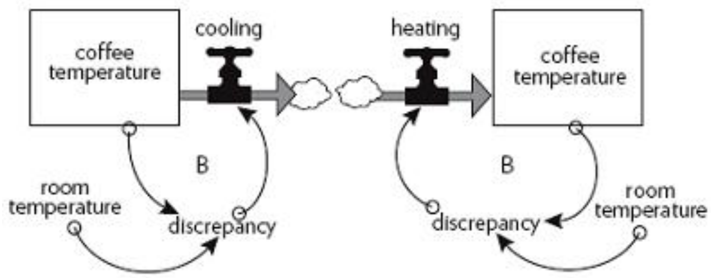


Figure 10. A cup of coffee cooling (*left*) or warming (*right*).

Starting with coffee at different temperatures, from just below boiling to just above freezing, the graphs in Figure 11 show what will happen to the temperature over time (if you don't drink the coffee). You can see here the "homing" behavior of a balancing feedback loop. Whatever the initial value of the system stock (coffee temperature in this case), whether it is above or below the "goal" (room temperature), the feedback loop brings it toward the goal. The change is faster at first, and then slower, as the discrepancy between the stock and the goal decreases.

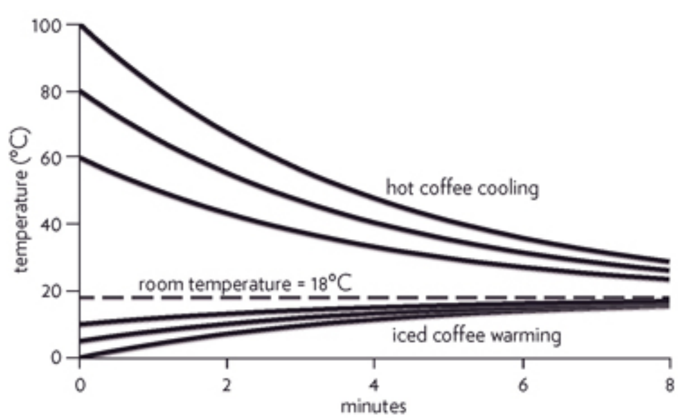


Figure 11. Coffee temperature as it approaches a room temperature of 18°C.

This behavior pattern—gradual approach to a system-defined goal— also can be seen when a radioactive element decays, when a missile finds its target, when an asset depreciates, when a reservoir is brought up or down to its desired level, when your body adjusts its blood-sugar concentration, when you pull your car to a stop at a stoplight. You can think of many more examples. The world is full of goal-seeking feedback loops.

Balancing feedback loops are equilibrating or goal-seeking structures in systems and are both sources of stability and sources of resistance to change.

The presence of a feedback mechanism doesn't necessarily mean that the mechanism works *well*. The feedback mechanism may not be strong enough to bring the stock to the desired level. Feedbacks—the interconnections, the information part of the system—can fail for many reasons. Information can arrive too late or at the wrong place. It can be unclear or incomplete or hard to interpret. The action it triggers may be too weak or delayed or resource-constrained or simply ineffective. The goal of the feedback loop may never be reached by the actual stock. But in the simple example of a cup of coffee, the drink eventually will reach room temperature.

Runaway Loops— Reinforcing Feedback

> I'd need rest to refresh my brain, and to get rest it's necessary to travel, and to travel one must have money, and in order to get money you have to work. . . . I am in a vicious circle . . . from which it is impossible to escape.
>
> —Honoré Balzac,[4] 19th century novelist and playwright

> Here we meet a very important feature. It would seem as if this were circular reasoning; profits fell because investment fell, and investment fell because profits fell.
>
> —Jan Tinbergen,[5] Jan Tinbergen, quoted in ibid, 44.economist

The second kind of feedback loop is amplifying, reinforcing, self-multiplying, snowballing—a vicious or virtuous circle that can cause healthy growth or runaway destruction. It is called a **reinforcing feedback loop**, and will be noted with an R in the diagrams. It generates more input to a stock the more that is already there (and less input the less that is already there). A reinforcing feedback loop enhances whatever direction of change is imposed on it.

For example:

- When we were kids, the more my brother pushed me, the more I pushed him back, so the more he pushed me back, so the more I pushed him back.
- The more prices go up, the more wages have to go up if people are to maintain their standards of living. The more wages go up, the more prices have to go up to maintain profits. This means that wages have to go up again, so prices go up again.
- The more rabbits there are, the more rabbit parents there are to make baby rabbits. The more baby rabbits there are, the more grow up to become rabbit parents, to have even more baby rabbits.
- The more soil is eroded from the land, the less plants are able to grow, so the fewer roots there are to hold the soil, so the more soil is eroded, so less plants can grow.
- The more I practice piano, the more pleasure I get from the sound, and so the more I play the piano, which gives me more practice.

Reinforcing loops are found wherever a system element has the ability to reproduce itself or to grow as a constant fraction of itself. Those elements include populations and economies. Remember the example of the interest-bearing bank account? The more money you have in the bank, the more interest you earn, which is added to the money already in the bank, where it earns even more interest.

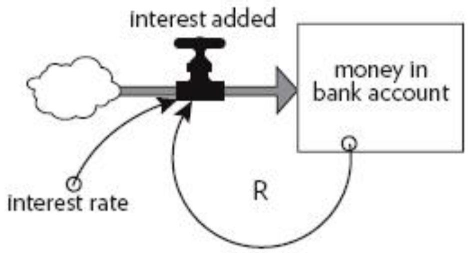


Figure 12. Interest-bearing bank account.

Figure 13 shows how this reinforcing loop multiplies money, starting with $100 in the bank, and assuming no deposits and no withdrawals over a period of twelve years. The five lines show five different interest rates, from 2 percent to 10 percent per year.

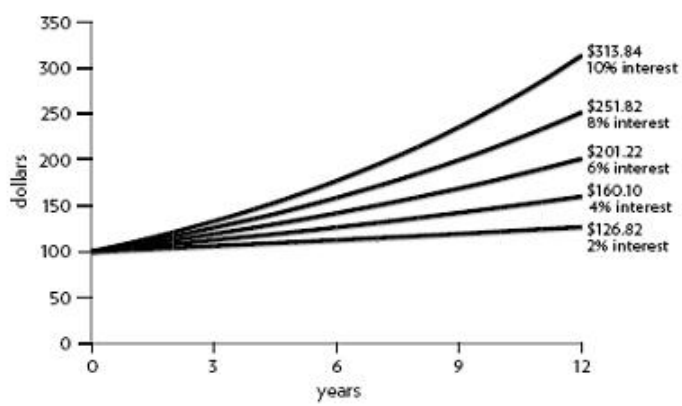


Figure 13. Growth in savings with various interest rates.

This is not simple linear growth. It is not constant over time. The growth of the bank account at lower interest rates may look linear in the first few years. But, in fact, growth goes faster and faster. The more is there, the more is added. This kind of growth is called "exponential." It's either good news or bad news, depending on what is growing—money in the bank, people with HIV/AIDS, pests in a cornfield, a national economy, or weapons in an arms race.

Reinforcing feedback loops are self-enhancing, leading to exponential growth or to runaway collapses over time. They are found whenever a stock has the capacity to reinforce or reproduce itself.

In Figure 14, the more machines and factories (collectively called “capital”) you have, the more goods and services (“output”) you can produce. The more output you can produce, the more you can invest in new machines and factories. The more you make, the more capacity you have to make even more. This reinforcing feedback loop is the central engine of growth in an economy.

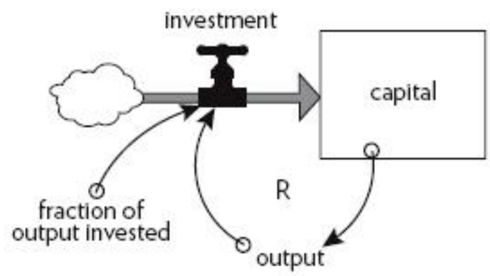


Figure 14. Reinvestment in capital.

By now you may be seeing how basic balancing and reinforcing feedback loops are to systems. Sometimes I challenge my students to try to think of any human decision that occurs *without* a feedback loop—that is, a decision that is made without regard to any information about the level of the stock it influences. Try thinking about that yourself. The more you do, the more you’ll begin to see feedback loops everywhere.

The most common “non-feedback” decisions students suggest are falling in love and committing suicide. I’ll leave it to you to decide whether you think these are *actually* decisions made with no feedback involved.

Watch out! If you see feedback loops everywhere, you’re already in danger of becoming a systems thinker! Instead of seeing only how A causes B, you’ll begin to wonder how B may *also* influence A—and how A might reinforce or reverse itself. When you hear in the nightly news that the Federal Reserve

HINT ON REINFORCING LOOPS AND DOUBLING TIME

Because we bump into reinforcing loops so often, it is handy to know this shortcut: The time it takes for an exponentially growing stock to double in size, the "doubling time," equals approximately 70 divided by the growth rate (expressed as a percentage).

Example: If you put $100 in the bank at 7% interest per year, you will double your money in 10 years (70 ÷ 7 = 10). If you get only 5% interest, your money will take 14 years to double.

Bank has done something to control the economy, you'll also see that the economy must have done something to affect the Federal Reserve Bank. When someone tells you that population growth causes poverty, you'll ask yourself how poverty may cause population growth.

THINK ABOUT THIS:

If A causes B, is it possible that B also causes A?

You'll be thinking not in terms of a static world, but a dynamic one. You'll stop looking for who's to blame; instead you'll start asking, "What's the system?" The concept of feedback opens up the idea that a system can cause its own behavior.

So far, I have limited this discussion to one kind of feedback loop at a time. Of course, in real systems feedback loops rarely come singly. They are linked together, often in fantastically complex patterns. A single stock is likely to have several reinforcing and balancing loops of differing strengths pulling it in several directions. A single flow may be adjusted by the contents of three or five or twenty stocks. It may fill one stock while it drains another and feeds into decisions that alter yet another. The many feedback loops in a system tug against each other, trying to make stocks

— FOUR —

Why Systems Surprise Us

> The trouble . . . is that we are terrifyingly ignorant. The most learned of us are ignorant. . . . The acquisition of knowledge always involves the revelation of ignorance—almost *is* the revelation of ignorance. Our knowledge of the world instructs us first of all that the world is greater than our knowledge of it.
>
> —Wendell Berry,[1] writer and Kentucky farmer

The simple systems in the zoo may have perplexed you with their behavior. They continue to surprise me, although I have been teaching them for years. That you and I are surprised says as much about us as it does about dynamic systems. The interactions between what I think I know about dynamic systems and my experience of the real world never fails to be humbling. They keep reminding me of three truths:

> 1. Everything we think we know about the world is a model. Every word and every language is a model. All maps and statistics, books and databases, equations and computer programs are models. So are the ways I picture the world in my head—my *mental* models. None of these is or ever will be the *real* world.
>
> 2. Our models usually have a strong congruence with the world. That is why we are such a successful species in the biosphere. Especially complex and sophisticated are the mental models we

develop from direct, intimate experience of nature, people, and organizations immediately around us.

3. However, and conversely, our models fall far short of representing the world fully. That is why we make mistakes and why we are regularly surprised. In our heads, we can keep track of only a few variables at one time. We often draw illogical conclusions from accurate assumptions, or logical conclusions from inaccurate assumptions. Most of us, for instance, are surprised by the amount of growth an exponential process can generate. Few of us can intuit how to damp oscillations in a complex system.

In short, this book is poised on a duality. We know a tremendous amount about how the world works, but not nearly enough. Our knowledge is amazing; our ignorance even more so. We can improve our understanding, but we can't make it perfect. I believe both sides of this duality, because I have learned much from the study of systems.

Everything we think we know about the world is a model. Our models do have a strong congruence with the world. Our models fall far short of representing the real world fully.

This chapter describes some of the reasons why dynamic systems are so often surprising. Alternately, it is a compilation of some of the ways our mental models fail to take into account the complications of the real world—at least those ways that one can see from a systems perspective. It is a warning list. Here is where hidden snags lie. You can't navigate well in an interconnected, feedback-dominated world unless you take your eyes off short-term events and look for long term behavior and structure; unless you are aware of false boundaries and bounded rationality; unless you take into account limiting factors, nonlinearities and delays. You are likely to mistreat, misdesign, or misread systems if you don't respect their properties of resilience, self-organization, and hierarchy.

The bad news, or the good news, depending on your need to control the world and your willingness to be delighted by its surprises, is that even if you do understand all these system characteristics, you may be surprised less often, but you will still be surprised.

Beguiling Events

A system is a big black box
Of which we can't unlock the locks,
And all we can find out about
Is what goes in and what comes out.
Related by parameters,
Permits us, sometimes, to relate
An input, output and a state.
If this relation's good and stable
Then to predict we may be able,
But if this fails us—heaven forbid!
We'll be compelled to force the lid!

—Kenneth Boulding,[2] economist

Systems fool us by presenting themselves—or we fool ourselves by seeing the world—as a series of events. The daily news tells of elections, battles, political agreements, disasters, stock market booms or busts. Much of our ordinary conversation is about specific happenings at specific times and places. A team wins. A river floods. The Dow Jones Industrial Average hits 10,000. Oil is discovered. A forest is cut. Events are the outputs, moment by moment, from the black box of the system.

Events can be spectacular: crashes, assassinations, great victories, terrible tragedies. They hook our emotions. Although we've seen many thousands of them on our TV screens or the front page of the paper, each one is different enough from the last to keep us fascinated (just as we never lose our fascination with the chaotic twists and turns of the weather). It's endlessly engrossing to take in the world as a series of events, and constantly surprising, because that way of seeing the world has almost no predictive or explanatory value. Like the tip of an iceberg rising above the water, events are the most visible aspect of a larger complex—but not always the most important.

We are less likely to be surprised if we can see how events accumulate into dynamic patterns of *behavior*. The team is on a winning streak. The variance of the river is increasing, with higher floodwaters during rains and lower flows during droughts. The Dow has been trending up for two years. Discoveries of oil are becoming less frequent. The felling of forests is happening at an ever-increasing rate.

The behavior of a system is its performance over time—its growth, stagnation, decline, oscillation, randomness, or evolution. If the news did a better job of putting events into historical context, we would have better behavior-level understanding, which is deeper than event-level under standing. When a systems thinker encounters a problem, the first thing he or she does is look for data, time graphs, the history of the system. That's because long term behavior provides clues to the underlying system structure. And structure is the key to understanding not just *what* is happening, but *why*.

The structure of a system is its interlocking stocks, flows, and feedback loops. The diagrams with boxes and arrows (my students call them "spaghetti-and-meatball diagrams") are pictures of system structure. Structure determines what behaviors are latent in the system. A goal-seeking balancing feedback loop approaches or holds a dynamic equilibrium. A reinforcing feedback loop generates exponential growth. The two of them linked together are capable of growth, decay, or equilibrium. If they also contain delays, they may produce oscillations. If they work in periodic, rapid bursts, they may produce even more surprising behaviors.

System structure is the source of system behavior. System behavior reveals itself as a series of events over time.

Systems thinking goes back and forth constantly between structure (diagrams of stocks, flows, and feedback) and behavior (time graphs). Systems thinkers strive to understand the connections between the hand releasing the Slinky (event) and the resulting oscillations (behavior) and the mechanical characteristics of the Slinky's helical coil (structure).

Simple examples like a Slinky make this event-behavior-structure distinction seem obvious. In fact, much analysis in the world goes no deeper than events. Listen to every night's explanation of why the stock market did what it did. Stocks went up (down) because the U.S. dollar fell (rose), or the prime interest rate rose (fell), or the Democrats won (lost), or one country invaded another (or didn't). Event-event analysis.

These explanations give you no ability to predict what will happen tomorrow. They give you no ability to change the behavior of the system—to make the stock market less volatile or a more reliable indicator of the health of corporations or a better vehicle to encourage investment, for instance.

Most economic analysis goes one level deeper, to behavior over time. Econometric models strive to find the statistical links among past trends in income, savings, investment, government spending, interest rates, output, or whatever, often in complicated equations.

These behavior-based models are more useful than event-based ones, but they still have fundamental problems. First, they typically overemphasize system flows and underemphasize stocks. Economists follow the behavior of flows, because that's where the interesting variations and most rapid changes in systems show up. Economic news reports on the national production (flow) of goods and services, the GNP, rather than the total physical capital (stock) of the nation's factories and farms and businesses that produce those goods and services. But without seeing how stocks affect their related flows through feedback processes, one cannot understand the dynamics of economic systems or the reasons for their behavior.

Second, and more seriously, in trying to find statistical links that relate flows to each other, econometricians are searching for something that does not exist. There's no reason to expect any flow to bear a stable relationship to any other flow. Flows go up and down, on and off, in all sorts of combinations, in response to stocks, not to other flows.

Let me use a simple example to explain what I mean. Suppose you knew nothing at all about thermostats, but you had a lot of data about past heat flows into and out of the room. You could find an equation telling you how those flows have varied together in the past, because under ordinary circumstances, being governed by the same stock (temperature of the room), they do vary together.

Your equation would hold, however, only until something changes in the system's structure—someone opens a window or improves the insulation, or tunes the furnace, or forgets to order oil. You could predict tomorrow's room temperature with your equation, as long as the system didn't change or break down. But if you were asked to make the room warmer, or if the room temperature suddenly started plummeting and you had to fix it, or if you wanted to produce the same room temperature with a lower fuel bill, your behavior-level analysis wouldn't help you. You would have to dig into the system's structure.

That's why behavior-based econometric models are pretty good at predicting the near-term performance of the economy, quite bad at predicting the longer-term performance, and terrible at telling one how to improve the performance of the economy.

And that's one reason why systems of all kinds surprise us. We are too fascinated by the events they generate. We pay too little attention to their history. And we are insufficiently skilled at seeing in their history clues to the structures from which behavior and events flow.

Linear Minds in a Nonlinear World

> Linear relationships are easy to think about: the more the merrier. Linear equations are solvable, which makes them suitable for textbooks. Linear systems have an important modular virtue: you can take them apart and put them together again—the pieces add up.

> Nonlinear systems generally cannot be solved and cannot be added together. . . . Nonlinearity means that the act of playing the game has a way of changing the rules. . . . That twisted changeability makes nonlinearity hard to calculate, but it also creates rich kinds of behavior that never occur in linear systems.
>
> —James Gleick, author of *Chaos: Making a New Science* [3]

We often are not very skilled in understanding the nature of relationships. A **linear relationship** between two elements in a system can be drawn on a graph with a straight line. It's a relationship with constant proportions. If I put 10 pounds of fertilizer on my field, my yield will go up by 2 bushels. If I put on 20 pounds, my yield will go up by 4 bushels. If I put on 30 pounds, I'll get an increase of 6 bushels.

A **nonlinear relationship** is one in which the cause does not produce a proportional effect. The relationship between cause and effect can only be drawn with curves or wiggles, not with a straight line. If I put 100 pounds of fertilizer on, my yield will go up by 10 bushels; if I put on 200, my yield will not go up at all; if I put on 300, my yield will go down. Why? I've damaged my soil with "too much of a good thing."

The world is full of nonlinearities.

So the world often surprises our linear-thinking minds. If we've learned that a small push produces a small response, we think that twice as big a push will produce twice as big a response. But in a nonlinear system, twice the push could produce one-sixth the response, or the response squared, or no response at all.

Here are some examples of nonlinearities:

- As the flow of traffic on a highway increases, car speed is affected only slightly over a large range of car density. Eventually, however, small further increases in density produce a rapid drop-off in speed. And when the number of cars on the highway builds up to a certain point, it can result in a traffic jam, and car speed drops to zero.

- Soil erosion can proceed for a long time without much affect on crop yield—until the topsoil is worn down to the depth of the root zone of the crop. Beyond that point, a little further erosion can cause yields to plummet.
- A little tasteful advertising can awaken interest in a product. A lot of blatant advertising can cause disgust for the product.

You can see why nonlinearities produce surprises. They foil the reasonable expectation that if a little of some cure did a little good, then a lot of it will do a lot of good—or alternately that if a little destructive action caused only a tolerable amount of harm, then more of that same kind of destruction will cause only a bit more harm. Reasonable expectations like these in a nonlinear world produce classic mistakes.

Nonlinearities are important not only because they confound our expectations about the relationship between action and response. They are even more important because they *change the relative strengths of feedback loops*. They can flip a system from one mode of behavior to another.

Nonlinearities are the chief cause of the shifting dominance that characterizes several of the systems in the zoo—the sudden swing between exponential growth caused by a dominant reinforcing loop, say, and then decline caused by a suddenly dominant balancing loop.

To take a dramatic example of the effects of nonlinearities, consider the destructive irruptions of the spruce budworm in North American forests.

INTERLUDE • *Spruce Budworms, Firs, and Pesticides*

Tree ring records show that the spruce budworm has been killing spruce and fir trees periodically in North America for at least 400 years. Until this century, no one much cared. The valuable tree for the lumber industry was the white pine. Spruce and fir were considered “weed species.” Eventually, however, the stands of virgin pine were gone, and the lumber industry turned to spruce and fir. Suddenly the budworm was seen as a serious pest.

So, beginning in the 1950s, northern forests were sprayed with DDT to control the spruce budworm. In spite of the spraying, every year there was a budworm resurgence. Annual sprays were continued through the 1950s, 1960s, and 1970s, until DDT was banned. Then the sprays were changed to fenitrothion, acephate, Sevin, and methoxychlor.

Insecticides were no longer thought to be the ultimate answer to the budworm problem, but they were still seen as essential. “Insecticides buy time,” said one forester, “That’s all the forest manager wants; to preserve the trees until the mill is ready for them.”

By 1980, spraying costs were getting unmanageable—the Canadian province of New Brunswick spent $12.5 million on budworm “control” that year. Concerned citizens were objecting to the drenching of the landscape with poisons. And, in spite of the sprays, the budworm was still killing as many as 20 million hectares (50 million acres) of trees per year.

C. S. Holling of the University of British Columbia and Gordon Baskerville of the University of New Brunswick put together a computer model to get a whole-system look at the budworm problem. They discovered that before the spraying began, the budworm had been barely detectable in most years. It was controlled by a number of predators, including birds, a spider, a parasitic wasp, and several diseases. Every few decades, however, there was a budworm outbreak, lasting from six to ten years. Then the budworm population would subside, eventually to explode again

The budworm preferentially attacks balsam fir, secondarily spruce. Balsam fir is the most competitive tree in the northern forest. Left to its own devices, it would crowd out spruce and birch, and the forest would become a monoculture of nothing but fir. Each budworm outbreak cuts back the fir population, opening the forest for spruce and birch. Eventually fir moves back in.

As the fir population builds up, the probability of an outbreak increases—*nonlinearly*. The reproductive potential of the budworm increases more than proportionately to the availability of its favorite food supply. The final trigger is two or three warm, dry springs, perfect for the survival of budworm larvae. (If you're doing event-level analysis, you will blame the outburst on the warm, dry springs.)

The budworm population grows too great for its natural enemies to hold in check—*nonlinearly*. Over a wide range of conditions, greater budworm populations result in more rapid multiplication of budworm predators. But beyond some point, the predators can multiply no faster. What was a reinforcing relationship—more budworms, faster predator multiplication—becomes a nonrelationship—more budworms, no faster predator multiplication—and the budworms take off, unimpeded.

Now only one thing can stop the outbreak: the insect reducing its own food supply by killing off fir trees. When that finally happens, the budworm population crashes—*nonlinearly*. The reinforcing loop of budworm reproduction yields dominance to the balancing loop of budworm starvation. Spruce and birch move into the spaces where the firs used to be, and the cycle begins again.

The budworm/spruce/fir system oscillates over decades, but it is ecologically stable within bounds. It can go on forever. The main effect of the budworm is to allow tree species other than fir to persist. But in this case what is ecologically stable is economically unstable. In eastern Canada, the economy is almost completely dependent on the logging industry, which is dependent on a steady supply of fir and spruce.

> **Many relationships in systems are nonlinear.** Their relative strengths shift in disproportionate amounts as the stocks in the system shift. Nonlinearities in feedback systems produce shifting dominance of loops and many complexities in system behavior.

When industry sprays insecticides, it shifts the whole system to balance uneasily on different points within its nonlinear relationships. It kills off not only the pest, but the natural enemies of the pest, thereby weakening the feedback loop that normally keeps the budworms in check. It keeps the density of fir high, moving the budworms up their nonlinear reproduction curve to the point at which they're perpetually on the edge of population explosion.

The forest management practices have set up what Holling calls "persistent semi-outbreak conditions" over larger and larger areas. The managers have found themselves locked into a policy in which there is an incipient volcano bubbling, such that, if the policy fails, there will be an outbreak of an intensity that has never been seen before."[4]

Nonexistent Boundaries

> When we think in terms of systems, we see that a fundamental misconception is embedded in the popular term "side-effects.". . . This phrase means roughly "effects which I hadn't foreseen or don't want to think about.". . . Side-effects no more deserve the adjective "side" than does the "principal" effect. It is hard to think in terms of systems, and we eagerly warp our language to protect ourselves from the necessity of doing so.

—Garrett Hardin,[5] ecologist

Remember the clouds in the structural diagrams of Chapters One and Two? Beware of clouds! They are prime sources of system surprises.

Clouds stand for the beginnings and ends of flows. They are stocks—sources and sinks—that are being ignored at the moment for the purposes of simplifying the present discussion. They mark the boundary of the system diagram. They rarely mark a real boundary, because systems rarely have real boundaries. Everything, as they say, is connected to everything else, and not neatly. There is no clearly determinable boundary between the sea and the land, between sociology and anthropology, between an automobile's exhaust and your nose. There are only boundaries of word, thought, perception, and social agreement—artificial, mental-model boundaries.

The greatest complexities arise exactly at boundaries. There are Czechs on the German side of the border and Germans on the Czech side of the border. Forest species extend beyond the edge of the forest into the field;

field species penetrate partway into the forest. Disorderly, mixed-up borders are sources of diversity and creativity.

In our system zoo, for instance, I showed the flow of cars into a car dealer’s inventory as coming from a cloud. Of course, cars don’t come from a cloud, they come from the transformation of a stock of raw materials, with the help of capital, labor, energy, technology, and management (the means of production). Similarly, the flow of cars out of the inventory goes not to a cloud, but through sales to the households or businesses of consumers.

Whether it is important to keep track of raw materials or consumers’ home stocks (whether it is legitimate to replace them in a diagram with clouds) depends on whether these stocks are likely to have a significant influence on the behavior of the system over the time period of interest. If raw materials are guaranteed to be abundant and consumers continue to demand the products, then clouds will do. But if there could be a materials shortage or a product glut, and if we drew a mental boundary around the system that did not include these stocks, then we could be surprised by future events.

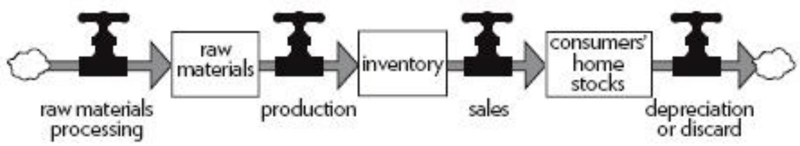


Figure 47. Revealing some of the stocks behind the clouds.

There are still clouds in Figure 47. The boundary can be expanded further. Processed raw materials come from chemical plants, smelters, or refineries, whose input comes, ultimately, from the earth. Processing creates not only products, but also employment, wages, profits, and pollution. Discarded consumers’ stocks go to landfills or incinerators or recycling centers, from which they go on to have further effects on society and the environment. Landfills leach into drinking-water wells, incinerators produce smoke and ash, recycling centers move materials back into the production stream.

Whether it's important to think about the full flow from mine to dump, or as industry calls it, "from cradle to grave," depends on who wants to know, for what purpose, over how long. In the long term, the full flow is important and, as the physical economy grows and society's "ecological footprint" expands, the long term is increasingly coming to be the short term. Landfills fill up with a suddenness that has been surprising for people whose mental models picture garbage as going "away," into some sort of a cloud. Sources of raw materials—mines, wells, and oil fields—can be exhausted with surprising suddenness too.

With a long enough time horizon, even mines and dumps are not the end of the story. The great geological cycles of the earth keep moving materials around, opening and closing seas, raising up and wearing down mountains. Eons from now, everything put in a dump will end up on the top of a mountain or deep under the sea. New deposits of metals and fuels will form. On planet Earth there are no system "clouds," no ultimate boundaries. Even real clouds in the sky are part of a hydrological cycle. Everything physical comes from somewhere, everything goes somewhere, everything keeps moving.

Which is not to say that every model, mental or computer, has to follow each connection until it includes the whole planet. Clouds are a necessary part of models that describe metaphysical flows. Anger literally "comes out of a cloud," as does love, hatred, self esteem, and so on. If we're to understand anything, we have to simplify, which means we have to make boundaries. Often that's a safe thing to do. It's usually not a problem, for example, to think of populations with births and deaths coming from and going to clouds, as in Figure 48.

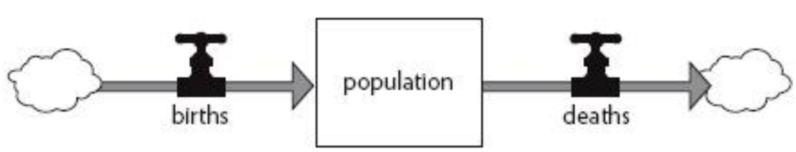


Figure 48. More clouds.

Figure 48 shows actual “cradle to grave” boundaries. Even these boundaries would be unserviceable, however, if the population in question experienced significant in- or out-migration, or if the problem under discussion was limited cemetery space.

The lesson of boundaries is hard even for systems thinkers to get. There is no single, legitimate boundary to draw around a system. We have to invent boundaries for clarity and sanity; and boundaries can produce problems when we forget that we’ve artificially created them.

> **There are no separate systems. The world is a continuum. Where to draw a boundary around a system depends on the purpose of the discussion**—the questions we want to ask.

When you draw boundaries too narrowly, the system surprises you. For example, if you try to deal with urban traffic problems without thinking about settlement patterns, you build highways, which attract housing developments along their whole length. Those households, in turn, put more cars on the highways, which then become just as clogged as before.

If you try to solve a sewage problem by throwing the waste into a river, the towns downstream make it clear that the boundary for thinking about sewage has to include the whole river. It might also have to include the soil groundwater surrounding the river. It probably doesn’t have to include the next watershed or the planetary hydrological cycle.

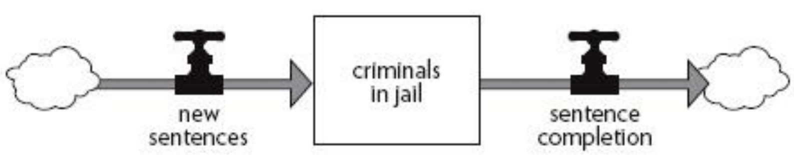
Planning for a national park used to stop at the physical boundary of the park. But park boundaries around the world are regularly crossed by nomadic peoples, by migrating wildlife, by waters that flow into, out of, or under the park, by the effects of economic development at the park’s edges, by acid rain, and now by a climate changing from greenhouse gases in the atmosphere. Even without climate change, to manage a park you have to think about a boundary wider than the official perimeter.

Systems analysts often fall into the opposite trap: making boundaries too large. They have a habit of producing diagrams that cover several pages with small print and many arrows connecting everything with everything. *There* is the system! they say. If you have considered anything less, you are academically illegitimate.

This “my model is bigger than your model” game results in enormously complicated analyses, which produce piles of information that may only serve to obscure the answers to the questions at hand. For example, modeling the earth’s climate in full detail is interesting for many reasons, but may not be necessary for figuring out how to reduce a country’s CO2 emissions to reduce climate change.

The right boundary for thinking about a problem rarely coincides with the boundary of an academic discipline, or with a political boundary. Rivers make handy borders between countries, but the worst possible borders for managing the quantity and quality of the water. Air is worse than water in its insistence on crossing political borders. National boundaries mean nothing when it comes to ozone depletion in the stratosphere, or greenhouse gases in the atmosphere, or ocean dumping.

Ideally, we would have the mental flexibility to find the appropriate boundary for thinking about each new problem. We are rarely that flexible. We get attached to the boundaries our minds happen to be accustomed to. Think how many arguments have to do with boundaries—national boundaries, trade boundaries, ethnic boundaries, boundaries between public and private responsibility, and boundaries between the rich and the poor, polluters and pollutees, people alive now and people who will come in the future. Universities can maintain disputes for years about the boundaries between economics and government, art and art history, literature and literary criticism. Too often, universities are living monuments to boundary rigidity.



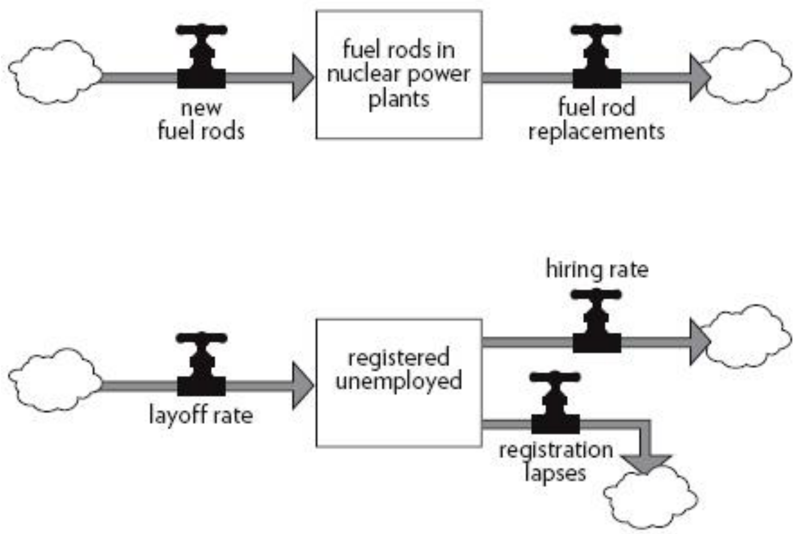


Figure 49. Examples of more clouds. These are systems in which a boundary or cloud should not stop you from thinking beyond the borders of the system, but start you thinking beyond those borders. What is driving the supply of people being given new sentences? Where do the fuel rods go after replacement? What happens to an unemployed person whose registration for unemployment lapses?

It's a great art to remember that *boundaries are of our own making, and that they can and should be reconsidered for each new discussion, problem, or purpose*. It's a challenge to stay creative enough to drop the boundaries that worked for the last problem and to find the most appropriate set of boundaries for the next question. It's also a necessity, if problems are to be solved well.

Layers of Limits

Systems surprise us because our minds like to think about single causes neatly producing single effects. We like to think about one or at most a few things at a time. And we don't like, especially when our own plans and desires are involved, to think about limits.

But we live in a world in which many causes routinely come together to produce many effects. Multiple inputs produce multiple outputs, and virtually all of the inputs, and therefore outputs, are limited. For example, an industrial manufacturing process needs:

- capital
- labor
- energy
- raw materials
- land
- water
- technology
- credit
- insurance
- customers
- good management
- public-funded infrastructure and government services (such as police and fire protection and education for managers and workers)
- functioning families to bring up and care for both producers and consumers
- a healthy ecosystem to supply or support all these inputs and to absorb or carry away their wastes

A patch of growing grain needs:

- sunlight
- air
- water

- nitrogen
- phosphorus
- potassium
- dozens of minor nutrients
- a friable soil and the services of a microbial soil community
- some system to control weeds and pests
- protection from the wastes of the industrial manufacturer

It was with regard to grain that Justus von Liebig came up with his famous "law of the minimum." It doesn't matter how much nitrogen is available to the grain, he said, if what's short is phosphorus. It does no good to pour on more phosphorus, if the problem is low potassium.

Bread will not rise without yeast, no matter how much flour it has. Children will not thrive without protein, no matter how many carbohydrates they eat. Companies can't keep going without energy, no matter how many customers they have—or without customers, no matter how much energy they have.

This concept of a **limiting factor** is simple and widely misunderstood. Agronomists assume, for example, that they know what to put in artificial fertilizer, because they have identified many of the major and minor nutrients in good soil. Are there any essential nutrients they have not identified? How do artificial fertilizers affect soil microbe communities? Do they interfere with, and therefore limit, any other functions of good soil? And what limits the production of artificial fertilizers?

At any given time, the input that is most important to a system is the one that is most limiting.

Rich countries transfer capital or technology to poor ones and wonder why the economies of the receiving countries still don't develop, never thinking that capital or technology may not be the most limiting factors.

Economics evolved in a time when labor and capital were the most common limiting factors to production. Therefore, most economic production functions keep track only of these two factors (and sometimes technology). As the economy grows relative to the ecosystem, however, and the limiting factors shift to clean water, clean air, dump space, and acceptable forms of energy and raw materials, the traditional focus on only capital and labor becomes increasingly unhelpful.

One of the classic models taught to systems students at MIT is Jay Forrester's corporate-growth model. It starts with a successful young company, growing rapidly. The problem for this company is to recognize deal with its shifting limits—limits that change in response to the company's own growth.

The company may hire salespeople, for example, who are so good that they generate orders faster than the factory can produce. Delivery delays increase and customers are lost, because production capacity is the most limiting factor. So the managers expand the capital stock of production plants. New people are hired in a hurry and trained too little. Quality suffers and customers are lost because labor skill is the most limiting factor. So management invests in worker training. Quality improves, new orders pour in, and the order-fulfillment and record-keeping system clogs. And so forth.

There are layers of limits around every growing plant, child, epidemic, new product, technological advance, company, city, economy, and population. Insight comes not only from recognizing which factor is limiting, but from seeing that *growth itself depletes or enhances limits* and therefore changes what is limiting. The interplay between a growing plant and the soil, a growing company and its market, a growing economy and its resource base, is dynamic. Whenever one factor ceases to be limiting, growth occurs, and the growth itself changes the relative scarcity of factors until another becomes limiting. To shift attention from the abundant factors to the next potential limiting factor is to gain real understanding of, and control over, the growth process.

Any physical entity with multiple inputs and outputs—a population, a production process, an economy—is surrounded by layers of limits. As the system develops, it interacts with and affects its own limits. The growing entity and its limited environment together form a coevolving dynamic system.

Understanding layers of limits and keeping an eye on the next upcoming limiting factor is not a recipe for perpetual growth, however. For any physical entity in a finite environment, perpetual growth is impossible. Ultimately, the choice is not to grow forever but to decide what limits to live within. If a company produces a perfect product or service at an affordable price, it will be swamped with orders until it grows to the point at which some limit decreases the perfection of the product or raises its price. If a city meets the needs of all its inhabitants better than any other city, people will flock there until some limit brings down the city's ability to satisfy peoples' needs.[6]

Any physical entity with multiple inputs and outputs is surrounded by layers of limits.

There always will be limits to growth. They can be self-imposed. If they aren't, they will be system-imposed. No physical entity can grow forever. If company managers, city governments, the human population do not choose and enforce their own limits to keep growth within the capacity of the supporting environment, then the environment will choose and enforce limits.

There always will be limits to growth. They can be self-imposed. If they aren't, they will be system-imposed.

Ubiquitous Delays

> I realize with fright that my impatience for the re-establishment of democracy had something almost communist in it; or, more generally, something rationalist. I had wanted to make history move ahead in the same way that a child pulls on a plant to make it grow more quickly.

> I believe we must learn to wait as we learn to create. We have to patiently sow the seeds, assiduously water the earth where they are sown and give the plants the time that is their own. One cannot fool a plant any more than one can fool history.
>
> —Václav Havel,[7] playwright, last President of Czechoslovakia and first president of the Czech Republic

It takes time for a plant or a forest or a democracy to grow; time for letters put into a mailbox to reach their destinations; time for consumers to absorb information about changing prices and alter their buying behavior, or for a nuclear power plant to be built, or a machine to wear out, or a new technology to penetrate an economy.

We are surprised over and over again at how much time things take. Jay Forrester used to tell us, when we were modeling a construction or processing delay, to ask everyone in the system how long they thought the delay was, make our best guess, and then multiply by three. (That correction factor also works perfectly, I have found, for estimating how long it will take to write a book!)

Delays are ubiquitous in systems. Every stock is a delay. Most flows have delays—shipping delays, perception delays, processing delays, maturation Here are just a few of the delays we have found important to include in various models we have made:

- The delay between catching an infectious disease and getting sick enough to be diagnosed—days to years, depending on the disease.
- The delay between pollution emission and the diffusion or percolation or concentration of the pollutant in the ecosystem to the point at which it does harm.
- The gestation and maturation delay in building up breeding populations of animals or plants, causing the characteristic oscillations of commodity prices: 4-year cycles for pigs, 7 years for cows, 11 years for cocoa trees.[8]

- The delay in changing the social norms for desirable family size—at least one generation.
- The delay in retooling a production stream and the delay in turning over a capital stock. It takes 3 to 8 years to design a new car and bring it to the market. That model may have 5 years of life on the new-car market. Cars stay on the road an average of 10 to 15 years.

Just as the appropriate boundaries to draw around one's picture of a system depend on the purpose of the discussion, so do the important delays. If you're worrying about oscillations that take weeks, you probably don't have to think about delays that take minutes, or years. If you're concerned about the decades-long development of a population and economy, you usually can ignore oscillations that take weeks. The world peeps, squawks, bangs, and thunders at many frequencies all at once. What is a significant delay depends—usually—on which set of frequencies you're trying to understand.

The systems zoo has already demonstrated how important delays in feedback are to the behavior of systems. Changing the length of a delay may utterly change behavior. Delays are often sensitive leverage points for policy, if they can be made shorter or longer. You can see why that is. If a decision point in a system (or a person working in that part of the system) is responding to delayed information, or responding with a delay, the decisions will be off target. Actions will be too much or too little to achieve the decision maker's goals. On the other hand, if action is taken too fast, it may nervously amplify short-term variation and create unnecessary instability. Delays determine how fast systems can react, how accurately they hit their targets, and how timely is the information passed around a system. Overshoots, oscillations, and collapses are always caused by delays.

Understanding delays helps one understand why Mikhail Gorbachev could transform the information system of the Soviet Union virtually overnight, but not the physical economy. (That takes decades.) It helps one see why the absorption of East Germany by West Germany produced more hardship over a longer time than the politicians foresaw. Because of long delays in building new power plants, the electricity industry is plagued with cycles of overcapacity and then undercapacity leading to brownouts. Because of decades-long delays as the earth's oceans respond to warmer temperatures, human fossil-fuel emissions have already induced changes in climate that will not be fully revealed for a generation or two.

> **When there are long delays in feedback loops, some sort of foresight is essential.** To act only when a problem becomes obvious is to miss an important opportunity to solve the problem.

Bounded Rationality

> As every individual, therefore, endeavours as much as he can both to employ his capital in the support of domestic industry, and so to direct that industry that its produce may be of greatest value. . . he generally, indeed, neither intends to promote the public interest, nor knows how much he is promoting it. . . . He intends his own security; . . . he intends only his own gain and he is in this . . . led by an invisible hand to promote an end which was no part of his intention. By pursuing his own interest he frequently promotes that of society more effectually than when he really intends to promote it.
>
> —Adam Smith,[9] 18th century political economist

It would be so nice if the "invisible hand" of the market really did lead individuals to make decisions that add up to the good of the whole. Then not only would material selfishness be a social virtue, but mathematical of the economy would be much easier to make. There would be no need to think about the good of other people or about the operations of complex feedback systems. No wonder Adam Smith's model has had such strong appeal for two hundred years!

Unfortunately, the world presents us with multiple examples of people acting rationally in their short-term best interests and producing aggregate results that no one likes. Tourists flock to places like Waikiki or Zermatt and then complain that those places have been ruined by all the tourists. Farmers produce surpluses of wheat, butter, or cheese, and prices plummet. Fishermen overfish and destroy their own livelihood. Corporations collectively make investment decisions that cause business-cycle downturns. Poor people have more babies than they can support.

Why?

Because of what World Bank economist Herman Daly calls the "invisible foot" or what Nobel Prize–winning economist Herbert Simon calls **bounded rationality**.[10]

Bounded rationality means that people make quite reasonable decisions based on the information they have. But they don't have perfect information, especially about more distant parts of the system. Fishermen don't know how many fish there are, much less how many fish will be caught by other fishermen that same day.

Businessmen don't know for sure what other businessmen are planning to invest, or what consumers will be willing to buy, or how their products will compete. They don't know their current market share, and they don't know the size of the market. Their information about these things is incomplete and delayed, and their own responses are delayed. So they systematically under- and overinvest.

We are not omniscient, rational optimizers, says Simon. Rather, we are blundering "satisficers," attempting to meet (*satisfy*) our needs well enough (*sufficiently*) before moving on to the next decision.[11] We do our best to further our own nearby interests in a rational way, but we can take into account only what we know. We don't know what others are planning to do, until they do it. We rarely see the full range of possibilities before us.

We often don't foresee (or choose to ignore) the impacts of our actions on the whole system. So instead of finding a long term optimum, we discover within our limited purview a choice we can live with for now, and we stick to it, changing our behavior only when forced to.

We don't even interpret perfectly the imperfect information that we do have, say behavioral scientists. We misperceive risk, assuming that some things are much more dangerous than they really are and others much less. We live in an exaggerated present—we pay too much attention to recent experience and too little attention to the past, focusing on current events rather than long term behavior. We discount the future at rates that make no economic or ecological sense. We don't give all incoming signals their appropriate weights. We don't let in at all news we don't like, or information that doesn't fit our mental models. Which is to say, we don't even make decisions that optimize our own individual good, much less the good of the system as a whole.

When the theory of bounded rationality challenged two hundred years of economics based on the teachings of political economist Adam Smith, you can imagine the controversy that resulted—one that is far from over. Economic theory as derived from Adam Smith assumes first that *homo economicus* acts with perfect optimality on complete information, and second that when many of the species *homo economicus* do that, their actions add up to the best possible outcome for everybody.

Neither of these assumptions stands up long against the evidence. In the next chapter on system traps and opportunities, I will describe some of the most commonly encountered structures that can cause bounded rationality to lead to disaster. They include such familiar phenomena as addiction, policy resistance, arms races, drift to low performance, and the tragedy of the commons. For now, I want to make just one point about the biggest surprise that comes from not understanding bounded rationality.

Suppose you are for some reason lifted out of your accustomed place in society and put in the place of someone whose behavior you have never understood. Having been a staunch critic of government, you suddenly become part of government. Or having been a laborer in opposition to management, you become management (or vice versa). Perhaps having been an environmental critic of big business, you find yourself making environmental decisions for big business. Would that such transitions could happen much more often, in all directions, to broaden everyone's horizons!

In your new position, you experience the information flows, the incentives and disincentives, the goals and discrepancies, the pressures—the bounded rationality—that goes with that position. It's possible that you retain your memory of how things look from another angle, and that you burst forth with innovations that transform the system, but it's distinctly unlikely. If you become a manager, you probably will stop seeing labor as a deserving partner in production, and start seeing it as a cost to be minimized. If you become a financier, you probably will overinvest during booms and underinvest during busts, along with all the other financiers. If you become very poor, you will see the short-term rationality, the hope, the opportunity, the necessity of having many children. If you are now a fisherman with a mortgage on your boat, a family to support, and imperfect knowledge of the state of the fish population, you will overfish.

We teach this point by playing games in which students are put into situations in which they experience the realistic, partial information streams seen by various actors in real systems. As simulated fishermen, they over fish. As ministers of simulated developing nations, they favor the needs of their industries over the needs of their people. As the upper class, they feather their own nests; as the lower class, they become apathetic or rebellious. So would you. In the famous Stanford prison experiment by psychologist Philip Zimbardo, players even took on, in an amazingly short time, the attitudes and behaviors of prison guards and prisoners.[12]

Seeing how individual decisions are rational within the bounds of the information available does not provide an excuse for narrow-minded behavior. It provides an understanding of why that behavior arises. Within the bounds of what a person in that part of the system can see and know, the behavior is reasonable. Taking out one individual from a position of bounded rationality and putting in another person is not likely to make much difference. Blaming the individual rarely helps create a more desirable outcome.

Change comes first from stepping outside the limited information that can be seen from any single place in the system and getting an overview. From a wider perspective, information flows, goals, incentives, and disincentives can be restructured so that separate, bounded, rational actions do add up to results that everyone desires.

It's amazing how quickly and easily behavior changes can come, with even slight enlargement of bounded rationality, by providing better, more complete, timelier information.

INTERLUDE • ***Electric Meters in Dutch Houses***

Near Amsterdam, there is a suburb of single-family houses all built at the same time, all alike. Well, nearly alike. For unknown reasons it happened that some of the houses were built with the electric meter down in the basement. In other houses, the electric meter was installed in the front hall.

These were the sort of electric meters that have a glass bubble with a small horizontal metal wheel inside. As the household uses more electricity, the wheel turns faster and a dial adds up the accumulated kilowatt-hours.

During the oil embargo and energy crisis of the early 1970s, the Dutch began to pay close attention to their energy use. It was discovered that some of the houses in this subdivision used one-third less electricity than the other houses. No one could explain this. All houses were charged the same price for electricity, all contained similar families.

The difference, it turned out, was in the position of the electric meter. The families with high electricity use were the ones with the meter in the basement, where people rarely saw it. The ones with low use had the meter in the front hall where people passed, the little wheel turning around, adding up the monthly electricity bill many times a day.[13]

Some systems are structured to function well despite bounded rationality. The right feedback gets to the right place at the right time. Under ordinary circumstances, your liver gets just the information it needs to do its job. In undisturbed ecosystems and traditional cultures, the average individual, species, or population, left to its own devices, behaves in ways that serve and stabilize the whole. These systems and others are self-regulatory. They do not cause problems. We don’t have government agencies and dozens of failed policies about them.

Since Adam Smith, it has been widely believed that the free, competitive market is one of these properly structured self-regulating systems. In some ways, it is. In other ways, obvious to anyone who is willing to look, it isn’t. A free market does allow producers and consumers, who have the best information about production opportunities and consumption choices, to make fairly uninhibited and locally rational decisions. But those decisions can’t, by themselves, correct the overall system’s tendency to create monopolies and undesirable side effects (externalities), to discriminate against the poor, or to overshoot its sustainable carrying capacity.

To paraphrase a common prayer: God grant us the serenity to exercise our bounded rationality freely in the systems that are structured appropriately, the courage to restructure the systems that aren’t, and the wisdom to know the difference!

The bounded rationality of each actor in a system—determined by the information, incentives, disincentives, goals, stresses, and constraints impinging on that actor—may or may not lead to decisions that further the welfare of the system as a whole. If they do not, putting new actors into the same system will not improve the system’s performance. What makes a difference is redesigning the system to improve the information, incentives, disincentives, goals, stresses, and constraints that have an effect on specific actors.

The bounded rationality of each actor in a system may not lead to decisions that further the welfare of the system as a whole.