Changing the delays in a system can make it much easier or much harder to manage. You can see why system thinkers are somewhat fanatic on the subject of delays. We're always on the alert to see where delays occur in systems, how long they are, whether they are delays in information streams or in physical processes. We can't begin to understand the dynamic behavior of systems unless we know where and how long the delays are. And we are aware that some delays can be powerful policy levers. Lengthening or shortening them can produce major changes in the behavior of systems.

In the big picture, one store's inventory problem may seem trivial and fixable. But imagine that the inventory is that of all the unsold automobiles in America. Orders for more or fewer cars affect production not only at assembly plants and parts factories, but also at steel mills, rubber and glass plants, textile producers, and energy producers. Everywhere in this system are perception delays, production delays, delivery delays, and construction delays. Now consider the link between car production and jobs—increased production increases the number of jobs allowing more people to buy cars. That's a reinforcing loop, which also works in the opposite direction—less production, fewer jobs, fewer car sales, less production. Put in another reinforcing loop, as speculators buy and sell shares in the auto and auto-supply companies based on their recent performance, so that an upsurge in production produces an upsurge in stock price, and vice versa.

That very large system, with interconnected industries responding to each other through delays, entraining each other in their oscillations, and being amplified by multipliers and speculators, is the primary cause of business cycles. Those cycles don't come from presidents, although presidents can do much to ease or intensify the optimism of the upturns and the pain of the downturns. Economies are extremely complex systems; they are full of balancing feedback loops with delays, and they are inherently oscillatory.[5]

Two-Stock Systems

A Renewable Stock Constrained by a Nonrenewable Stock—an Oil Economy

The systems I've displayed so far have been free of constraints imposed by their surroundings. The capital stock of the industrial economy model didn't require raw materials to produce output. The population didn't need food. The thermostat-furnace system never ran out of oil. These simple models of the systems have been able to operate according to their unconstrained internal dynamics, so we could see what those dynamics are.

But any real physical entity is always surrounded by and exchanging things with its environment. A corporation needs a constant supply of energy and materials and workers and managers and customers. A growing corn crop needs water and nutrients and protection from pests. A population needs food and water and living space, and if it's a human population, it needs jobs and education and health care and a multitude of other things. Any entity that is using energy and processing materials needs a place to put its wastes, or a process to carry its wastes away.

Therefore, any physical, growing system is going to run into some kind of constraint, sooner or later. That constraint will take the form of a balancing loop that in some way shifts the dominance of the reinforcing loop driving the growth behavior, either by strengthening the outflow or by weakening the inflow.

Growth in a constrained environment is very common, so common that systems thinkers call it the "limits-to-growth" archetype. (We'll explore more archetypes—frequently found system structures that produce familiar behavior patterns—in Chapter Five.) Whenever we see a growing entity, whether it be a population, a corporation, a bank account, a rumor, an epidemic, or sales of a new product, we look for the reinforcing loops that are driving it and for the balancing loops that ultimately will constrain it. We know those balancing loops are there, even if they are not yet dominating the system's behavior, because no real physical system can grow forever. Even a hot new product will saturate the market eventually. A chain reaction in a nuclear power plant or bomb will run out of fuel. A virus will run out of susceptible people to infect. An economy may be constrained by physical capital or monetary capital or labor or markets or management or resources or pollution.

In physical, exponentially growing systems, there must be at least one reinforcing loop driving the growth *and* at least one balancing loop constraining the growth, because no physical system can grow forever in a finite environment.

Like resources that supply the inflows to a stock, a pollution constraint can be renewable or nonrenewable. It's nonrenewable if the environment has no capacity to absorb the pollutant or make it harmless. It's renewable if the environment has a finite, usually variable, capacity for removal. Everything said here about resource-constrained systems, therefore, applies with the same dynamics but opposite flow directions to pollution-constrained systems.

The limits on a growing system may be temporary or permanent. The system may find ways to get around them for a short while or a long while, but eventually there must come some kind of accommodation, the system adjusting to the constraint, or the constraint to the system, or both to each other. In that accommodation come some interesting dynamics.

Whether the constraining balancing loops originate from a renewable or nonrenewable resource makes some difference, not in whether growth can continue forever, but in how growth is likely to end.

Let's look, to start, at a capital system that makes its money by extracting a nonrenewable resource—say an oil company that has just discovered a huge new oil field. See Figure 37.

The diagram in Figure 37 may look complicated, but it's no more than

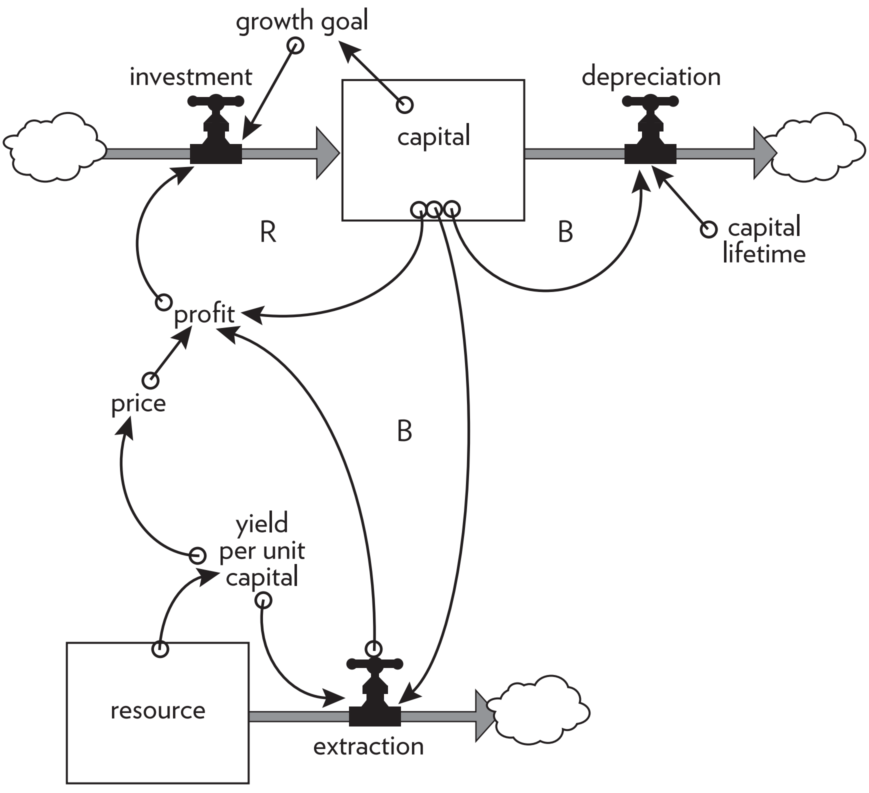

Figure 37. Economic capital, with its reinforcing growth loop constrained by a nonrenewable resource.

a capital-growth system like the one we've already seen, using "profit" instead of "output." Driving depreciation is the now-familiar balancing loop: the more capital stock, the more machines and refineries there are that fall apart and wear out, reducing the stock of capital. In this example, the capital stock of oil drilling and refining equipment depreciates with a 20-year lifetime—meaning 1/20 (or 5 percent) of the stock is taken out of commission each year. It builds itself up through investment of profits from oil extraction. So we see the reinforcing loop: More capital allows more resource extraction, creating more profits that can be reinvested. I've assumed that the company has a goal of 5 percent annual growth in its business capital. If there isn't enough profit for 5 percent growth, the company invests whatever profits it can.

Profit is income minus cost. Income in this simple representation is just the price of oil times the amount of oil the company extracts. Cost is equal to capital times the operating cost (energy, labor, materials, etc.) per unit of capital. For the moment, I'll make the simplifying assumptions that both price and operating cost per unit of capital are constant.

What is not assumed to be constant is the yield of resource per unit of capital. Because this resource is not renewable, as in the case of oil, the stock feeding the extraction flow does not have an input. As the resource is extracted—as an oil well is depleted—the next barrel of oil becomes harder to get. The remaining resource is deeper down, or more dilute, or in the case of oil, under less natural pressure to force it to the surface. More and more costly and technically sophisticated measures are required to keep the resource coming.

Here is a new balancing feedback loop that ultimately will control the growth of capital: the more capital, the higher the extraction rate. The higher the extraction rate, the lower the resource stock. The lower the resource stock, the lower the yield of resource per unit of capital, so the lower the profit (with price assumed constant) and the lower the investment rate—therefore, the lower the rate of growth of capital. I could assume that resource depletion feeds back through operating cost as well as capital efficiency. In the real world it does both. In either case, the ensuing behavior pattern is the same—the classic dynamics of depletion (see Figure 38).

The system starts out with enough oil in the underground deposit to supply the initial scale of operation for 200 years. But, actual extraction peaks at about 40 years because of the surprising effect of exponential

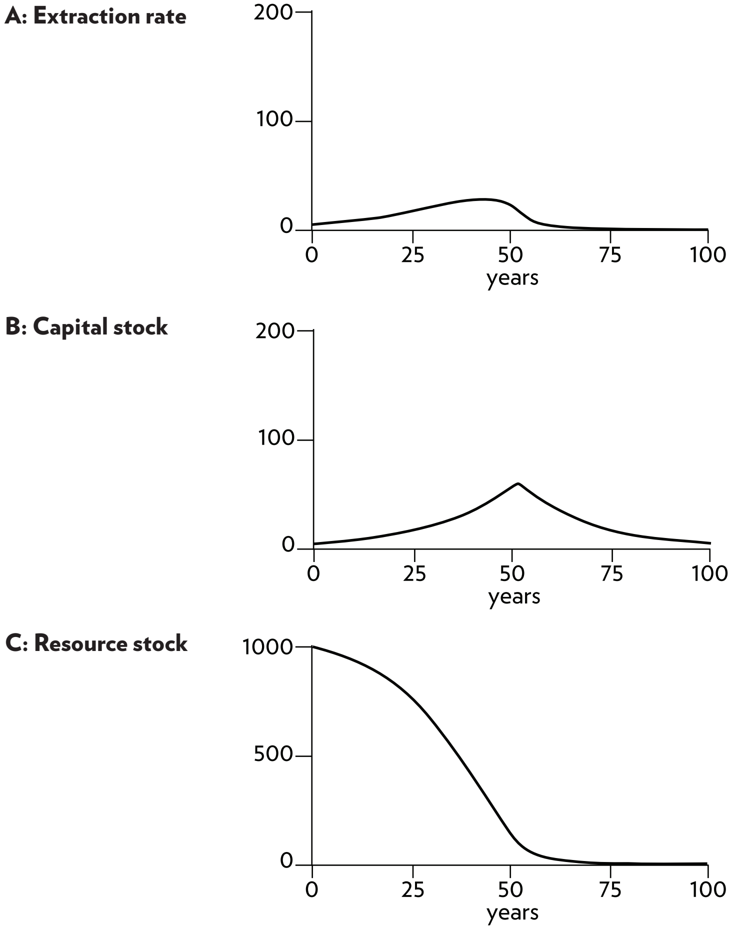

Figure 38. Extraction (A) creates profits that allow for growth of capital (B) while depleting the nonrenewable resource (C). The greater the accumulation of capital, the faster the resource is depleted.

growth in extraction. At an investment rate of 10 percent per year, the capital stock and therefore the extraction rate both grow at 5 percent per year and so double in the first 14 years. After 28 years, while the capital stock has quadrupled, extraction is starting to lag because of falling yield per unit of capital. By year 50 the cost of maintaining the capital stock has overwhelmed the income from resource extraction, so profits are no longer sufficient to keep investment ahead of depreciation. The operation quickly shuts down, as the capital stock declines. The last and most expensive of the resource stays in the ground; it doesn't pay to get it out.

What happens if the original resource turns out to be twice as large as the geologists first thought—or four times as large? Of course, that makes a huge difference in the total amount of oil that can be extracted from this field. But with the continued goal of 10 percent per year reinvestment producing 5 percent per year capital growth, each doubling of the resource makes a difference of only about 14 years in the timing of the peak extraction rate, and in the lifetime of any jobs or communities dependent on the extraction industry (see Figure 39).

A quantity growing exponentially toward a constraint or limit reaches that limit in a surprisingly short time.

The higher and faster you grow, the farther and faster you fall, when you're building up a capital stock dependent on a nonrenewable resource. In the face of exponential growth of extraction or use, a doubling or quadrupling of the nonrenewable resource give little added time to develop alternatives.

If your concern is to extract the resource and make money at the maximum possible rate, then the ultimate size of the resource is the most important number in this system. If, say, you're a worker at the mine or oil field, and your concern is with the lifetime of your job and stability of your community, then there are two important numbers: the size of the resource and the desired growth rate of capital. (Here is a good example of the goal of a feedback loop being crucial to the behavior of a system.) The real choice in the management of a nonrenewable resource is whether to get rich very fast or to get less rich but stay that way longer.

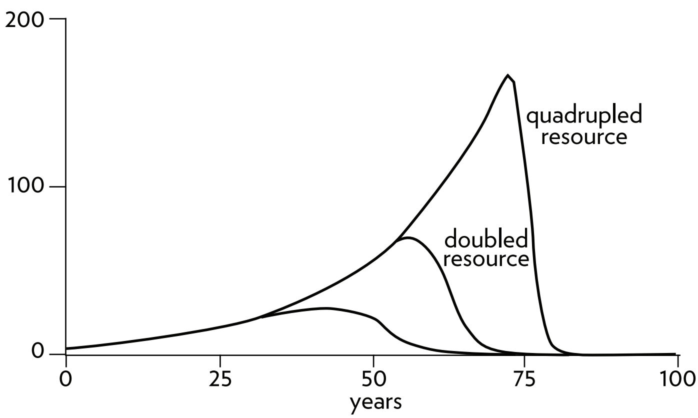

Figure 39. Extraction with two times or four times as large a resource to draw on. Each doubling of the resource makes a difference of only about fourteen years in the peak of extraction.

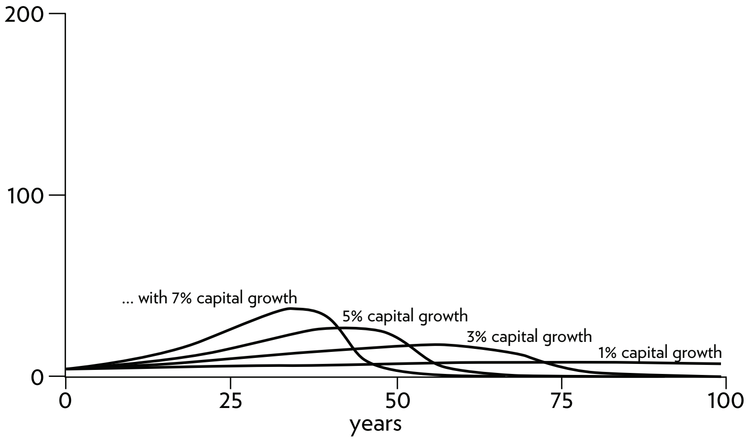

Figure 40. The peak of extraction comes much more quickly as the fraction of profits reinvested increases.

The graph in Figure 40 shows the development of the extraction rate over time, given desired growth rates above depreciation varying from 1 percent annually, to 3 percent, 5 percent, and 7 percent. With a 7 percent growth rate, extraction of this "200-year supply" peaks within 40 years. Imagine the effects of this choice not only on the profits of the company, but on the social and natural environments of the region.

Earlier I said I would make the simplifying assumption that price was constant. But what if that's not true? Suppose that in the short term the resource is so vital to consumers that a higher price won't decrease demand. In that case, as the resource gets scarce and price rises steeply, as shown in Figure 41.

The higher price gives the industry higher profits, so investment goes up, capital stock continues rising, and the more costly remaining resources can be extracted. If you compare Figure 41 with Figure 38, where price was held constant, you can see that the main effect of rising price is to build the capital stock higher before it collapses.

The same behavior results, by the way, if prices don't go up but if technology brings operating costs down—as has actually happened, for example, with advanced recovery techniques from oil wells, with the beneficiation process to extract low-grade taconite from exhausted iron mines, and with the cyanide leaching process that allows profitable extraction even from the tailings of gold and silver mines.

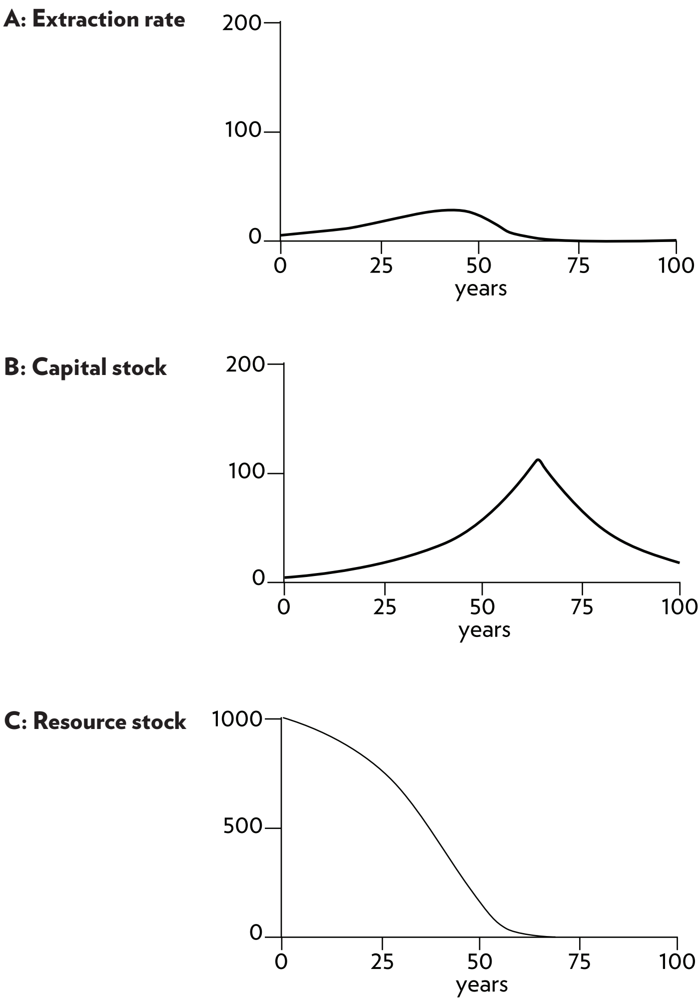

Figure 41. As price goes up with increasing scarcity, there is more profit to reinvest, and the capital stock can grow larger (B) driving extraction up for longer (A). The consequence is that the resource (C) is depleted even faster at the end.

We all know that individual mines and fossil fuel deposits and groundwater aquifers can be depleted. There are abandoned mining towns and oil fields all over the world to testify to the reality of the behavior we've seen here. Resource companies understand this dynamic too. Well before depletion makes capital less efficient in one place, companies shift investment to discovery and development of another deposit somewhere else. But, if there are local limits, eventually will there be global ones?

I'll leave you to have this argument with yourself, or with someone of the opposite persuasion. I will just point out that, according to the dynamics of depletion, the larger the stock of initial resources, the more new discoveries, the longer the growth loops elude the control loops, and the higher the capital stock and its extraction rate grow, and the earlier, faster, and farther will be the economic fall on the back side of the production peak.

Unless, perhaps, the economy can learn to operate entirely from renewable resources.

Renewable Stock Constrained by a Renewable Stock—a Fishing Economy

Assume the same capital system as before, except that now there is an inflow to the resource stock, making it renewable. The renewable resource in this system could be fish and the capital stock could be fishing boats. It also could be trees and sawmills, or pasture and cows. Living renewable resources such as fish or trees or grass can regenerate themselves from themselves with a reinforcing feedback loop. Nonliving renewable resources such as sunlight or wind or water in a river are regenerated not through a reinforcing loop, but through a steady input that keeps refilling the resource stock no matter what the current state of that stock might be. This same "renewable resource system" structure occurs in an epidemic of a cold virus. It spares its victims who are then able to catch another cold. Sales of a product people need to buy regularly is also a renewable resource system; the stock of potential customers is ever regenerated. Likewise an insect infestation that destroys part but not all of a plant; the plant can regenerate and the insect can eat more. In all these cases, there is an input that keeps refilling the constraining resource stock (as shown in Figure 42).

We will use the example of a fishery. Once again, assume that the lifetime of capital is 20 years and the industry will grow, if it can, at 5 percent per year. As with the nonrenewable resource, assume that as the resource gets scarce it costs more, in terms of capital, to harvest it. Bigger fishing boats that can go longer distances and are equipped with sonar are needed to find the last schools of fish. Or miles-long drift nets are needed to catch them. Or on-board refrigeration systems are needed to bring them back to port from longer distances. All this takes more capital.

The regeneration rate of the fish is not constant, but is dependent on the number of fish in the area—fish density. If the fish are very dense, their reproduction rate is near zero, limited by available food and habitat. If the fish population falls a bit, it can regenerate at a faster and faster rate,

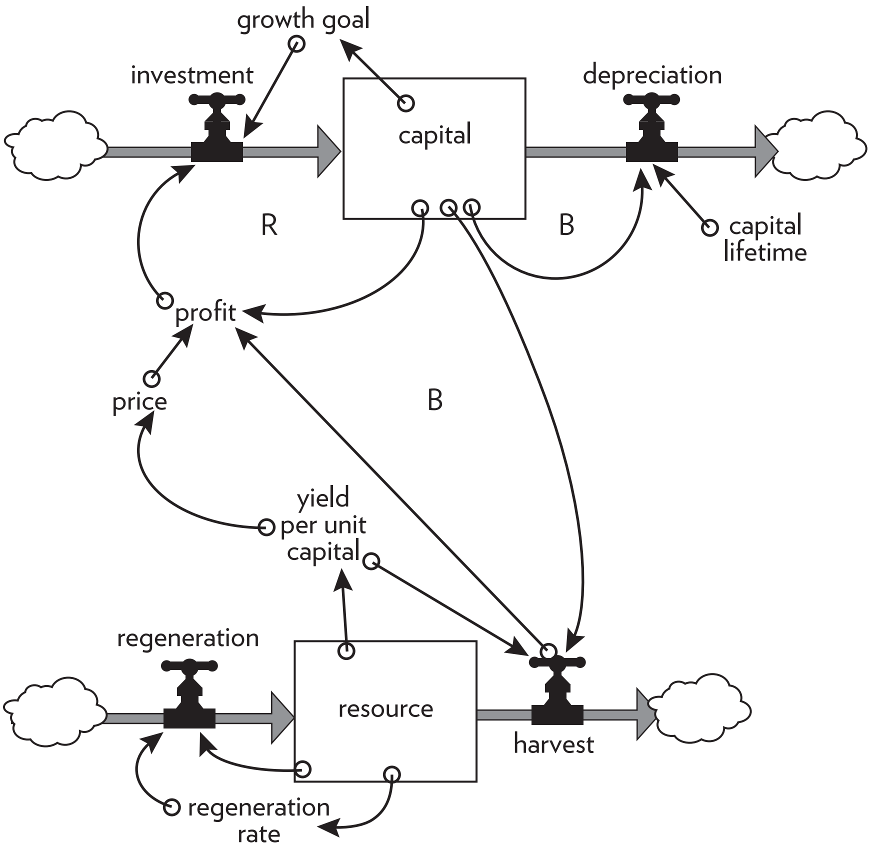

Figure 42. Economic capital with its reinforcing growth loop constrained by a renewable resource.

because it can take advantage of unused nutrients or space in the ecosystem. But at some point the fish reproduction rate reaches its maximum. If the population is further depleted, it breeds not faster and faster, but slower and slower. That's because the fish can't find each other, or because another species has moved into its niche.

This simplified model of a fishery economy is affected by three nonlinear relationships: price (scarcer fish are more expensive); regeneration rate (scarcer fish don't breed much, nor do crowded fish); and yield per unit of capital (efficiency of the fishing technology and practices).

This system can produce many different sets of behaviors. Figure 43 shows one of them.

In Figure 43, we see capital and fish harvest rise exponentially at first.

The fish population (the resource stock) falls, but that stimulates the fish reproduction rate. For decades the resource can go on supplying an exponentially increasing harvest rate. Eventually, the harvest rises too far and the fish population falls low enough to reduce the profitability of the fishing fleet. The balancing feedback of falling harvest reducing profits brings

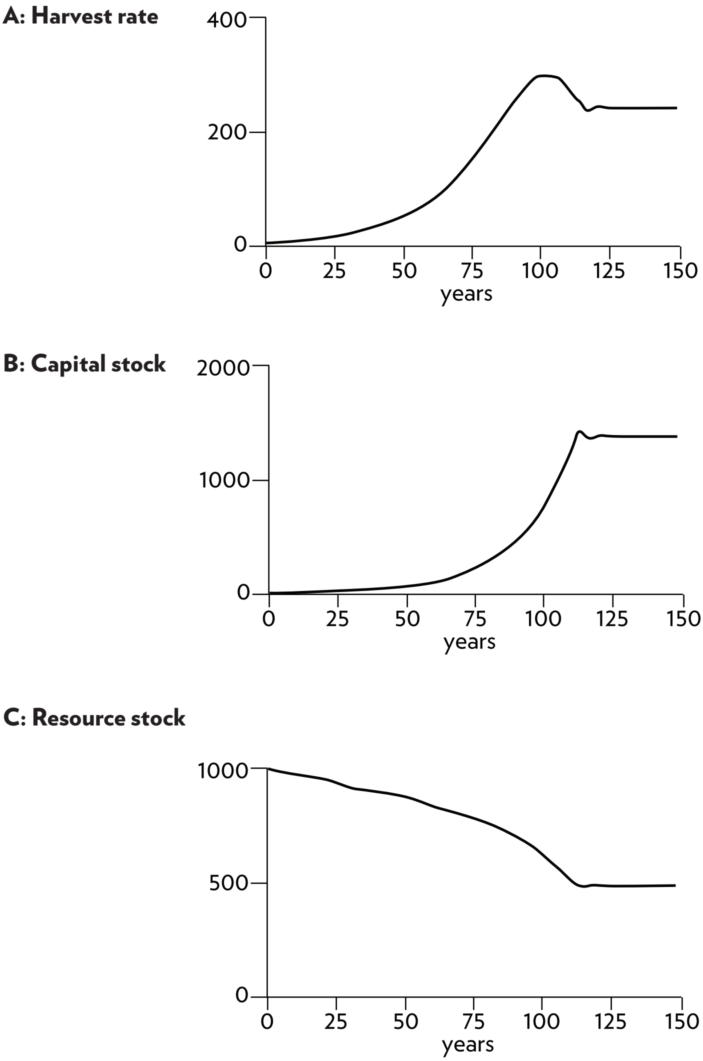

Figure 43. Annual harvest (A) creates profits that allow for growth of capital stock (B), but the harvest levels off, after a small overshoot in this case. The result of leveling harvest is that the resource stock (C) also stabilizes.

down the investment rate quickly enough to bring the fishing fleet into equilibrium with the fish resource. The fleet can't grow forever, but it can maintain a high and steady harvest rate forever.

Just a minor change in the strength of the controlling balancing feedback loop through yield per unit of capital, however, can make a surpris-

A: Harvest rate

B: Capital stock

C: Resource stock

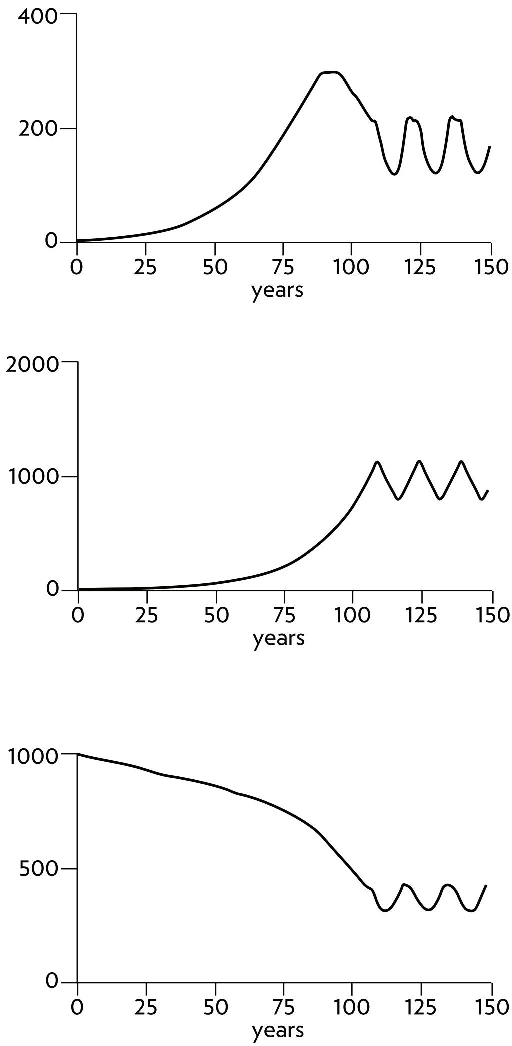

Figure 44. A slight increase in yield per unit of capital—increasingly efficient technology in this case—creates a pattern of overshoot and oscillation around a stable value in the harvest rate (A), the stock of economic capital (B), and in the resource stock.

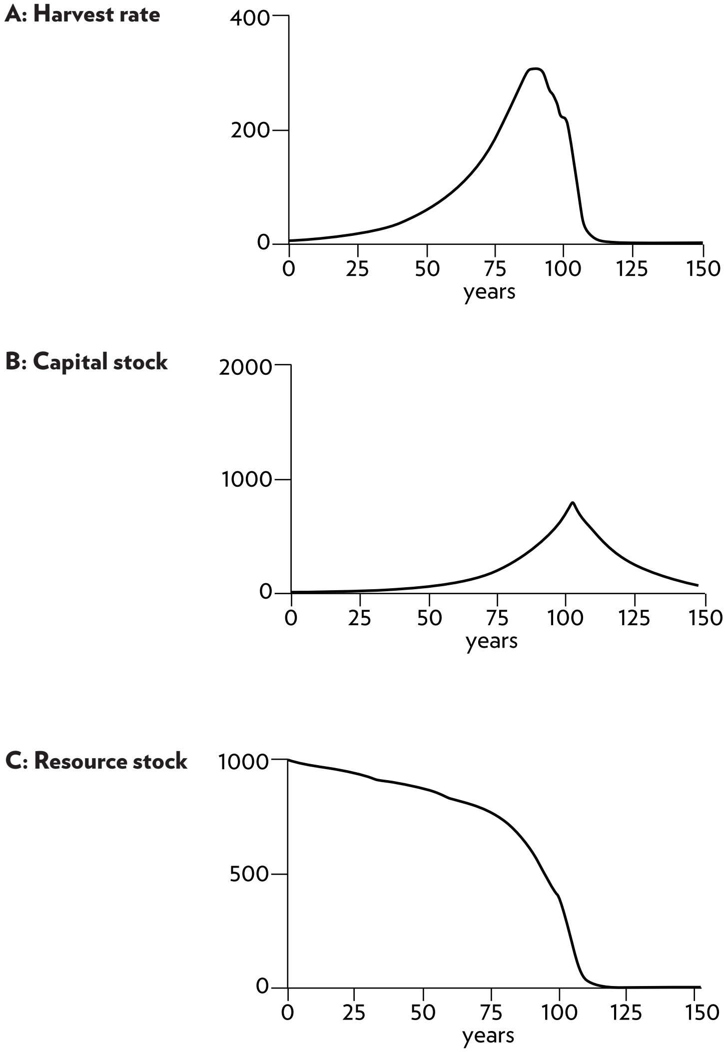

Figure 45. An even greater increase in yield per unit of capital creates a patterns of overshoot and collapse in the harvest (A), the economic capital (B), and the resource (C).

ing difference. Suppose that in an attempt to raise the catch in the fishery, the industry comes up with a technology to improve the efficiency of the boats (sonar, for example, to find the scarcer fish). As the fish population declines, the fleet's ability to pull in the same catch per boat is maintained just a little longer (see Figure 44).

Figure 44 shows another case of high leverage, wrong direction! This technical change, which increases the productivity of all fishermen, throws the system into instability. Oscillations appear!

If the fishing technology gets even better, the boats can go on operating economically even at very low fish densities. The result can be a nearly complete wipeout both of the fish and of the fishing industry. The consequence is the marine equivalent of desertification. The fish have been turned, for all practical purposes, into a nonrenewable resource. Figure 45 illustrates this scenario.

In many real economies based on real renewable resources—as opposed to this simple model—the very small surviving population retains the potential to build its numbers back up again, once the capital driving the harvest is gone. The whole pattern is repeated, decades later. Very long-term renewable-resource cycles like these have been observed, for example, in the logging industry in New England, now in its third cycle of growth, overcutting, collapse, and eventual regeneration of the resource. But this is not true for all resource populations. More and more, increases in technology and harvest efficiency have the ability to drive resource populations to extinction.

Nonrenewable resources are *stock*-limited. The entire stock is available at once, and can be extracted at any rate (limited mainly by extraction capital). But since the stock is not renewed, the faster the extraction rate, the shorter the lifetime of the resource.

Renewable resources are *flow*-limited. They can support extraction or harvest indefinitely, but only at a finite flow rate equal to their regeneration rate. If they are extracted faster than they regenerate, they may eventually be driven below a critical threshold and become, for all practical purposes, nonrenewable.

Whether a real renewable resource system can survive overharvest depends on what happens to it during the time when the resource is severely depleted. A very small fish population may become especially vulnerable to pollution or storms or lack of genetic diversity. If this is a forest or grassland resource, the exposed soils may be vulnerable to erosion. Or the nearly empty ecological niche may be filled in by a competitor. Or perhaps the depleted resource can survive and rebuild itself again.

I've shown three sets of possible behaviors of this renewable resource system here:

- overshoot and adjustment to a sustainable equilibrium,

- overshoot beyond that equilibrium followed by oscillation around it, and
- overshoot followed by collapse of the resource and the industry dependent on the resource.

Which outcome actually occurs depends on two things. The first is the critical threshold beyond which the resource population's ability to regenerate itself is damaged. The second is the rapidity and effectiveness of the balancing feedback loop that slows capital growth as the resource becomes depleted. If the feedback is fast enough to stop capital growth before the critical threshold is reached, the whole system comes smoothly into equilibrium. If the balancing feedback is slower and less effective, the system oscillates. If the balancing loop is very weak, so that capital can go on growing even as the resource is reduced below its threshold ability to regenerate itself, the resource and the industry both collapse.

Neither renewable nor nonrenewable limits to growth allow a physical stock to grow forever, but the constraints they impose are dynamically quite different. The difference comes because of the difference between stocks and flows.

The trick, as with all the behavioral possibilities of complex systems, is to recognize what structures contain which latent behaviors, and what conditions release those behaviors—and, where possible, to arrange the structures and conditions to reduce the probability of destructive behaviors and to encourage the possibility of beneficial ones.