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

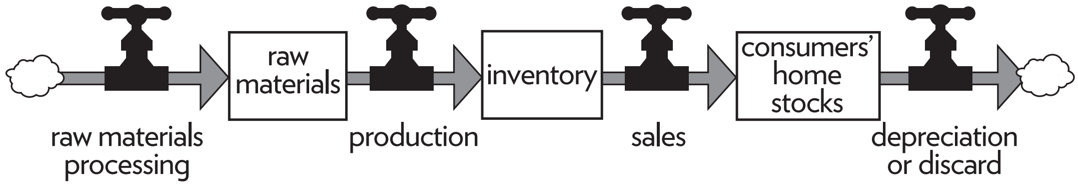

Figure 47. Revealing some of the stocks behind the clouds.

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.

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 and 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 CO_2 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.

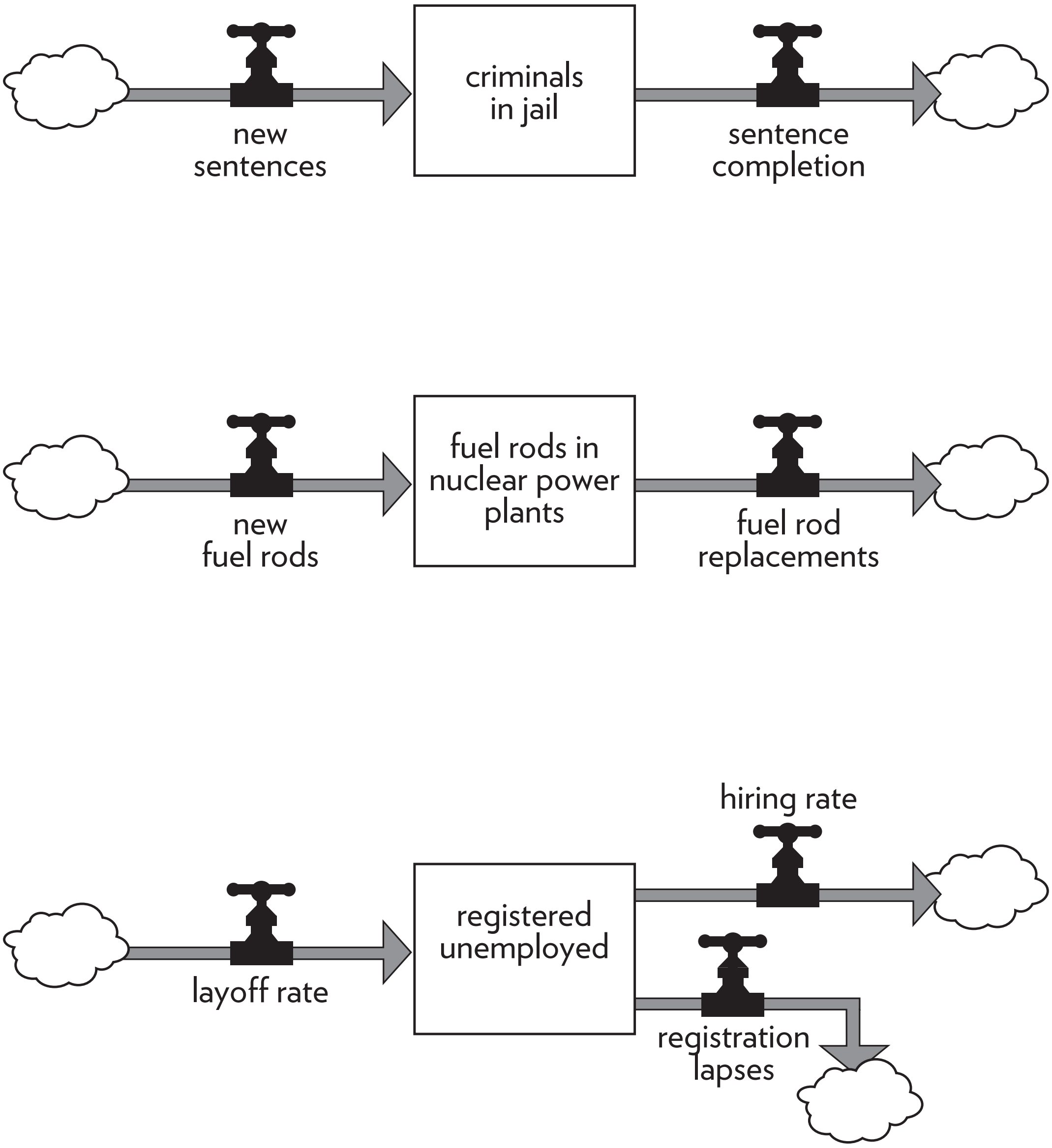

Figure 49. Examples of more clouds. These are systems in which a boundary or cloud should not stop you from thinking beyond the borders of the system, but start you thinking beyond those borders. What is driving the supply of people being given new sentences? Where do the fuel rods go after replacement? 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 and 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 delays. 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 models 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 could 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 overfish. 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.