



The Role of Models for Good and Evil

- 20.1 Definitions: Models and Analytic vs. Simulation Models – 426
 - 20.2 Models and Reality – 427
 - 20.3 The Importance of Paradigms – 428
 - 20.4 Paradigms and Models – 429
 - 20.5 So, then, Why Is Economics, Which Is So Complex, So Analytical? – 430
 - 20.6 How Have Models in Fact Been Used in Economics – 431
 - 20.7 Some Problems with the Standard Neoclassical Model – 432
 - 20.8 If the Basic Neoclassical Model Is Unrealistic, Why Do Economists Continue to Use It? – 432
 - 20.9 A Final Thought on the Proper Use of Mathematics – 435
 - 20.10 Now We Will Appear to Contradict Ourselves – 436
- References – 436

The words “model” and “modeling” are found increasingly in economics and indeed in science in general. Therefore, it is important that we consider here some of the most important characteristics of these words and concepts and introduce the reader to how they are used in energy studies and in economics. Most generally the word “model” means a simplification. For example, we all work with models of human behavior that a person will act in a particular way because he or she is a teenager, a man, a woman, rich, poor, black, white, or whatever. Of course one of the important aspects of growing up is to realize that such models are wrong so often that they are essentially useless and that we need to meet and judge people one person at a time. So perhaps one of the most important things you can learn about models of any kind is that they are often wrong. But often they are correct, and usually, even when incorrect, they can be useful by allowing us to generate and test hypotheses formally. So armed with a healthy skepticism we can go on to see what models really are. This chapter is in some respects a continuation of ► Chap. 16 on mathematical tools and our earlier work in ecology [1].

20.1 Definitions: Models and Analytic vs. Simulation Models

There are many definitions of the word “model.” One, given above, is a purposive simplification, such as a model airplane. A second is “a device for predicting a complex whole from the operation of parts that are thought to be known.” The definition that we like the most, from Hall and Day [1], is “a formalization of our assumptions about a system.” Whether we formalize them or not, we use models constantly: models of scientific outcome, models of economic decisions, models of your own behavior, or that of others. In our view, quantitative (or occasionally non-quantitative) models are necessary in the complex world of ecology and economics because they allow one to apply the scientific method to complex real systems. Despite the many problems of modeling, we do not understand how one can use the scientific method (i.e., to generate and test hypotheses) for any reasonably complicated system without the use of formal modeling. This is as true for

management and policy-related issues as for theoretical ones.

The power of models is to make our assumptions explicit, and hence testable. The power of mathematics (in its broad sense) and of mathematical models is to make the results of the prediction *quantitatively* explicit and hence quantitatively predictable. Generally we are seeking a *solution*, that is, a quantitative prediction for the value of some variable at some different place or time. The process of examining whether a model is correct or at least adequate is called *validation*. The examination of the degree to which uncertainty in model formulation or (more generally) parameterization allows you to trust your results, or reach certain conclusions, is called *sensitivity analysis*. It is through validation and sensitivity analysis that models generate their (occasional) tremendous power in resolving truth, such as that is accessible to the human mind.

What then is the role of mathematics in this process? First of all, it is necessary to distinguish *mathematical* from *quantitative*. Quantitative means simply using appropriate numbers in your analysis: 3 salmon vs 7 salmon. This does not necessarily require any particular mathematical skills (although getting accurate numbers may require enormous skills of a different kind). Mathematical means using the complex tools of quantitative analysis to manipulate those numbers, often to make a prediction, that is, an educated guess of the value of something modeled (such as oil production or GDP). These tools include algebra, geometry, calculus, simulation, and so on. There are two principle means of manipulating or solving numbers: *analytic* (or closed form) and *numeric* (or simulation). The first, generally using paper and pencil, gives usually explicit and exact solutions to relatively simple equations for a particular point in time or set of conditions, generally using rather complex and difficult equations (e.g., see ► Chap. 16). The second gives approximate answers to a broader set of possible equations using (generally) simpler equations put together in complex patterns and solved stepwise *in a computer*. In theory, either method can be used to solve many particular quantitative problems, and sometimes this is done. In practice the mathematical training required to undertake analytic approaches precludes its use by many. In addition there are severe restrictions to the class of mathematical problems that can be solved analytically, often requiring a series of

sometimes unrealistic assumptions to put the problem into a mathematically tractable format. On the other hand, simulation allows one to solve very complex problems using relatively simple mathematics. Hence, there is a curious paradox: the most complex mathematics actually requires the simplest basic equations for starters.

A final problem is that there has been frequent confusion between *mathematical* and *scientific rigor* or *proof*. Mathematics can generate real proofs relatively easily because you are working in a defined universe (through the assumptions and the equations used) to which it applies. If you define a straight line as the shortest distance between two points, then you can solve many problems requiring straight lines. But the world handed to us by nature is not so defined, and we must constantly struggle to represent it with our equations. Hence, a mathematical proof becomes a scientific proof only in the relatively rare circumstances when the equations do indeed capture the essence of the problem.

20.2 Models and Reality

The truth of the matter is that humans have often found that models of reality are much easier to deal with conceptually and operationally than reality itself, which tends to be very messy. There is a very long history of models getting in the way of truth, and this continues today. Perhaps the clearest and oldest example of both the strength and the potential fallacies of models are those associated with our understanding of astronomy. Most educated ancients were extremely interested in astronomy because of their belief that the movements of heavenly bodies had great importance to their day-to-day affairs (this lives on today as astrology). Sometimes the reasons were clear and scientific. As agriculture became more and more important, it became obvious that an understanding of the movement of the sun North and South with the seasons was a much more reliable index of when to plant than was temperature, which could not be measured anyway and which varied much more than the stately daily progression of the sun. Thus, the ancients built entire buildings and even cities to help measure the movement of the sun and other heavenly bodies, as beautifully told by archaeoastronomers such as Anthony Aveni [2]. These ancient astronomers

needed very large instruments in those times before the invention of brass instruments so that the relation of inaccuracies in construction was not too large compared to the size of the instruments. Consequently, they built entire cities that would track the movement of the sun and other heavenly bodies through the seasons. Those who planted according to the schedules of astronomer-priests tended to get rewarded with larger and more reliable crops, and political power flowed to the priests accordingly. Stonehenge, the pyramids of Egypt and Mexico, as well as many lesser known ancient cities are built, at least in part, as giant celestial observatories.

Most of these ancient astronomers thought that the sun, the moon, and the planets went around the Earth (after all it was obvious) and that all heavenly bodies traveled in perfect circles, since that would reflect the perfection of God—as well as God putting humans at the center of all things. Probably the greatest of these ancient astronomers was the Greek-Egyptian Ptolemy, and today we must understand him as a person with tremendous mathematical and modeling skills. Ptolemy could predict the seasons and even the movement of the planets with great precision and even predict when the Nile would flood even though the rain that caused this to occur was thousands of miles to the South. They were able to do this with relatively simple mathematics—with one exception. In order to explain the observations of the interior planets (Venus and Mercury), Ptolemy and his colleagues had to come up with a series of circular “epicycles” in which these planets circled the sun, which was circling the Earth. This was a remarkably successful approach to astronomy and could explain the observed data to within a few percent.

We now know that Ptolemy, who was a remarkably intelligent person and gifted mathematician, was dead wrong. It took more than a thousand years for the Polish astronomer Copernicus to come along and, with the extremely accurate sightings of Tycho Brahe, show that not only did the Earth revolve around the sun but that also the Earth did not follow a circular orbit, but rather an ellipse. The search for circular perfection over a thousand years had got in the way of understanding reality – that the earth went around the sun in an elliptical orbit. Or we might say putting too much faith in religious perfection got in the way of science. But for a long time, the incorrectly

developed model of Ptolemy was a better predictor than the correctly constructed model of Copernicus, because Ptolemy was such a good mathematician. Today there are many scientists and economists who do not wish to abandon mathematically “perfect” solutions for a more accurate but less elegant explanation.

Seeking perfect and simplified models in other disciplines has also interfered with understanding truth and reality. In fact it is probably more often the rule than the exception. The creation model from the bible of the origin of species story of the creation probably made as much sense as any other explanation until Charles Darwin came along and gave us a model that was much more consistent with our observations and the fossil record. God may certainly exist (that question is well outside the aegis of Science) but so does evolution. Just ask any hospital administrator or agricultural pest manager who has to deal with the routine evolution of hospital and agricultural pathogens. That is pretty hard to explain by the actions of a benevolent God. Meanwhile, apparently more Americans believe in Angels than in evolution.

For another example, fisheries science lost decades of understanding and ultimately contributed to the destruction of many of the world’s most important fisheries because fisheries scientists, hampered by the overwhelming complexity of interannual variations in numbers of a fish species, chose to believe a model, the Ricker curve, rather than to look more carefully at their own data. In fisheries science, for a long time, it was believed that the number of fish in a population (i.e., sockeye salmon in British Columbia) depended principally upon the number of parents, with there being the possibility of both too few and too many parents for maximum production of young. This idea “allowed” managers to let fishermen take large numbers of salmon that had been considered “excess.” More recent work has shown that the main determinants of the salmon populations are climate and other environmental factors, although number of parents may also be important although not necessarily in the way initially proposed [3, 4]. More generally in population biology, it has become clear that the simple, elegant mathematical models that once dominated thinking about populations were almost certainly misleadingly incomplete when not entirely wrong [5]. But we have learned, and now it is usually the

case that we use ongoing data from the fisheries itself to set the seasons and otherwise manage the fish through “adaptive management” (where politics or too much greed does not get in the way). Likewise, ecologists and game managers believed for too long in the simplistic, “perfect,” and almost always wrong logistic and Lotka-Volterra mathematical models of population dynamics, rather than to concentrate on the environmental factors that were generally far more powerful predictors of actual populations. The point is that in all of these issues, there is a huge tendency for people to want to believe in models of perfection rather than in the messy reality that surrounds us, although usually that too can be understood, even if painfully slowly, by a proper use of science.

20.3 The Importance of Paradigms

Models are far more than complex mathematical entities that live in mathematics books or in computers. More generally models are *conceptual*—that is, mental pictures of the structure and/or function of a system or of how something operates. Such conceptual models are often called *paradigms* when they become expansive and general. Nearly all disciplines, including economics, work from what is usually called a paradigm or a set of paradigms. Paradigms (sometimes called “pre-analytical visions”) are conceptual constructs that synthesize the main ideas of a discipline, explain a wide set of observations, and allow for the positioning of new ideas into the existing intellectual structure. Examples include evolution in biology and plate tectonics in geology. Before Charles Darwin’s synthesis in 1859, there were many observations of nature that simply did not make sense or at least were not related to each other. These observations include the fact that organisms tended to have far more offspring than was needed to replace themselves, that animal breeders were able to change very much the characteristics of their animals and these characteristics were passed on to their offspring, and that there existed a vast record of past life in rocks that in some cases showed a regular progression of change from one stratum to another. At that time, the principal idea as to where life had come from for most Europeans was the story of creation in the bible. Darwin was himself religious and initially believed like other

educated people of his time that the biblical explanation for creation was all that one needed to know. But Darwin also knew from the work of the earlier geologists Hutton and Lyell that the earth was very old and that processes that had shaped the earth in the past were often still occurring now. Finally he knew that these processes (such as erosion of landscapes) could be very powerful even though they were very slow because they played out over such a large amount of time. Darwin brilliantly synthesized all of these different observations, and many more, in his book *The Origin of Species*. His concept of evolution through natural selection has become a paradigm for all of the biological world since then. His particular genius was to come up with the mechanism, *natural selection*, that could explain the process, which was evolution. As we gain new information, we have made additions and revisions to his basic idea, but the idea itself has withstood the test of time very well. For example, in the past several decades, we have made astonishing progress in understanding the nature of DNA and the many ways it works at the cellular and the molecular level. Nevertheless, all of this exceedingly detailed and powerful new information has not changed the basic way that we understand how evolution works and in fact adds considerable additional insight and support. Evolution is, essentially, *the* paradigm for biology.

Similarly in the 1950s, geology was a rather sleepy science which had a whole series of unrelated observations about the earth: that volcanoes appear in specific regions and that earthquakes were associated with these regions as were mountain chains. As probably every schoolchild has thought about when staring at a map of the world during a boring class, the shape of the African West Coast snuggles up very nicely against South American and so on. Additionally they knew that biologists had found that a particular type of tree, the southern beech (the genus *Nothofagus*), was found in very similar, but not exactly the same, forms in Southern South America, in Australia and New Zealand, and in South Africa. Although biologists such as Philip Darlington had considered for a long time that the continents must have moved, geologists were not buying it, or more usually not even thinking about it, because they had no idea of a *mechanism* to move the continents. Remember *theory* is the device that explains the mechanism that underlies our observations. The continents were just too large, there was no concept of where

the energy might come from to do that much work, and the concept was too weird. But in the 1950s, a group of geologists, many of them at Princeton University, began to connect the dots [6]. The most important knowledge was coming from, surprisingly, the bottom of the oceans. Oceanographers had begun to map the bottom of the ocean with powerful new sonar, and they found a very surprising thing—the middle of the Atlantic (and other) oceans had a series of underwater volcanoes that stretched from Iceland in the North (Iceland is itself a series of volcanoes) to below the tip of South America. Further studies showed that some of these volcanoes were actually active, spewing forth lava and heat under water, and that the sea bottom on either side of the volcanoes was spreading away from each other. Here was the needed mechanism to explain continental drift! It was energy from deep inside the earth, moving up in these oceanic rift zones, that was pushing the continents apart! Soon geology was abuzz with excitement and many new concepts tumbled out, all aided by this continental drift paradigm. For example, we could now see and even measure with lasers that the Red Sea was hinging apart, and the beautiful rift lakes of East Africa could be seen as the first stage in land masses splitting apart. In time lakes such as Tanganyika and Malawi will split apart entirely, and the sea will pour into what is now the middle of Africa—as it has with the Red Sea and the area between Africa and Madagascar.

20.4 Paradigms and Models

In these, and other, examples, scientists are usually most satisfied when they can formalize their paradigm, or some derivative of it, as a *model*. As we stated earlier, the definition for a model that we like best is “a formalization of our assumptions about a system.” The beauty of models from that perspective is that it says essentially that a model is a working hypothesis about how the world works, and as such it can be tested explicitly. It allows one to put reasonably complex issues such as continental drift into a format where they can be tested quantitatively. While most of you who have thought much about models probably think of them as some kind of mathematical or computer entity, in fact there are five major types or classes of models: *conceptual*, *physical*, *diagrammatic (or graphical)*, *mathematical*, and *computer*. Each of

them in some way attempts to capture the essence of a problem or situation, in a formalized although simplified way. Of course models can be good or bad, correct or incorrect, and complete or incomplete. But they should be consistent with the general principles of science outlined at the start of ► Chap. 15, they should contain appropriate mechanisms, and they should explain considerable empirical observations. A good paradigm meets all those criteria and can be considered a sort of super model that cements knowledge in an entire discipline. Both of the paradigms given above, natural selection and continental drift, meet those criteria. But many other models, and even some paradigms, have been found to be sadly lacking.

Clearly we have to build our models and our paradigms very carefully. The beauty of science and the scientific method is that it allows one to construct tentative models of how the world might work. Subsequent testing may find through empirical (i.e., related to observation and data) observation and testing that the assumptions used to construct that model were good or poor. Then the model can be adjusted or abandoned. There is no disgrace in constructing a model that turns out to be incorrect. That is how science moves forward. In science when one model or paradigm is shown to be false, there is often another to take its place, or sometimes we have to conclude that a good model just is not possible yet or maybe ever.

Models are great devices for bringing problems that are otherwise too large or too small into a scale humans can understand and conceptualize. Trying to imagine something as large as the atmosphere or the world economy, or as small as a hydrogen atom, can be a pretty daunting task. But by using models, we can write them all down on a piece of notebook paper or carry them around on a data stick. Most people are visual creatures. From an evolutionary perspective sight dominates most of our other senses. Think about it, would you tolerate the amount of pollution you now do if you primarily sensed the world through the chemistry of smell, as does a salamander?

A model must be simpler than the world it is attempting to explain. If it were not, it would be a description and not a model. What we mean by simplification is that the model contains fewer variables than the world we are trying to explain by means of a model. In addition, the independent variables should be as independent as possible. If they are not, it becomes very difficult to separate

cause from effect. Finally, if the models start out with its variables arrayed linearly, the model is simpler. We would like to include a word of warning for the student who is not yet accomplished in modeling. Please do not confuse simple with easy. Simple means there are but a few independent variables which are linear and which do not strongly interact. Simple does NOT mean immediately apparent by casual observation. Even simple models often require a great deal of work to get the relations with the real world good.

But here is the rub. Just because a model is simple, or even just because it might make considerable intuitive sense, does not mean that the model has correctly captured the essence of the system or the essence required for the question being asked at the time. It is amazing how infrequently this question has been asked. In our extensive and very different experience with modeling, we do not believe that 10% of the models that we have seen are in any way sufficiently well constructed to be appropriate for the questions they are being put to. Is the Hubbert model of oil production sufficient to predict the future? If so what data do we need to parameterize it? Certainly the simple firms and households model (■ Fig. 3.1) is completely inappropriate to resolve questions about national debts, pollution, climate change, or a host of other issues that it or its manifestations have been used for.

Why is this so? Is it because economists have no other place to turn to? That economists need a model to get their work done whether or not they have a good one to work with? One gets that impression from the review of development models by LeClerc [7]. Some people are poor, others are wealthy and want to help, money is thrown at aid, and economists are supposed to come up with a good development scheme and a model to justify it. Sometimes, of course, that works, more generally it seems to not work. Or maybe it would work if the population were not growing at the same time, eating up whatever new wealth is produced.

20.5 So, then, Why Is Economics, Which Is So Complex, So Analytical?

Nevertheless, there remains within academia a great deal of what we might call “physics envy,” that is, a desire to emulate the power and prestige of successful applications of simple equations in physics.

Mathematical rigor is often very important for impressing colleagues and deans whether the analysis has a secure connection with reality or not. In some few cases, it has led to the most brilliant and important advances in all of human knowledge. Mathematical rigor, however, while useful in its own right and in some applications, is hardly by itself a criteria of acceptable science, although it is often promoted as such. Thus the advanced economist is often reduced to simplifying quite complex economic questions into a format that is analytically tractable, that is, can be solved using analytic means and sometimes using essentially ideological concepts such as “free markets generate the optimal use of resources.” It is a lovely idea, requires enormous skills and concentration, and sometimes generates very useful results. Very often, however, we believe it generates results that represent only the mathematics and not the real system. We give some examples throughout this book but especially in ► Chaps. 4 and 11. Of course we use models too, so the reader should ask “have they validated their models.” We think so and give as an example the work of Hallock et al., where we predicted the oil production for 46 countries and then went back 10 years later to see how we did [8] (► Fig. 8.8). The answer is “pretty well for most countries, but miserably for a few.”

What you need to make *analytical* mathematical models work is really very simple systems, often described as the *two body* system. Real atmospheric or real economic systems are not so simple, and pushing real systems kicking and screaming into a small enough box (i.e., few enough equations) to be analytically tractable is not science. In our opinion, there are very few real problems in economics that can be adequately represented by such simple relations, and much of the economics that is done by complex analytic analysis is deriving mathematical and not economic results. But the use of analytical mathematics does have one major benefit. Through the manipulation of equations, you can transform a cause and effect relation that is obtuse into a way in which you can sometimes see, derive and test patterns.

20.6 How Have Models in Fact Been Used in Economics

We believe that models have rarely been used in economics in their proper role, that is, as a formalization of our assumptions that would allow the

testing of the hypotheses that are represented by the equations therein. Rather models have been used mostly as conceptual shortcuts that take the very complex biophysical and social entities that real economies are composed of and represent them as caricatures that demand acceptance (or dismissal), but not testing. While of course any model needs to be in some sense a simplification, the important issue is that that simplification must represent the basic reality modeled. But in fact we have shown in ► Chap. 3 that the most important models in economics, such as the firm-household model, do not represent the essential biophysical reality that constitutes real economies. Why should this absurdly simplistic model that is not even true as a first approximation be allowed to be represented over and over in introductory economics text books with so few economists speaking up (other than Leontief) that the king has no clothes?

It is true that within economics there are complex empirically-based models. An example is the University of Pennsylvania Wharton model, a huge, data-rich computer simulation of linked economic transactions throughout the economy. It gives very detailed predictions about each section of the economy, although it failed to predict the 2008 market crash [9]. As such it is a useful predictive device, and as such it *could* be used to generate and test hypotheses. But it was not generated upon a series of hypotheses about how the economy works, nor was it asked, to our knowledge, to test the basic hypotheses of economics. Instead the structure of the economy is specified (given), and then a massive amount of information is fed into the calibration phase of the model. The computer cleverly fits all of the actual data collectively to all of the equations in a process known as parameterization. The net effect is that the model can predict well small changes, say from 1 year to the next, because of the “can’t fail structure” of the model, which is in some ways a tautology. But in no way that we are aware of does this model test the underlying conceptual base of the neoclassical model of economic reality. We love the article by Krugman in the *New York Times* “How did economists get it so wrong: Mistaking beauty for truth” [10] where Krugman found no economists predicted the market and housing crash despite their extremely sophisticated “quant” mathematical models. This reminded us of Ptolemy’s model of the solar system: it worked very well when you are recreating the known, but if the mechanism is incorrect, you have no chance with changing forcing functions.

20.7 Some Problems with the Standard Neoclassical Model

Thus, while there are some good attributes to the basic neoclassical supply-demand-market model, there are also some extreme problems, as the reader probably has guessed by now. The first problem, well understood by any economist, is that of *externalities*. Externalities refer to a gain, or (more generally) a loss, associated with a market transformation (often a third party) that is not expressed in the market price. Classic examples are pollution impacting a downstream fishery, or worker's compensation. In, say 1850, when an industrial worker making, say, chairs loses an arm in a piece of machinery such as a mechanical saw or lathe it was catastrophic financially as well as physically, for if he had lost his arm he was no longer able to do his job and so was let go, generally leaving his family with no means of support. If he was lucky, the mill owner might take pity on him and allow him to push a broom at a reduced salary, but this was hardly guaranteed. Nevertheless that loss of limb and of income was in fact part of the cost of producing that chair. Worker's compensation, which was mandated by federal law, recognized that if the cost of some kind of insurance could be entered into the price of the good being produced, that would form a fund called "workman's compensation" which was held in reserve for the occasional catastrophe. The injured worker was given money to pay for medical treatment as well as a pension to cover wages lost. This fund was paid for by the manufacturer, who passed it along in the price of his or her products. Then we could say that the cost (losing a limb and also income) had been *internalized* into the price of the product. The market alone could not do that, nor should it be expected that it would. It requires intervention by governments (usually at the state level), and although the idea was at first fought by early manufacturers, it has been pretty well accepted by all now and in fact is also responsible in part for making working conditions safer, for example, by the simple and very effective practice of putting covers over belts and gears to avoid the possibility of a worker slipping and getting chewed by the machinery. From [11]: "Externalities are ad hoc corrections introduced as needed to save appearances, like the epicycles of Ptolemaic astronomy...As long as externalities

involve minor details, this is perhaps a reasonable procedure. But when vital issues (e.g. the capacity of the earth to support life) have to be classified as externalities, it is time to restructure the basic concepts and start with a different set of abstractions that can embrace what was previously external."

Many advocates of the use of "pure" neoclassical economics have called for a reduction in government intervention in the economy. A classic example is their response to the Glass-Steagall Act, passed in 1933, which had as its main objective the keeping of investment banks (think Goldman Sachs) separate from commercial banks, of the sort that exists on main streets and may be principally concerned with e.g., making housing loans. It was thought that this was part of the poor banking processes that resulted in the great market crash of 1929. The idea was to protect those who had their money in the commercial banks (which was presumably protecting their money) from the possible impacts of an investment bank making too risky loans with main street cash. So in fact after a dozen attempts, the large Wall Street agencies in 1999 were able to repeal the Glass-Steagall Act, allowing financial agencies much greater freedom in what they did. Many blame this repeal and the repeal of other such financial controls on the great market crash of 2008.

20.8 If the Basic Neoclassical Model Is Unrealistic, Why Do Economists Continue to Use It?

As suggested in ► Chap. 6, all cultures live at least partly by myths, a set of deeply held and sometimes true beliefs that validate the everyday experiences and propagate patterns of behavior thought compatible with the social and economic well-being of at least some of its members. When today we examine ancient cultures we often marvel at what we perceive to be the strange and foolish (to us) myths that guided their activities. Ancient Mayans apparently believed that sacrificing virgins would bring rains and prosperity; the people of Easter Island apparently thought (or their priests and leaders bamboozled them into thinking) that constructing huge statues would insure the continuance of their early economic well-being and later compensate for their reduc-

tion in quality of life occasioned by their overexploitation of birds, forests, and soils; ancient Egyptians thought that the worship of Ra would make the Nile flood properly; and Medieval Europeans thought that the plague was caused by their sins, as do contemporary social conservatives when they attribute the AIDS pandemic to “immoral lifestyle choices.” Some of these, and other, ways that humans have hooked their myths to their economic well-being and lack thereof are marvelously developed in Jared Diamond’s important book *Collapse*. (The story on Greenland is particularly poignant). In many cases what we call today the “myths of old” were, and sometimes still are, very serious religious issues to the people who follow them. After all, a myth to one group is generally someone else’s religion or cultural values. Most of these old myths appear today as more or less harmless ways to try to understand or control a world before science gave us more powerful tools, but some, like sacrificing virgins or the letting of blood from a sick person to “drain their bad humors,” were extremely destructive by today’s standards, and, apparently, they sometimes led to the destruction of their cultures.

Contemporary Western society also operates according to a number of sometimes contradictory myths embodied in various established conventions, religious tenets, folk wisdoms, and, we think, economic “truths.” For example, the future might tell us that the basic tenets of market capitalism, including the primacy and/or virtue of individual initiative, survival of the economic fittest, the need for economic growth, the indefinite possibilities of exploitation of particular resources, material consumption as the road to happiness, unlimited substitution, that technology will solve any economic shortages, that nature is there to be exploited as we wish, and so on, are just as much myths as whatever the Easter Island statues relate to. Or they may not be. Or they may be perceived as an extremely effective way by which people at one time can live very well, but at the expense of their descendants. The application of conventional economics, whether that is a series of myths or a pipeline to reality (or some mixture) have given the residents of the wealthy North an unprecedented material standard of living and tremendous technological achievements. Yet we do believe that these myths (or realities) now threaten to undermine the affluent society they

helped build without necessarily generating the unalloyed happiness it was supposed to and while, clearly, generating enormous misery (and also sometimes happiness) to many in the global South.

We believe that what separates myths from reality is the judicious use of the scientific method. Of course science itself has been, and remains, hardly immune to the need for and use of myths. In the natural sciences, we are familiar with large-scale “paradigm shifts,” where fundamental scientific ideas that have been widely accepted and well developed are suddenly found to be quite wrong, leading to the replacement of the entire conceptual basis of a discipline. Some examples include: One of our freshmen asked us “Do you mean that capitalism actually encourages its own destruction by encouraging the destruction of its resource base as rapidly as possible?” “Well, we responded, that hypothesis is consistent with the data.” We could not say that his statement was not true, but did say that it is a long-term process in the wealthy parts of the world. We believe that the sixteenth-century replacement of the Earth-centered Ptolemaic theory of the solar system with the sun-centered Copernican view, the ongoing replacement of population-intrinsic concepts for the population dynamics of commercial fisheries with a more complex ecosystem view, and only 50 years ago the replacement of a static view of continents with that of dynamic plate tectonics were all good paradigm shifts. The main questions are: do we need, and are we ready for, such a paradigm shift in economic models? And if we are prepared intellectually for that task can we possibly implement it given the enormous intellectual and financial investment in neoclassical economics as it is applied around the world? Our answer to the first question is that it is probably too late for most of the older economists steeped in neoclassical theory, but there are many younger economists, economists to be, and certainly a vast army of environmental, geological, and physical scientists ready to learn and help create a new economics more consistent with their own empirically based view of the world. The answer to the second is that it would be an extremely difficult and demanding task to actually implement a new policy approach to economics, even if it could be agreed as to what that should be. The other side of the coin is, however, that it might be much worse

not to do so, especially if the plight of the third world degrades substantially, which we perceive as not unlikely as oil and other critical materials become increasingly scarce over the coming decades.

And there exists procedures by which we can do this and it is called the scientific method as it is applied in the biophysical sciences. Within this framework, one is able to come up with whatever hypothesis you might want as to what is the truth. But if you are inconsistent with known reality you are likely to get shot down by your colleagues. For example, when in the early 1950s several scientists were closing in on the structure of DNA (where the “A” stands for acid), the great biochemist Linus Pauling proposed a chemical model that he thought represented DNA. But Watson and Crick, who later came up with the correct structure, noticed that Pauling’s structure was not an acid and so immediately shot down Pauling’s model—it was not consistent with known science. Likewise, all kinds of mechanical devices for generating energy have been shown false because they are thermodynamically incorrect. We think that there has to be a lot more of this kind of analysis applied to all economic models.

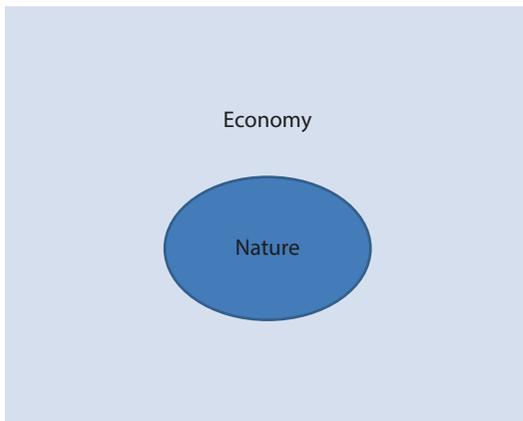
We expect a great deal of resistance from established economists to what we develop here. Past criticisms of neoclassical welfare economics are almost invariably dismissed by economists as attacks on a “straw man.” This response by economists is so prevalent it is worth addressing in some detail. In one sense, economists are correct to point out that the theory of many present-day economists has gone far beyond e.g., the restrictive and unscientific assumptions of *homo economicus* and perfect competition. A growing number of economists, particularly the most respected theorists in the field, have already abandoned the models of human behavior we criticize in ► Chap. 3. The applied work and policy recommendations of most economists, however, remain grounded in these models. Most economists still believe that contemporary work in behavioral economics and game theory can be integrated into the standard welfare model. This is wishful thinking. If the restrictive assumptions of *Homo economicus* are relaxed to incorporate current knowledge about actual human behavior, the conditions for efficient resource allocation by markets (Pareto efficiency) cannot be met.

Another tactic by economists in responding to criticism is to claim that welfare theory is based on very general, reasonable assumptions—ignoring their unsupportable interpretations of those assumptions. For example, according to economist Herbert Gintis, a definition of the “rational actor model” is that it: “holds that individual choice can be modeled as maximization of an objective function subject to informational and material constraints.” In other words, people try to do the best they can with the limited means at their disposal. Their objective is said to be “utility” or “well-being” broadly defined. These seem to be reasonable and harmless assumptions. But in economic texts and applied work, “well-being” is equated *only* with the consumption of market goods chosen in a manner that conforms to the mathematical requirements of constrained optimization. We ask the reader to think what are the most important factors in your own life. For most of us family, friends, health, justice, fairness, a clean, non-degraded and uncrowded environment, spiritual issues, and good associates are all ahead of issues that could be bought or sold in the market. But every leading text in economic theory follows the pattern based on consumption. For example, the respected economists Pyndyck and Rubinfeld [12] write:

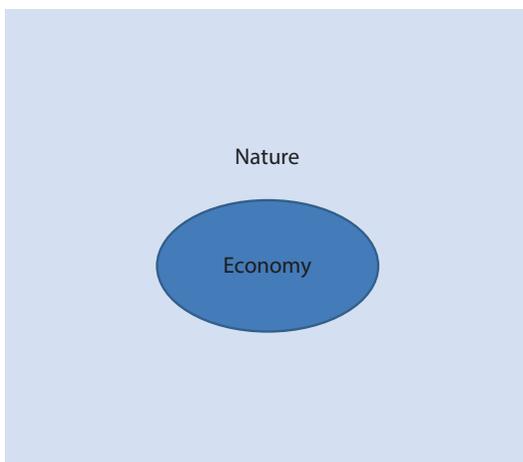
» In everyday language, the word *utility* has rather broad connotations, meaning, roughly, “benefit” or “well-being.” Indeed, people obtain “utility” by getting things that give them pleasure and by avoiding things that give them pain. In the language of economics, the concept of **utility** refers to *the numerical score representing the satisfaction a consumer gets from a market basket.*

Thus, the complex issue of individual utility becomes reduced to only the consumption of collections of market goods. The analysis of market choice proceeds by making the three basic assumptions of completeness, transitivity, and that more is always preferred to less. These are the kinds of assumptions economists have refused to empirically test until recently. Without these assumptions Walrasian (neoclassical) analysis cannot work. As a leading microeconomic text points out regarding just one of these assumptions: “...substantial portions of economic theory would not survive if economic agents could not be assumed to have transitive preferences.” Therefore,

we believe that attempting to “fix” the NCE model through, for example, internalizing externalities (such as by adding a dollar value for essential properties or services of nature into the existing market-based evaluative scheme) is missing the point of what should be (in our opinion) our major undertaking, which is to start our economic conceptualization from scratch in a way that represents what actually occurs in a real economy. In essence we must put our conceptual economic models *inside* nature where it *must* exist (e.g., ■ Fig. 20.2), rather than attempt through internalizing externalities to put nature inside the economic framework (■ Fig. 20.1). We believe that this is necessary for two reasons. First, we believe



■ Fig. 20.1 Too often in ecological economics nature is placed “within” the economy where functions of nature are given monetary values that were originally evaluated in the economy



■ Fig. 20.2 The economy must exist within nature for it cannot exist any other way

that the basic structure of neoclassical economics is so flawed as to be impossible to jury-rig back to credibility and, second, that for this and other reasons, the practical consequences of the application of NCE result in actions that are immoral and self-defeating. While we recognize that probably most older economists will not agree with our assessment, we do think it is about time to flush this question into the open so that we can have a much more substantive discussion of what kind of economics we should be constructing.

20.9 A Final Thought on the Proper Use of Mathematics

Part of what defines science as science in most peoples’ minds (including scientists themselves) is the use of mathematics, and mathematical models, to define and resolve problems. The power of mathematics (in its broad sense) is to make the results of the prediction quantitatively explicit and hence quantitatively predictable. The process of examining whether your model is a correct or at least adequate is called *validation*. An examination of the degree to which uncertainty in model formulation (how it is structured) or parameterization (what numerical coefficients are assigned) allows one to trust your results or reach certain conclusions is called *sensitivity analysis*. It is through validation and sensitivity analysis that models generate their (occasional) tremendous power in resolving truth, such as that is accessible to the human mind.

The use of mathematics was especially important in the development of physics in the early part of the past century, and the creation of the atom bomb was tangible evidence to many of the power of pure mathematics combined with practical application. Nevertheless, even Einstein preferred to solve his problems without mathematics when that was possible. Other sciences in which mathematical models have been especially important include astronomy, some aspects of chemistry and some aspects of biology such as demography and in some cases epidemiology. The importance of mathematics for most of biology is a little harder to pin down. Certainly the most important discovery in biology was that of Charles Darwin, who used essentially no mathematics in the development of the theory of natural selection beyond the concept of the potential of organisms

for exponential growth. Likewise, mathematics by itself had little to do with the development of the cell theory, the structure and nature of DNA, and most modern molecular biology. On the other hand genetics, from Mendel to contemporary population genetics, has been heavily influenced by, and sometimes tends to lend itself well to, mathematics.

A final problem that we repeat from before is that there has been frequent confusion between *mathematical* and *scientific* proof. Mathematics can generate real proofs relatively easily because you are working in a defined universe (through the assumptions and the equations used) to which it applies. If you define a straight line as the shortest distance between two points, then you can solve many problems requiring straight lines. But the world handed to us by nature is neither so straight nor so cleanly defined, and we must constantly struggle to represent it with our equations. Hence, a mathematical proof becomes a scientific proof only in the relatively rare circumstances when the equations do indeed capture the essence of the problem.

20.10 Now We Will Appear to Contradict Ourselves

Despite all of the many problems of modeling, we do not understand how one can use the scientific method, that is, generate and test hypotheses, on complex issues without the use of formal modeling. This is as true for management and policy-related issues as for theoretical ones. The reason is that models are an explicit formalization of our assumptions about a system, and such allow for explicit testing of how you think the world works. In our view quantitative (or occasionally non-quantitative) models of at least sufficient complexity are necessary in the complex world of economics (and of environmental sciences) because it allows one to apply the scientific method to complex real systems of nature and of humans and nature. *But it is critical that the right kind of models be used.* And the way to do that is quite simple: Try to represent the real system that you are dealing with rather than some abstraction that happens to be analytically tractable. Quite simply most real problems require computer modeling, not analytic modeling. The power of models is to make our assumptions explicit, generally quantitative, and hence testable.

Questions

1. What is a model? Where do you find models?
2. When speaking of a model, what do we mean by “solution”?
3. What is the difference between something that is mathematical and something that is quantitative? Can something be both?
4. What is the difference between an analytical solution and a numerical one?
5. Explain how some cities were astronomical instruments.
6. Give one or more examples of a model that is conceptually incorrect but that nevertheless gives good predictions.
7. Give one or more examples of models that are very commonly used but that are probably incorrect.
8. What is a paradigm? Give several examples.
9. Can you give five general types of models (Hint: One of them is computer).
10. Can you explain the apparent paradox that one can use complex mathematics only on a rather simple model?
11. What is an externality?
12. How can we separate myth from reality?
13. What are some of the ways in which some economists today have criticized the basic models of contemporary economics?
14. Discuss the conceptual advantage of putting our economic models inside our models of nature vs. the opposite.
15. What is validation? Sensitivity analysis? How would you use them in economics?

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