The Origin of Wealth

EVOLUTION, COMPLEXITY, AND THE RADICAL REMAKING OF ECONOMICS

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The Question

HOW IS WEALTH CREATED?

I SAT PERCHED on a small ledge, with my back pressed against a dung wall, in the smoky center room of a thatched hut belonging to an elderly Maasai tribesman. The hut was in a remote village in southwestern Kenya. The Maasai elder, with his wise, weather-beaten face and sharp eyes, had been asking me polite questions about my family and where I came from. Now he wanted to get the measure of me. He fixed his gaze on mine across the cooking fire and asked, "How many cattle do you own?" I paused for a moment and then quietly replied, "None." A local Maasai teacher, who had befriended me and was acting as my guide, translated my reply. There was a murmur around the small room as various members of the village, curious about the stranger, digested this piece of information. After a few moments' consideration, the elder replied, "I am very sorry for you." But the pity evident in his voice and on his face was also tinged with puzzlement as to how someone so poor could afford to travel such long distances and own a camera. As the discussion turned back to questions about my family I remarked that I have an uncle who once owned a large herd of cattle on his farm in Maryland. There was then a quick nodding of understanding as the mystery was solved—the visitor was clearly the ne'er-do-well nephew of a rich uncle, traveling and living off his relative's bovine wealth.

The Mysteries of Wealth

What is wealth? For a Maasai tribesman, wealth is measured in cattle. For most of the readers of this book, it is measured in dollars, pounds, euros, yen, or some other currency. Over two hundred years ago, the great economist

Adam Smith noted the rich variety of ways that people have measured their wealth throughout history: "In the [earlier] ages of society, cattle are said to have been the common instrument of commerce; though they must have been a most inconvenient one . . . Salt is said to be the common instrument of commerce and exchanges in Abyssinia; a species of shells in some parts of the coast of India; dried cod at Newfoundland; tobacco in Virginia; sugar in some of our West India colonies; hides or dressed leather in some other countries; and there is at this day a village in Scotland where it is not uncommon, I am told, for a workman to carry nails instead of money *to* the baker's shop or the alehouse."[1]

Is wealth an intrinsic, tangible thing? Is there something inherent in cows, cod, and nails that gives them value? For a Maasai tribesman, the wealth embedded in his cattle is there for all to see. It provides him and his family with milk, meat, bone, hide, and horn. Yet, as Smith showed in his Wealth *of* Nations, wealth is not a fixed concept; the value of something depends on what someone else is willing to pay for it at a particular point in time. Even for a Maasai, the value of a cow today may not be the value of a cow tomorrow For those who measure their wealth in the paper of currencies, wealth is an even more ephemeral concept. Most people in developed countries never see or touch the bulk of their wealth—their hard-earned savings exist only as electronic blips on a banks faraway computer. Yet those ghostly blips can be converted into the tangible goods of cows, cod, nails, or whatever else one desires (or can afford) with the swipe of a credit card or the click of a mouse.

But where does wealth come from in the first place? How does the sweat of our brows and the knowledge of our brains lead to its creation? Why has the world grown richer over time? How have we gone from trading cattle to trading microchips? This line of inquiry ultimately leads us to perhaps the most important mystery of wealth: how can we create more of it? We can ask this question out of narrow self-interest, but we can also ask the larger question of how the wealth of society can be increased. How can managers grow their companies to provide more jobs and opportunities for people? How can governments grow their economies and address issues of poverty and inequality? How can societies around the world create the resources needed for better education, health care, and other priorities? And, how can the global economy grow in a way that is environmentally sustainable? Wealth may not buy happiness, but poverty does buy misery for millions around the world.[2]

The questions this book will explore—What is wealth? How is it created? How can it be increased?—are among the most important questions for society and among the oldest questions in economics. Yet, they are questions economics has historically struggled to answer. The thesis of this book is that new answers to these fundamental questions are beginning to emerge from work carried out over the past few decades. These new answers come not just fi-om the work of economists, but also from biologists, physicists, evolutionary theorists, computer scientists, anthropologists, psychologists, and cognitive Scientists. We will see that modern science, in particular evolutionary theory and the theory of complex adaptive systems, provides us with a radically new perspective on these long-standmg economic questions.

In this chapter, I will outline the major themes of the book and give a brief preview of the ideas we will explore. But before we develop a new perspective on the answers, we need to shift our perspective on the questions. The economy is something most people take for granted in their daily lives and don't often think about. When we do think about the economy, it is often in the context of what Princeton economist Paul Krugman has called "up and down economics," as in "the stock market is up" and "unemployment is down."[3] But we need to step back fi-om the wiggling graphs of the economy's short-term ups and downs for a moment and consider the economy as a whole, as a system.

Humanity's Most Complex Creation

Take a look around your house. Take a look at what you are wearing. Take a look out your window. No matter where you are, from the biggest industrialized city to the smallest rural village, you are surrounded by economic activity and its results. Twenty-four hours a day, seven days a week, the planet is abuzz with humans designing, organizing, manufacturing, servicing, transporting, communicating, buying, and selling.[4]

The complexity of all this activity is mind-boggling. Imagine a small rural town, the kind of quiet, simple place you might go to escape the hurly-burly of modern life. Now imagine that the townspeople have made you their benevolent dictator, but in exchange for your awesome powers, you are responsible for making sure the town is fed, clothed, and sheltered each day. No one will do anything without your say-so, and therefore each morning, you have to create a to-do list for organizing all the town's economic activities.' You have to write down all the jobs that must get done, all the things that need to get coordinated, and the timing and sequence of everything. No detail is too small, whether it is making sure that Mrs. Wetherspoon's flower shop gets her delivery of roses or that Mr. Nutley's insurance claim for his lumbago is processed. Even for a small town, it would be an impossibly long and complex list. Now think about what a similar to-do list might look like for managing the global economy as a whole. Think of the trillions of intricately coordinated decisions that must be made every minute of every day around the world to keep the global economy humming. Yet, there is no one in charge of the global to-do list. There is no benevolent dictator making sure that fish gets from a fisherman in Mozambique to a restaurant in Korea to provide the lunch for a computer worker who makes parts for a PC that a fashion designer in Milan uses to design a suit for an interest-rate futures trader in Chicago. Yet, extraordinarily, these sorts of things happen every day in a bottom-up, self-organized way.

The most startling empirical fact in economics is that there is an economy at all. The second most startling empirical fact is that day in and day out, for the most part, it works. It provides most (but sadly not all) of the worlds 6.4 billion people with employment, food, shelter, clothing, and products ranging from Hello Kitty handbags to medical lasers. If one thinks of other highly complex human-made systems, such as the International Space Station, the government of China, or the Internet, it is clear that the global economy is orders of magnitude more complex than any other physical or social structure ever built by humankind.[6]

The economy is a marvel of complexity. Yet no one designed it and no one runs it. There are, of course, CEOs, government officials, international organizations, investors, and others who attempt to manage their particular patch of it, but when one steps back and looks at the entirety of the $36.5 trillion global economy, it is clear that no one is really in charge.'

Yet how did the economy get here? Science tells us that our history began in a state of nature, literally "without a shirt on our backs." Our immediate ancestors were hominid protohumans who had large brains and nimble hands and who roamed the African savanna not far from where I sat with the Maasai tribespeople. How did humankind travel from a state of nature to the stunning self-organized complexity of the modern global economy?

2.5 Million Years of Economic History in Brief

Intuitively, many people imagine that humankind's upward climb in economic sophistication was a slow, steady journey, a h e a r progression from stone tools to DVD players. The actual story, pieced together by archaeologists, anthropologists, historians, and economists, is not at all like that. It is far more dramatic.*

The story begins when the first hominids appeared on earth around 7 million years ago and their descendents, *Australopithecus africanus,* began to walk upright around 4 million years ago.[9] By about 2.5 million years ago, *Homo* *habilis* began to use its relatively large brain to begin making crude stone tools. We can think of these stone tools as the first products, and we can imagine that at some point two of our hominid ancestors, probably from the same band of close relatives, sat in the dust of the savanna and traded tools. We will use this very approximate point of 2.5 million years ago as the marker for the beginning of the human "economy." It then took roughly another million years for Homo *erectus* to discover fire and begin to produce a wider range of tools made out of stone, wood, and bone. Biologically modern humans, Homo sapiens, appeared around 130,000 years ago and developed increasingly sophisticated and diverse tools. At some point—there is much debate on when—Homo sapiens evolved the critical skill of language. The economic activity of these first modern humans was primarily limited to foraging in roving bands of close relatives and to basic tool manufacturing.

It is not until around 35,000 years ago that we begin to see the first evidence of a more settled lifestyle, with burial sites, cave drawings, and decorative objects. During this period, archaeologists also begin to see evidence of trading ***between*** groups of early humans; the evidence included burial-site tools made from nonlocal materials, seashell jewelry found with noncoastal tribes, and patterns of movement suggesting trading routes.[10] One of the great benefits of trade is that it enables specialization, and during this period, the record shows a dramatic increase in the variety of tools and artifacts. As Paul Seabright of the University of Toulouse notes, cooperative trading between nonrelatives is a uniquely human activity.'' No other species has developed the combination of trading among strangers and a division of labor that characterizes the human economy. In fact, Richard Horan of Michigan State University and his colleagues argue that it was this unique ability of Homo sapiens to trade that gave them the critical advantage in their competition with rival hominid species such as Homo *neanderthalensis* (the Neanderthals), enabling our ancestors to survive while the other hominids became extinct."

With permanent settlements, a variety of tools, and the creation of trading networks, our ancestors achieved a level of cultural and economic sophistication that anthropologists refer to as a **hunter-gatherer** *lifestyle.* From the archaeological record, we have some knowledge of how our hunter-gatherer ancestors lived and what their economy looked like, but we also have another rich source of information on this way of life. There are still a few very isolated places on earth where hunter-gatherer tribes continue to live with very little contact with the modern world, virtually unchanged from tens of thousands of years ago. Anthropologists think of these tribes as living time capsules of an earlier era.

A Tale of Two Tribes

Consider two tribes. First, we have the Yanomamö, a stone-tool-making hunter-gatherer tribe living along the Orinoco River on the remote border of Brazil and Venezuela.[13] Second, we have the New Yorkers, a cell-phone-talking, café-latte-drinking tribe living along the Hudson River on the border of New York and New Jersey Both tribes share the same thirty thousand or so genes that all humans do and thus, in terms of biology and innate intelligence, are essentially identical. Yet, the lifestyle of the New Yorkers is vastly different from the well-preserved hunter-gatherer lifestyle of the Yanomamö, who have yet to invent the wheel, have no writing, and have a numbering system that does not go beyond one, *two,* and *many.*

If we take a closer look at the economies of the two tribes, we see that Yanomamö employment is focused on collecting food in the forest, hunting small game, gardening a limited number of fruits and vegetables, and maintaining shelters. The Yanomamö also make items such as baskets, hammocks, stone tools, and weapons. They live in villages of forty to fifty people and trade goods and services among each other, as well as among the 250 or so other villages in the area. The average income of a Yanomamö tribesperson is approximately $90 per person per year (this, naturally, is an estimate as they do not use money or keep statistics), while the average income of a New Yorker in 2001 was around $36,000, or 400 times that of a Yanomamö.[14] Without any judgments on who is happier, morally superior, or more in tune with their environment, there is clearly a wide gap in material wealth between the two tribes. The Yanomamö have shorter life expectancies than the New Yorkers, and during their lives, the Yanomamö must endure uncertainties, diseases, violence, threats fi-om their environment, and other hardships that even the poorest New Yorkers do not face—one is eight times more likely to die in a given year living in a Yanomamö village than living in a New York borough.[15]

But it is not just the absolute level of income that makes New Yorkers so wealthy; it is also the incredible variety of things their wealth can buy Imagine you had the income of a New Yorker, but you could only spend it on things in the Yanomamö economy.[16] If you spent $36,000 fixing up your mud hut, buying the best clay pots in the village, and eating the finest Yanomamö cuisine, you would be extraordinarily wealthy by Yanomamö standards, but you would still feel far poorer than a typical New Yorker with his or her Nike sneakers, televisions, and vacations in Florida. The number of economic choices the average New Yorker has is staggering." The Wal-Mart near JFK Airport has over 100,000 different items in stock, there are over 200 television channels offered on cable TV, Barnes & Noble lists over 8 million titles, the local supermarket has 275 varieties of breakfast cereal, the typical department store offers 150 types of lipstick, and there are over 50,000 restaurants in New York City alone.

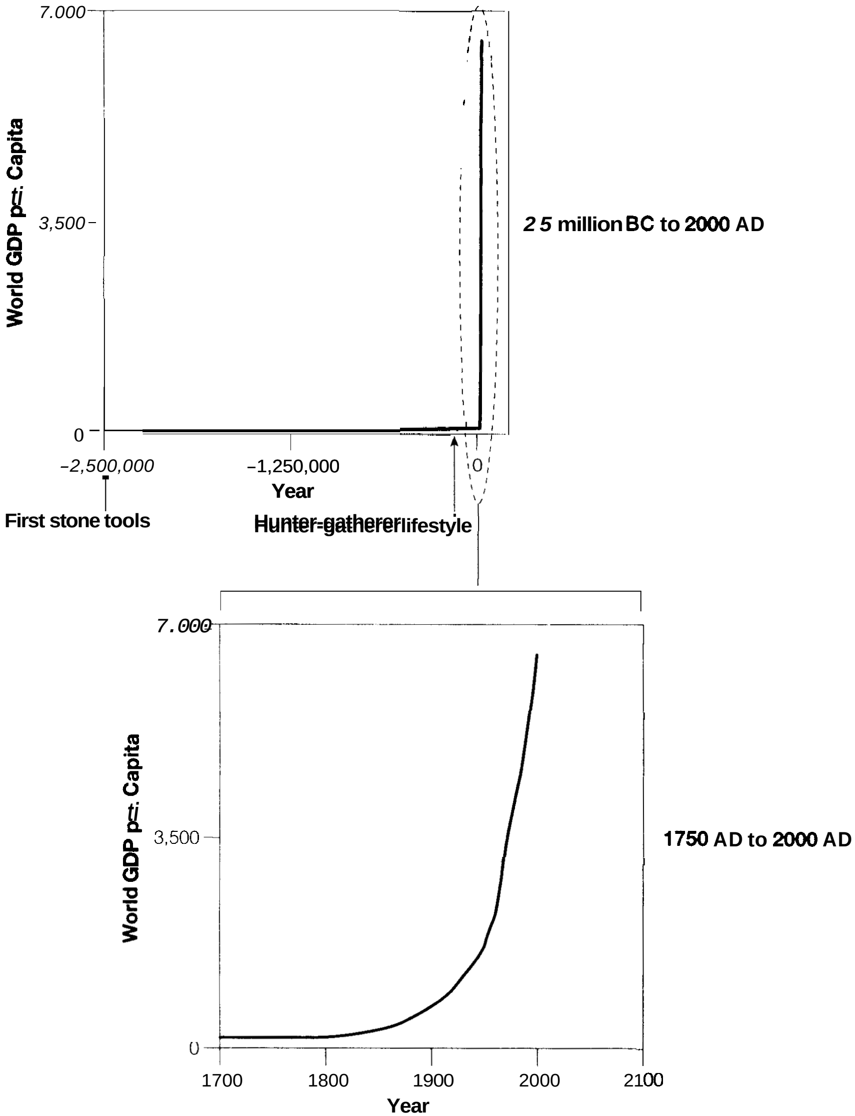
Retailers have a measure, known as stock keeping units, or *SKUs,* that is used to count the number of types of products sold by their stores. For example, five types of blue jeans would be five SKUs. If one inventoried all the types of products and services in the Yanomamö economy, that is, the different models of stone axes, the number of types of food, and so on, one would find that the total number of SKUs in the Yanomamö economy can probably be measured in the several hundreds, and at the most in the thousands.'' The number of SKUs in the New Yorker's economy is not precisely known, but using a variety of data sources, I very roughly estimate that it is on the order of 10^{10} (in other words, tens of billions).[19] To put this enormous number in perspective, estimates of the total number of species on earth range from 10^6 to 10^8. Thus, the most dramatic difference between the New Yorker and Yanomamö economies is not their "wealth' measured in dollars, a mere 400-fold difference, but rather the hundred-million-fold, or eight orders of magnitude difference in the complexity and diversity of the New Yorkers' economy versus the Yanomamö economy.

The lifestyle of the Yanomamö is fairly typical of our ancestors circa 15,000 years ago.[20] This sounds like a long time ago, but in terms of the total economic history of our species, the world *of* the *Yanomamö* is the very, *very* recent *past.* If we use the appearance of the first tools as our starting point, it took about 2,485,000 years, or 99.4 percent, of our economic history to go from the first tools to the hunter-gatherer level of economic and social sophistication typified by the Yanomamö (figure 1-1). It then took only 0.6 percent of human history to leap from the $90 per capita 10^2 SKU economy of the Yanomamö, to the $36,000 per capita 10^{10} SKU economy of the New Yorkers.

Zooming in for a more granular look into the past 15,000 years reveals something even more surprising. The economic journey between the hunter-gatherer world and the modern world was also very slow over most of the 15,000-year period, and then progress exploded in the last 250 years. According to data compiled by Berkeley economist J. Bradford DeLong, it took 12,000 years to inch from the $90 per-person hunter-gatherer economy to the roughly $150 per-person economy of the Ancient Greeks in 1000 BC.[21] It wasn't until 1750 AD, when world gross domestic product (GDP) per person reached around $180, that the figure had finally managed to double from our hunter-gatherer days 15,000 years ago. Then in the mid-eighteenth century, something extraordinary happened—world GDP per person increased 37-fold in an incredibly short **250** years to its current level of $6,600, with the richest societies, such as the New Yorkers, climbing well above that.[22] Global wealth rocketed onto a nearly vertical curve that we are still climbing today.

FIGURE 1-1

The Explosive Growth in Human Wealth



Source: **Estimates for 1 million BC to 2000 AD from J. Bradford DeLong, University of California, Berkeley. Estimates for 2.5 million BC to 1 million BC are an extrapolation. GDP per capita is measured in 1990 international dollars.**

To summarize 2.5 million years of economic history in brief for a very, very, very long time not much happened; then all of a sudden, all hell broke loose. It took 99.4 percent of economic history to reach the wealth levels of the Yanomamö, 0.59 percent to double that level by 1750, and then just 0.01 percent for global wealth to leap to the levels of the modern world. Another way to think of it is that over 97 percent of humanity's wealth was created in just the last 0.01 percent of our history.[23] As the economic historian David Landes describes it, "the Englishman of 1750 was closer in material things to Caesar's legionnaires than to his own great-grand-children."[24]

We now have a greater sense of just what kind of a phenomenon we are dealing with and can add some additional questions to our inquiry:

- How can something as complex and highly structured as the economy be created and work in a self-organized and bottom-up way?
- Why has the complexity and diversity of the economy grown over time? And, why does there appear to be a correlation between the complexity of an economy and its wealth?
- Why has the growth in wealth and complexity been sudden and explosive rather than smooth?

Any theory that seeks to explain what wealth is and how it is created must answer these questions. Although we know the historical narrative of *what* has happened in the history of the economy, for example, the advent of settled agriculture, the Industrial Revolution, and so on, we still need a theory of *how* it happened and *why* it happened. We need a theory that can take us all the way from early humans living in a state of nature, to the hunter-gatherer lifestyle of the Yanomamö, and from the Yanomamö to New York and beyond.

The Economy Evolves

Modern science provides just such a theory. This book will argue that wealth creation is the product of a simple, but profoundly powerful, three-step formula—differentiate, select, and amplify—the formula of evolution. The same process that has driven the growing order and complexity of the biosphere has driven the growing order and complexity of the "econosphere."[25] And the same process that led to an explosion of species diversity in the Cambrian period led to an explosion in SKU diversity during the Industrial Revolution.

We are accustomed to thinking of evolution in a biological context, but modern evolutionary theory views evolution as something much more general. Evolution is an algorithm; it is an all-purpose formula for innovation, a formula that, through its special brand of trial and error, creates new designs and solves difficult problems. Evolution can perform its tricks not just in the "substrate" of DNA, but in any system that has the right information-processing and dormation-storage characteristics.[26] In short, evolution's simple recipe of "differentiate, select, and amplify" is a type of computer program—a program for creating novelty, knowledge, and growth. Because evolution is a form of information processing, it can do its order-creating work in realms ranging from computer software to the mind, to human culture, and to the economy.

Economics and evolutionary theory have a long history together (something we will return to). One of the criticisms of that history is that there has been too much loose analogizing about how the economy might be **like** an evolutionary system. For example, one might say that the computer industry is like an ecological niche, with different "species" of players such as chip designers, hard-drive manufacturers, software providers, and so on, engaged in a "survival of the fittest" struggle within that niche. Paul Krugman calls such metaphorical comparisons of economic and biological systems "biobabble."[27] Most of the researchers discussed in this book would agree with Krugman that such "biobabble" is neither good science nor very Illuminating. Modern efforts to understand the economy as an evolutionary system avoid such metaphors and instead focus on understandmg how the universal algorithm of evolution is literally and specifically implemented in the information-processing substrate of human economic activity. While both biological and economic systems share the core algorithm of evolution and thus have some similarities, their realizations of evolution are in fact very different and must be understood in their individual contexts.

From a scientific standpoint, the distinction between a metaphorical versus a literal understandmg of the global economy as an evolutionary system is critical. Saying that economic systems are **like** biological systems does not tell us much that is scientifically useful. But saying that both economic and biological systems are subclasses of a more general **and** universal **class** of evolutionary systems tells us a lot. This is because researchers believe that there are general laws of evolutionary systems.[28] Scientists consider certain features of nature universal. For example, gravity works the same way on the earth as it does in the farthest reaches of the universe, and it works the same way on atoms, apples, and galaxies. Modern evolutionary theorists believe that, like gravity, evolution is a universal phenomenon, meaning that no matter whether the algorithm is running in the substrate of biological **DNA,** a computer program, the economy, or in the substrate of an alien biology on a distant planet, evolution will follow certain general laws in its behavior.

If the economy is truly an evolutionary system, and there are general laws of evolutionary systems, then it follows that there are general laws of economics—a controversial notion for many. Saying that there are laws of economics does not imply that we will ever be able to make perfect predictions about the economy, but it does imply that we might someday have a far deeper understanding of economic phenomena than we do today. It also means that economics in the future may be able to make prescriptive recommendations about business and public policy with a level of scientific authority that it has not had before.

Some might see the prospect of a more scientific economics as tremendously exciting and offering many potential benefits for the world. Others might see this as yet another misguided attempt to apply science to the problems of human society. Such critics would remind us of the often-repugnant views that came out of the Social Darwinist movement during the late nineteenth and early twentieth centuries, when philosophers such as Herbert Spencer attempted to crudely and metaphorically apply Darwin's theories to the social and economic realm.[29] The Social Darwinists viewed the principle of "survival of the fittest" (a phrase often misattributed to Darwin, but actually from Spencer) as justifying class inequalities, racism, colonialism, and other social injustices. The new views of economic evolution that we will discuss have nothing in common with the old views of Social Darwinism. In fact, they point in the opposite direction, noting that cooperation is as vital an ingredient in economic development as "survival of the fittest" individualism. Likewise, critics might point to the numerous disasters in social engineering caused by the "scientific" theories of Marxism. The cautions on social engineering are duly noted, and the new theories we will discuss help reveal why economic phenomena are so unpredictable and why most efforts at large-scale social engineering have historically failed.

The Creation of Fit Design

Just what kind of an algorithm is evolution? What does it do? The evolutionary philosopher Daniel Dennett calls evolution a general-purpose algorithm for creating "design without a designer."[30] Take for example, ***Lumbricus*** *terrestris,* the common earthworm, an ingenious design for the purpose of surviving and reproducing in the soil environment of forests, meadows, and household gardens of North America and Europe. It is in essence a tube that propels itself through the earth, ingesting soil in one end and passing it out the other, absorbing lots of nutritious microorganisms in between and gaining sufficient calories for it to find more food and reproduce. This particular biological design comes fully equipped with touch and vibration sensors to help it avoid predators, and backup systems in most of its body segments so that if it is cut in two, it can regenerate itself. It can also reproduce in sufficient numbers to increase the odds that a good many of its offspring will survive to reproduce themselves. The brilliant design for *Lumbricus terrestris* was created by the algorithm of evolution without a rational designer (in this book I will take an unapologetically scientific stance toward evolution and not address religious debates around creationism or so-called "intelligent design").[31]

Evolution creates designs, or more appropriately discovers designs, through a process of trial and error. A variety of candidate designs are created and tried out in the environment; designs that are successful are retained, replicated, and built upon, while those that are unsuccessful are discarded. Through repetition, the process creates designs that are fit for their particular purpose and environment. If the conditions are right, competition between designs for finite resources drives the emergence of greater structure and complexity over time, as evolution builds on the successes of the past to create novel designs for the future.[32] Then as the world changes, so too do the designs that evolution creates, often in brilliant and sometimes surprising ways. Evolution is a method for searching enormous, almost infinitely large spaces of possible designs for the almost infinitesimally small fraction of designs that are "fit" according to their particular purpose and environment. As Dennett puts it, evolution is a search algorithm that "finds needles of good design in haystacks of possibility."[33]

Perhaps one needs "design without a designer" to explain biological evolution, but why do we need "design without a designer" to explain the process of wealth creation in the economy when we have lots of human designers around? Aren't we the gods of our own economic creation? We are accustomed to thinking of human rationality and creativity as the primary driving forces behind wealth creation. Wealth, after all, is created by smart, innovative people coming up with new ideas for products and services and lots of hard work to make and sell them. I will argue that human rationality and creativity do play an important role in wealth creation, but not the role we usually think of. Rationality and creativity feed and shape the workings of the evolutionary algorithm in the economy but do not replace it.

Consider the shirt, the blouse, or any other kind of top you are wearing—where did its design come from?[34] Well, you might reply, it's obvious; a clothes designer designed it. But there is more to the story than just that. What really happened was more or less the following. A number of clothes designers took preexisting ideas of what a shirt should look like and used their rationality and creativity to create all sorts of variations of "shirts" and sketched them out. Those clothes designers then looked at their various sketches and selected a subset of the designs that they thought consumers would like, and made a limited number of samples. The designers then showed those samples to the management of a clothing company, which selected a subset of the designs that it thought consumers would like, and arranged for their manufacture. The clothing company then showed its wares to various retailers, which likewise selected a subset of the designs that they thought consumers would like. With orders in hand, the clothing company then scaled up its manufacturing and supplied the retailer with the shirts. You then walked into a store, browsed through a wide variety of shirts, and selected the one you liked and bought it. Differentiation of designs, selection according to some criterion of fitness, and amplification or scaling up of the successful designs to the next stage of the process—all of this happened both within the clothing company itself and within the overall fashion marketplace. Your shirt was not designed; it was evolved.

But why does the fashion industry go through this iterative, and in many ways, wasteful, process? The reason that your shirt was evolved rather than designed is that no one could predict exactly what kind of shirt you would want out of the almost infinite space of possible shirt designs. The old Soviet Union tried this kind of rational prediction in its infamous five-year plans, and the results included both economic disasters and major fashion errors. As we will see, despite all the strengths and virtues of human rationality, prediction in a system as complex as the economy over anything but the very short term is next to impossible. We use our brains as best we can in economic decision making, but then we experiment and tinker our way into an unpredictable future, keeping and building on what works and discarding what does not. Our intentionality, rationality, and creativity do matter as a driving force in the economy, but they matter as part of a *larger* evolutionary process.

Economic evolution is not a single process, but rather the result of three interlinked processes. The first is the evolution of technology, a critical factor in economic growth throughout history. Most notably, the sharp bend in economic growth around 1750 coincides with the great technological leap of the Industrial Revolution. But the evolution of technology is only part of the story. The evolutionary economist Richard Nelson of Columbia University has pointed out that there are in fact two types of technology that play a major role in economic growth.[35] The first is Physical Technology; this is what we are accustomed to thinking of as technology, things such as bronze-making techniques, steam engines, and microchips. Social Technologies, on the other hand, are ways of organizing people to do things. Examples include settled agriculture, the rule of law, money, joint stock companies, and venture capital. Nelson notes that while Physical Technologies have clearly had an immense impact on society, the contributions of Social Technologies have been equally important and in fact, the two coevolve with each other.[36] During the Industrial Revolution, for example, Richard Arkwright's invention of the spinning frame (a Physical Technology) in the eighteenth century made it economical to organize cloth-making in large factories (a Social Technology), which in turn helped spur numerous innovations in the application of water power, steam, and electricity to manufacturing (back to Physical Technologie~). The stories of the agricultural, industrial, and information revolutions are all largely stories of the reciprocal dance between Physical and Social Technologies.

Yet the coevolution of Physical and Social Technologies is only two-thirds of the picture. Technologies alone are nothing more than ideas and designs. The Physical Technology for a cloth-spinning frame is not itself a cloth-spinning fi-ame—someone actually has to make one. Likewise, the Social Technology for a factory is not a factory—someone actually has to organize it. In order for technologies to have an impact on the world, someone, or some group of people, needs to turn the Physical and Social Technologies from concepts into reality. In the economic realm, that role is played by business. Businesses fuse Physical and Social Technologies together and express them into the environment in the form of products and services.

Businesses are themselves a form of design. The design of a business encompasses its strategy, organizational structure, management processes, culture, and a host of other factors. Business designs evolve over time through a process of differentiation, selection, and amplification, with the market as the ultimate arbiter of fitness. One of the major themes of this book is that it is the three-way coevolution of Physical Technologies, Social Technologies, and business designs that accounts for the patterns of change and growth we see in the economy

Complexity Economics

The notion that the economy is an evolutionary system is a radical idea, especially because it directly contradicts much of the standard theory in economics developed over the past one hundred years. It is far from a new idea, however. Evolutionary theory and economics have a long and intertwined history.[38] In fact it was an economist who helped spark one of Charles Darwin's most important insights. In 1798, the English economist Thomas Robert Malthus published a book titled *An Essay on the Principle of Population, as It Affects Future Improvements of Society,* in which he portrayed the economy as a competitive struggle for survival and a constant race between population growth and humankind's ability to improve its productivity. It was a race that, Malthus predicted, humankind would lose. Darwin read Malthus's work and described his reaction in his autobiography:

> In October 1838, that is fifteen months after I had begun my systematic enquiry, I happened to read for my amusement "Malthus on Population", and being well prepared to appreciate the struggle for existence which everywhere goes on from long-continued observation of the habits of animals and plants, it once struck me that under these circumstances favorable variations would tend to be preserved and unfavorable ones to be destroyed. The result of this would be the formation of new species.
>
> Here then I had at last got a theory by which to work.[39]

Darwin's great insight into the critical role of natural selection in evolution was thus inspired by economics.[40] It was not long after Darwin published his *Origin of Species* that the intellectual currents began to flow back the other way from evolutionary theorists to economists. In 1898, the economist Thorstein Veblen wrote an article that still reads remarkably well today arguing that the economy is an evolutionary system.[41] Not long afterward, Alfred Marshall, one of the founders of modern economic theory, wrote in the introduction to his famous *Principles of Economics*, "The Mecca of the economist lies in economic biology."[42] Over the following decades, a number of great economists, including Joseph Schumpeter and Friedrich Hayek, delved into the relationship between economics and evolutionary theory.[43] In 1982, Richard Nelson and Sidney Winter published a landmark book titled *An Evolutionary Theory of Economic Change*. It was the first major attempt to marry evolutionary theory, economics, and the then recently developed tool of computer simulation.[44]

Despite these efforts by some of the finest minds in economics, evolutionary thinking has had relatively little impact on mainstream economic theory. Beginning at about the same time as Darwin's *Origin of the Species*, economics took a turn down a very different road. Since the late nineteenth century, the organizing paradigm of economics has been the idea that the economy *is an equilibrium system*, essentially a system at rest. As we will see, the primary inspiration for economists from the late nineteenth through the mid-twentieth centuries was not biology, but physics, in particular the physics of motion and energy. Traditional economic theory views the economy as being like a rubber ball rolling around the bottom of a large bowl. Eventually the ball will settle down into the bottom of the bowl, to its resting, or equilibrium, point. The ball will stay there until some external force shakes, bends, or otherwise shocks the bowl, sending the ball to a new equilibrium point. The mainstream paradigm of economics over the past hundred years has portrayed the economy as a system that moves from equilibrium point to equilibrium point over time, propelled along by shocks from technology, politics, changes in consumer tastes, and other external factors.

While economists were pursuing their vision of the economy as an equilibrium system, during the latter half of the twentieth century, physicists, chemists, and biologists became increasingly interested in systems that were far from equilibrium, that were dynamic and complex, and that never settled into a state of rest. Beginning in the 1970s, scientists began to refer to these types of systems as *complex systems.* This is a term we will look at in detail later, but in brief, a complex system is a system of many dynamically interacting parts or particles. In such systems the micro-level interactions of the parts or particles lead to the emergence of macro-level patterns of behavior. For example, a single water molecule sitting in isolation is rather boring. But if one puts a few billion water molecules together and adds some energy in the right way, one gets the complex macro pattern of a whirlpool.[45] The pattern of the whirlpool is the result of the dynamic interactions between the individual water molecules. One cannot have a whirlpool with a single water molecule; rather, the whirlpool is a collective or "emergent" property of the system itself.

During the 1970s, as scientists came to know more about the behaviors of complex systems, they became increasingly interested in systems in which the particles were not simple things with fixed behaviors like water molecules, but were things with some intelligence and the capability of adapting to their environment. Water molecules cannot adapt their behavior, but ants, for example, can. An ant may not be terribly smart by human standards, but it can nonetheless process information from other ants and from its environment and modify its behavior accordingly. Like a water molecule, a single ant on its own is not terribly exciting. However, if you put a few thousand ants together, they interact with each other, communicate using chemical signals, and can coordinate their activities to do things such as build elaborate anthills and organize sophisticated defenses against attackers. Scientists refer to parts or particles that have the ability to process information and adapt their behavior as agents and call the systems that agents interact in complex adaptive *systems*.[46] Other examples of complex adaptive systems include the cells in your body's immune system, interacting organisms in an ecosystem, and users on the Internet. With the advent of inexpensive, high-powered computers in the 1980s, scientists began to make rapid progress in understanding complex adaptive systems in the natural world and to see such systems as forming a universal class, with many common behaviors. In fact, many biologists have come to view evolutionary systems as just one particular type, or subclass, of complex adaptive systems.

Social scientists following this work increasingly began to wonder whether economies too might be a type of complex adaptive system. The most obvious characteristic of economies is that they are collections of people interacting with each other in complex ways, processing information, and adapting their behaviors. In the 1980s and early 1990s, researchers began to experiment with models of economic phenomena that were radically different from traditional models.[47] Rather than portraying the economy as a static equilibrium system, these models presented the economy as a buzzing hive of dynamic activity, with no equilibrium in sight. Just as the pattern of a whirlpool arises from interacting water molecules, these models showed complex patterns of boom and bust and waves of innovation emerging from the interactions of simulated agents, just as they do in the real economy. Interest and research in understanding the economy as a complex adaptive system has grown rapidly during the past decade, and over the course of this book, we will undertake a review of that work.

I will refer to this body of work as Complexity Economics (credit—or blame—for coining this term goes to the economist Brian Arthur, formerly of Stanford University and the Santa Fe Institute).[48] One should not assume from this label that there is currently a single, synthetic theory of Complexity Economics. Rather, my use of the term is intended to cover the broad range of theories, hypotheses, tools, techniques, and speculations that we will survey in this book. At this stage in its development, Complexity Economics is a work in progress, or what philosophers of science refer to as a "program" rather than a unified theory.[49]

The Road Map Ahead

If the economy is indeed a complex adaptive system, then this has four important implications. First, it means that for the past century, economists have fundamentally misclassified the economy and that the mainstream economic theory reflected in textbooks, management thinking, and government policies today is either wrong or, at best, only approximately right. This is an argument we will explore over the remainder of part 1.

Second, viewing the economy as a complex adaptive system provides us with a new set of tools, techniques, and theories for explaining economic phenomena. We will discuss these new approaches in part 2.

Third, it means that wealth must be a product of evolutionary processes. Just as biological evolution summoned complex organisms and ecosystems out of the primordial soup, economic evolution has taken humankind fi-om a state of nature to the modern global economy, filling the world with order, complexity, and diversity along the way. In part 3, we will develop and discuss an evolutionary explanation for the creation of economic wealth.

Fourth and finally, history shows that each time there has been a major shift in the paradigm of economic theory, the tremors have been felt far beyond the academic world. Adam Smith's ideas had an important influence on the growth of free trade in the nineteenth century; Karl Marx's vision inspired revolutions and the rise of socialism in the early to mid-twentieth century; and the intellectual dominance of Anglo-American Neoclassical economics coincided with the ascendancy of global capitalism in the latter decades of the twentieth century. It will probably be several decades before the full socio-politico implications of Complexity Economics become clear. Nonetheless, the outlines of Complexity Economics are sufficiently formed that in part 4 we can begin to explore its implications for business and society.

We will arrive at the end with a message of optimism: if we can better understand the processes of wealth creation, then we can use that knowledge to develop new approaches to create economic growth and opportunity for people. Complexity Economics will not be a cure-all for the challenges of management or the ills of society But just as a more scientific understandmg of natural phenomena has been a major contributor to bettering the human condition, a more scientific understanding of economic phenomena has the potential to help improve the lives of people around the world.

Traditional Economics

A WORLD IN EQUILIBRIUM

IT WAS 1984 and John Reed had a problem.' At the age of forty-five, he had just been elected chairman and CEO of one of the world's largest companies, Citicorp. But Reed was inheriting a company that had recently been through a major trauma. Throughout the 1970s, Citicorp, along with other major American banks, had lent aggressively to the governments of developing countries, in particular to those in Latin America. Reeds predecessor, Walter Wriston, had proclaimed that such lending was "safe banking" because sovereign governments did not default on their debts. Wriston was proved badly wrong when in August 1982 the Mexican government was unable to roll over its massive debt. This set off a chain of events that resulted in a global financial crisis. The next several years saw widespread defaults, currency devaluations, and economic collapse in several countries. When the dust settled, millions of poor people found themselves even poorer, and the banks found that $300 billion had evaporated from their balance sheets. Citicorp alone had lost $1 billion in one year and was still sitting on $13 billion in bad debts.

Reed wanted to understand why the crisis had happened, how it had happened, and, most importantly, how it could be prevented from happening again. How had the best brains at Citibank and all the other major banks so badly misjudged the risks involved? Why had no one been able to foresee the problems these loans would create? How had a set of local events in Mexico spiraled into a global crisis? And why had governments around the world been *so* ineffectual in their responses?

Reed consulted various experts, including leading economists from academia, Wall Street, and government. Reed himself was well versed in economics from his student days at the Massachusetts Institute of Technology (MIT). If it was anyone's job to be able to answer these types of questions, surely it must be the economists. Yet, the economists had little new or useful to say about the crisis. In fact, Reed believed that their recommendations during the crisis had been dead wrong. According to the science writer Mitchell Waldrop, "When it came to world financial markets, Reed had decided that professional economists were off with the fairies . . . Reed thought that a whole new approach to economics might be necessary."[2]

The Need for a New Approach

Reed is not alone in questioning the state of economics. Over the past decade there has been a surge in criticism of economic theory.[3] For example, in 1996, John Cassidy wrote a controversial and widely read article for *The New Yorker* titled "The Decline of Economics."[4] Cassidy charged that economics had disappeared into an ivory-tower world of highly idealized theory, untested by data, and packed with unrealistic assumptions. He claimed that economics had become a "giant academic game" in which economists wrote papers for each other, showing off their mathematical brilliance, but demonstrating little interest in the relevance of their theories to the real world. He argued that most businesses had given up on economics, and he noted that companies such as IBM and GE had shut down their economics departments.

But it is not only businesspeople and journalists who are critical of the current state of economics; economists themselves are their own toughest critics.' In the *New Yorker* piece, Cassidy quoted Joseph Stiglitz, a former chairman of the U.S. President's Council of Economic Advisors, chief economist at the World Bank, and a Nobel Prize winner, saying, 'Anybody looking at these models would say they can't provide a good description of the modern world."[6] In the same piece, Gregory Mankiw of Harvard, and also a former chairman of the Council of Economic Advisors, suggested that, given the low useful output of economists, less money should go into their research, and he compared them to over-subsidzed dairy farmers. Even Alan Greenspan, the former chairman of the U.S. Federal Reserve and one of the most highly respected figures in economic policymaking, once remarked to his Federal Reserve colleagues, "We really do not know how [the economy] works . . . The old models just are not working," and in earlier comments noted, 'A surprising problem is that a number of economists are not able to distinguish between the economic models we construct and the real world."'

Although dissatisfaction with the state of economic theory has been growing, few critics would argue that the field has been completely useless or un-influential. On the contrary, most business leaders, policy makers, and even self-critical economists will admit that economics has produced some enormously powerful and influential ideas, ranging from the efficiency of markets to the benefits of free trade and the importance of individual choice. One measure of the success of economic theory can be found in the wealthy economies of the G7 countries (Britain, Canada, France, Germany, Italy, Japan, and the United States), where these ideas have been implemented to a greater extent than in most of the rest of the world. What most people in the G7 take for granted today—the use of interest rates to manage inflation; monetary and fiscal policies to dampen the business cycle; active encouragement of competition; a social safety net to take the rough edges off the market system; and product safety, environmental, and labor regulations to protect people from market failures—were all not quite so common one hundred, fifty, or even twenty years ago. All are ideas developed by academic economists during a century of very hard work.

Rather, the issue is a growing sense in the academic, business, and policy communities that economics is not fulfilling its true potential as a science.[8] Many of the "big ideas" of the field are now well over a century old, and too many of the fields formal theories and mathematical models are either hamstrung by unrealistic assumptions or directly contradicted by real-world data. The point is not to denigrate the contributions of the past, but rather to say "economics can do better" and it is time to move on.

In this chapter and the next, we will look at why a fundamentally new approach is needed. We will begin by defining the conventional wisdom in the field, or what I will refer to as Traditional Economics. We will then take a whirlwind tour of the history and key concepts of Traditional Economic theory and, in chapter 3, look at a synthesis of what the critics have to say. Inevitably we will only skim the surface of over two hundred years of economic ideas and leave out much important work. But the purpose of these two chapters is not to provide a textbook account of Traditional Economics or a comprehensive survey of the criticisms (far more complete accounts are referenced in the notes and listed in the bibliography).' Rather, the goal is to highlight a set of ideas that have been central to the development of modern economics, examine their strengths and weaknesses, and lay some groundwork for our discussions of Complexity Economics in part 2. As we will see, in order to fully appreciate where economics is going in the future, it is important to first understand its past.

Defining Traditional Economics

I will use the term Traditional Economics to refer to the set of ideas that have dominated economic theory for the past century. At this point, it is appropriate to define what I mean by the term. In general, Traditional Economics is the economics one finds in university textbooks, discussed in the news media, and referred to in the halls of business and government—it is the mainstream view of academic economics." In order to add some more precision to the term, I will follow the lead of two prominent critics of Traditional theory, Richard Nelson of Columbia University and Sidney Winter of the University of Pennsylvania, and use the literature of economics itself as the basis for my definition:[11]

> Traditional Economics is the set of concepts and theories articulated in undergraduate and intermediate graduate-level textbook. It also includes the concepts und theories that *peer-reviewed* **surveys** claim, or assume, that the *field* generally agrees on.[12]

Textbooks represent a consensus view of the profession and include the basic ideas that anyone being introduced to the field needs to know.[13] But textbooks inevitably omit more-advanced material. I have thus added survey books and articles to my definition as they summarize the state of the field at a given point in time. The limitation of both textbooks and surveys, of course, is that they typically focus on the conventional rather than the cutting edge.[14] But this restriction is intentional; I mean for Traditional Economics to refer to the historical core of economics, the stuff for which the Nobel Prizes have already been awarded.[15] The ideas that I will lump under the "Traditional" label will generally refer to what economists call Neoclassical economics, a term that will be defined later in the chapter.[16]

Inevitably, what is and is not included under the Traditional label will be somewhat subjective, and there will be a gray zone of ideas that are half in and half out. Nonetheless, the label will prove useful to our later discussions as we draw a distinction between the historical paradigm and the new ideas from Complexity Economics that are challenging it. With these caveats in mind, now that we have labeled the Traditional Economics box, let's look inside it.

Pin Making and the Invisible Hand

We will begin with perhaps the most famous economist of all, Adam Smith. Smith was not the first economist (that honor arguably goes to the ancient Greek philosopher Xenophon; the word economics is derived from the title of his work, *Oikonomikos*), but Smiths influence is such that he provides **an** appropriate jumping-off point for our discussion.[17] Smith was born in Kircaldy, a small town near Edinburgh in Scotland, and lived from 1723 to 1790, during what historians refer to as the *Classical* period of economic theory (circa 1680–1830).[18] Smith was educated at Oxford, but spent most of his career at the University of Glasgow. His first significant work was not in economics but in moral philosophy. The Theory of Moral Sentiments was published in 1759 and made him a key figure in the Scottish Enlightenment at a relatively young age. While at Glasgow he came to the attention of a wealthy young Scottish duke who took him on as his well-paid private tutor. Smith traveled with the duke to France, where the young tutor was exposed to the economic ideas being debated on the Continent at the time, in particular by the Physiocrats, a group of intellectuals who held the radical idea that governments should limit their interference in the economy and let markets do most of the work. Financially secure with his income from the duke, he returned to Kircaldy, where he lived with his mother in relative isolation for six years working on the manuscript for his Wealth of Nations. The book was published in 1776 and was instantly recognized as a great work.

There are two fundamental questions that economists have grappled with throughout the history of their field: how wealth is created and how wealth is allocated." Smith addressed both in The Wealth of *Nations.*[20] His answer to the first question was simple but powerful: economic value is created when people take raw materials from their environment and then, through their labor, turn those materials into something that people want. For example, a potter might take clay from the ground and use it to create a bowl. Smith's great insight was that the secret to wealth creation was improving the productivity of labor. The more bowls a potter can make in an hour, the richer he or she will be. The secret to greater productivity in turn was the division of labor and the specialization that it enables.[21] Smith famously cited the example of a pin factory, where he observed ten men at work, each of whom specialized in one or two steps of the pin-making process.[22] Smith noted that this specialization and cooperation enabled the group to make 48,000 pins per day, or 4,800 pins per man. Without this division of labor, he estimated, the factory would have only been able to make twenty pins per man per day, or in the case of the less-skilled men, none.

A growing population will increase the total wealth of a society as the amount of available labor grows. But growing wealth on a per-person basis (thus raising individual standards of living) requires increasing productivity, and increasing productivity requires specialization. This logic led Smith to the second great question of economics: What determines how wealth and resources are allocated in a society? If creating wealth requires specialization, then specialization requires trade—after all, the pin makers couldn't eat their pins, they had to trade them for other goods they needed. But if pin makers, farmers, fishermen, carpenters, and other producers are all trading their wares in an economy, what determines the way in which goods are allocated? How many pins equals a bushel of wheat? How many fish for a carpenter's chair? Who will be richer, the pin maker or the fisherman? The natural corollary for Smith, the moral philosopher, was not just the question of how resources are allocated, but how they *should* be allocated; what is a fair or just allocation of resources both for the individual and for society as a whole?

Smith's view was that the most just mechanism for allocating resources from the point of view of the individual was one that enabled people to pursue their own self-interest and make their own choices. After all, people are usually the best judges of their own happiness. At the same time, the best allocation of resources for society as a whole was the one that put resources to their most efficient uses, thus maximizing the total wealth of society. Wasting resources was morally unjust (especially to a frugal Scotsman) because it reduced the overall wealth available to society. Smith's maxim was taken from his mentor at Glasgow, Francis Hutcheson, who argued for "the greatest happiness of the greatest number."[23] Smith's view on how this objective should be achieved was (and to some people still is) a radical one: that competitive markets are the most morally just mechanism for allocating a society's resources. He argued that if people were left to trade freely, self-interest would drive them to provide the goods and services people need: "It is not from the benevolence of the butcher, brewer, or the baker that we expect our dinner, but from the regard to their own interest."[24] Furthermore, the combination of the profit motive and competition would drive them to provide those goods and services as efficiently as possible: "Every individual is continually exerting himself to find out the most advantageous employment for whatever capital he can command."[25]

Smith argued that this pursuit of self-interest would in turn benefit society as a whole: "[The merchant] intends only his own gain, and he is in this, as in many other cases, 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 the society more effectually than when he really intends to promote it."[26]

The "invisible hand' that led society to the happy result of efficient resource allocation was the mechanism of competitive markets. Smith described how price provides the key mechanism through which producers and consumers meet in the marketplace.[27] If there is too little supply for the available demand, then prices rise, producers increase production, and consumers decrease consumption. If there is too much supply for the available demand, then prices fall, producers decrease production, and consumers increase consumption. At some point the market reaches a price at which the two opposing forces come into balance: supply meets demand and the market clears. Smith argued that left to their own devices, the combination of self-interest and competitive markets would naturally bring the economy to this point of balance. Smith's point can be re-phrased in modern terms by quoting the character Gordon Gekko from the 1980s movie *Wall Street*, "greed is good' — a rather surprising conclusion coming from Smith the moral philosopher.

A Healthy Balance

The notion that the economy has a balancing point to which it naturally progresses is a theme that stretches back well before Smith to the field's earliest days and remains a core concept of Traditional Economics today Competition for finite resources inevitably means that there are opposing forces or tensions in the economy. For the seventeenth-century Irish financier Richard Cantillon, the central tension in the economy was between population and the food-growing capacity of land. Cantillon believed that the brutal mechanisms of overpopulation and starvation would cause wages and prices in the economy to self-adjust to a point where the two would eventually come into balance.[28] For the eighteenth-century French intellectual François Quesnay (the leader of the Physiocrats, with whom Smith spent much time in France), the central tension was between agriculture, manufacturing, and the land-owning aristocracy. With his famous Tableau Economique (in essence a flow diagram of the economy), Quesnay claimed to be able to calculate the prices and levels of production that would bring the economy into balance.[29] For Quesnay, who had been a physician prior to venturing into economics, a balanced economy was a healthy economy, just as in eighteenth-century me&-cine a body was healthy if its "humours" were in balance. For Smith, the central tension in the economy was between consumers and producers, and the balance to be achieved was that between supply and demand (we should note, though, that Smith's view of supply and demand was not the complete theory presented in textbooks today, which would be created later by John Stuart Mill and Alfred Marshall).

While Smith described the role of markets in achieving the balance between supply and demand, he did not describe in detail the decision-making process by which self-interested producers determined how much product to supply, or how self-interested consumers determined how much to demand. The core ideas on this would come from two of Smith's Classical contemporaries: Jacques Turgot and Jeremy Bentham.

Jacques Turgot was a minister in the government of Louis XV and a famous proponent of *laissez-faire,* or the philosophy that governments should minimize their interference in the workings of markets.[30] Despite Turgot's views, the French government at the time was very much involved in running the economy *(plus* ça change, *plus* c'est *la* même chose), and one of Turgot's jobs as a minister was to deal with food shortages.[31] In 1767 he observed that if a farmer simply throws seed on a plot of land, he will only get a very small crop. If he tills the soil just once before seeding, he will get a much larger crop. If he tills the land twice, he might not merely double but triple his output. As the farmer works the soil harder and harder, he will get progressively larger crops. But at some point the soil will become exhausted and each incremental unit of effort invested by the farmer will yield a smaller and smaller return. On the basis of these observations, Turgot articulated what has come to be known as the *law of* **diminishing returns.** In most production processes, whether it is farming, manufacturing, or a service business, as one inputs more and more of a particular factor (e.g., labor, raw materials, or machinery), at some point one gets progressively less output bang for the input buck. The law of diminishing returns is a critical force in helping the economy achieve balance. Given a price in the market, a producer will keep adding more inputs and expanding output until the payoff is no longer worth it, that is, until the incremental cost of producing the next unit of output is greater than the incremental revenue one would receive for it. Thus a farmer will work his land just the right amount demanded by the market, no more, no less. If the price of his crop goes up, he will work the land harder (or put more land under the till), while if the price goes down, he will grow less. If returns on production did not diminish at some point, then the farmer would keep expanding output infinitely—an absurd result.[32] Turgot's law provided a crucial concept linking producer costs into the supply side of supply and demand.[33]

At approximately the same time, an English philosopher, Jeremy Bentham, was making a similarly important contribution to the demand side. Bentham, born in London in 1748, was a child prodigy who learned Latin at age four and went to Oxford at age twelve.[34] Like Adam Smith, Bentham viewed himself as a moral and political philosopher. Smith had identified human self-interest as the motivating force that drove the economy, but did not have much to say on just how that self-interest translated into specific economic decisions. Bentham argued that the pursuit of self-interest was a rational activity based on a calculus of pleasure and pain. Bentham identified a quantity that he termed **utility** to measure individual pleasure and pain.[35] He argued that economic choices were the result of an individual's calculations as to what actions would maximize his or her utility.[36] If you like apples and dislike bananas, when faced with a choice between an apple and a banana, you will calculate that consuming the apple will provide you with greater utility and therefore choose it. For another person the utility of the banana might be higher. Bentham's ideas developed a strong following in late-eighteenth-century intellectual and political circles and came to be known as Utditarianism. The credo of the Utilitarians was that society should be organized in such a way as to maximize its collective utility, or happiness.

Some fifty years later the German economist Hermann Heinrich Gossen built on Bentham's ideas and gave us the *law of diminishing marginal utility*.[37] This was in essence the flip side of Turgot's law. Just as Turgot showed that there were diminishing benefits to increased production, Gossen showed that there were also diminishing benefits to increased consumption. For example, if one is very hungry and buys a doughnut, its consumption might provide quite a lot of satisfaction, or utility. If one was still hungry and bought a second doughnut, it too might be satisfying, but according to the law of diminishing marginal utility, it would be incrementally less so than the first. By the time one gets to the fifth or sixth doughnut, one's incremental satisfaction is likely to be pretty small (or perhaps even negative as one gets a stomachache). At some point, one will say, "I'm full and the next doughnut is just not worth the money." Just as a farmer will increase production if the price rises and will reduce production if the price falls, the point at which a consumer says "it is not worth it" and stops consuming will be lower or higher, depending on price. Thus, demand falls as price rises, and vice versa. Also, just as diminishing marginal returns keep farmers from growing an infinite quantity of crops, diminishing marginal utility keeps consumers from consuming an infinite quantity of doughnuts.

The combination of diminishing marginal returns on production and diminishing marginal utility on consumption means that markets have a natural balancing mechanism—price. Price is the key piece of information that producers and consumers share. A price increase will simultaneously lower the consumption point of consumers and raise the production point of producers, while a price decrease will accomplish the reverse.

Thus the Classical period of economics ended with a compelling framework in place for describing how markets balance the needs of consumers with the economics of production, and naturally progress to a point that satisfies both. But an important question remained unanswered: For a given commodity, a given set of utilities, and a given production process, what exactly would the price be? Could we calculate it? Could we predict it?

Dreams of a New Science

The work of the Classical economists was followed by the Marginalist era (circa 1830–1930). The central figure of this period was Léon Walras, who was born in 1834 in Evreux, France. The young Walras had a very shaky start to his career, and there was little foreshadowing of his later greatness. As a student, he was twice rejected from the prestigious École Polytechnique due to poor mathematical skills. He instead went to the École des Mines but failed as an engineer, then tried his hand as a novelist but was unsuccessful at that as well. One evening in 1858, a depressed Walras took a walk with his father, a teacher and writer, discussing what he should do with his life.[38] The elder Walras, a great admirer of science, said that there were two great challenges remaining in the nineteenth century: the creation of a complete theory of history, and the creation of a scientific theory of economics. He believed that differential calculus could be applied to economics to create a "science of economic forces, analogous to the science of astronomical forces."[39] The younger Walras was inspired by his father's vision of a scientific economics and decided to make achieving that vision his life's work. Walras then spent several years struggling as a newspaper writer and a bank employee, while in his spare time writing articles and pamphlets on economics. In **1870,** after much debate by the other professors, he was finally appointed to the faculty of the Lausanne Academy and, in 1872, completed his masterwork, Elements *of a* Pure *Economics.*[40]

Prior to Walras's Elements, economics was not a mathematical field. Many earlier economists, such as Smith and Bentham, regarded themselves as philosophers rather than scientists, and the mathematics of the Classical period is generally limited to a few numerical examples and a bit of algebra, but nothing more sophisticated.[41] Walras and his fellow Marginalists radically changed that. They lived in an era of great scientific progress. Following Newton's monumental discoveries in the seventeenth century, a series of scientists and mathematicians, including Leibniz, Lagrange, Euler, and Hamilton, developed a new mathematical language using differential equations to describe a staggeringly broad range of natural phenomena. Problems that had baffled humankind since the ancient Greeks, from the motions of planets to the vibrations of violin strings, were suddenly mastered. The success of these theories gave scientists a boundless optimism that they could describe any aspect of nature in their equations.[42] Walras and his compatriots were convinced that if the equations of differential calculus could capture the motions of planets and atoms in the universe, these same mathematical techniques could also capture the motion of human minds in the economy

In particular, Walras saw a parallel between the idea of balancing points in economic systems and balancing points in nature.[43] Many systems in nature have balancing points, or in the language of physics, equilibrium points. As described in the previous chapter, imagine you have a large glass bowl with a smooth, round bottom and a small, hard rubber ball in your hand. You place the ball on the lip of the bowl and let it go. The ball rolls around for a while, swinging back and forth, but eventually it comes to rest at the bottom of the bowl. The ball is now in equilibrium. Equilibrium is achieved when all the forces acting on the system cancel each other out and the system is in balance. In this case, the force of gravity pushing down on the ball is met exactly by the force of the bowl underneath pushing up. The ball will stay precisely in this position, at the bottom of the bowl, forever, unless some new force disturbs it. Notice that in this example, there is only one equilibrium point—the lowest point in the bowl. No matter how many times we drop it into the bowl, the ball will always come to rest at this same point.

Physical systems have a wide variety of types of equilibrium. For example, imagine balancing a pencil exactly on its tip. If you got it just right and were able to make the pencil stand up, it would be in equilibrium. However, unlike the ball in the bowl, this state would be a very unstable equilibrium, as the slightest breeze would tip the pencil over. There are also dynamic equilibrium states. When a planet is in orbit around a star, the gravitational force of the star pulling the planet inward is exactly counterbalanced by the centrifugal force of the planet's motion pushing it outward. This balance will be maintained and the planet will travel in a stable orbit until some outside force disturbs it. Finally, we could also imagine a bowl with a bumpy bottom that would have multiple equilibrium points for the ball to land in.

One of Walras's objectives in bringing mathematics to economics was to make economic systems predictable. Unfortunately, unstable equilibriums are inherently hard to predict, as small changes can send the system in one direction or another. Likewise, during Walras's time, determining whether a dynamic system was in a stable equilibrium was considered such a difficult problem that King Oscar II of Sweden offered a prize of 2,500 crowns to anyone who could solve it.[44] Finally, if a system has multiple equilibriums, then predicting which equilibrium the system will settle in is at a minimum difficult and in many cases an impossible problem. Walras wanted predictability, and that meant he needed a single, stable equilibrium point. Specifically, Walras saw the balance of supply and demand in a market as metaphorically like the balance of forces in a physical equilibrium system. He conjectured that for each commodity traded in a market, there was only one price, one equilibrium point, at which traders would be satisfied and the market would clear. Prices in a market would predictably settle to a single equilibrium level, just as a ball would predictably settle into the smooth bottom of a bowl.

To turn his conjecture into equations, Walras raided the physics textbooks of his time. One such textbook, *Elements of Statics*, published in 1803 by the French mathematician Louis Poinsot, was particularly influential on Walras (even to the extent that Walras echoed its title in his own *Elements*).[45] As Walras's biographer William Jaffé has pointed out, it was specifically from chapter *two* of that book, titled "On conditions of equilibrium expressed by means of equations," that Walras imported the concept of equilibrium from physics into economics and laid the mathematical foundations for the Traditional Economics found in textbooks and journals today.[46] This historical detail is noteworthy, because, as we will see in the next chapter, some critics argue that this borrowing of equilibrium from physics was a crucial scientific misstep that has had lasting consequences for the field.

In building his equilibrium model, Walras put to one side the production half of the economy and focused on trading between consumers. In his model, he assumed that various goods already exist in the economy and the problem is to determine how prices are set and how the goods would be allocated among the individuals involved. To see how Walras's model works, imagine a big room full of people. Each person is endowed with a random sampling of all the goods available in the economy. For example, I might be given five bananas, a washing machine, *two* pairs of shoes, five car tires, and so on, while you might be given a pair of blue jeans, *two* umbrellas, a telephone, three avocados, and other goods. Each person, however, has an in&-vidual set of utilities for the various goods. For example, you might like bananas and I might like avocados, but we both might value the telephone. Given that the initial endowment of goods was random, it is highly unlikely that all the participants will be happy with what they have been given, and so they will want to trade. Walras regarded this desire to trade as a sign that the system was out of equilibrium. It meant that there was a different allocation of goods that would make the group happier. The problem, then, is to find the allocation of goods that leaves everyone in the room as satisfied as possible, and to find the prices for trading that would enable the people to move from their initial state to the more satisfied state. This new state would be in equilibrium because once everyone was as satisfied as possible, given the goods available and prices, no one would want to trade anymore.[47]

To make the trading more organized (and mathematically simpler), Walras imagined that the group had an auctioneer. He assumed that one of the goods in the economy could be used as a form of money (e.g., gold pieces, glass beads, shells) and then the auctioneer would price **things** in terms of that commodity (e.g., an avocado might be worth ten glass beads). The auctioneer would call out prices for each of the goods and take down bids. If there was more demand than supply for the good, he would raise the price; if there was more supply than demand, he would lower the price. He would do this for all the goods in the economy until he reached a point at which supply and demand was balanced across all of them. With **all** the prices set, then and only then would everyone trade, thus ensuring that all the participants maximized the value they received from their trades. The trading would then move the group from their initial random, out-of-equilibrium state, into the happier, equilibrium state. Walras called this state the *general* **equilibrium** point. Walras referred to his auction process as *tâtonnement,* French for "groping," as the auctioneer groped for the general equilibrium point by trying out different prices for different goods.

While Walras's ideas were novel, what was truly revolutionary was his use of sophisticated mathematics borrowed from physics. If one accepted Walras's assumptions that people had different utilities, and that they were rational and self-interested in maximizing those utilities, then one could predict with mathematical precision how they would trade and the relative prices that would be set in the economy. There were a few minor details, like the existence of his godlike auctioneer and questions as to how one could observe and measure individuals' utilities, but these issues could be addressed in the future, a small price to pay for the ability to make mathematically precise, scientific predictions about things like prices in the economy for the first time.[48] Walras's willingness to make trade-offs in realism for the sake of mathematical predictability would set a pattern followed by economists over the next century.

As Predictable as Gravity

Walras was not the only economist during his era raiding physics textbooks in search of inspiration. William Stanley Jevons was born in 1835 in Liverpool, the ninth of eleven children in a prosperous industrial family.[49] Like Walras he was a late bloomer, leaving university without a degree and spending his twenties as an assayer at the Sydney mint during the Australian gold rush. Nevertheless, he had a restless mind, became fascinated by railroads (the Internet of their day), and in his spare time attempted to build mathematical models of railroad economics. This experience convinced him that economics needed to become a mathematical science. He decided to return to England to finish his degree by studying economics. Like Walras, he was a man on a mission determined "to define the foundations of our knowledge of man" and "re-establish the Science [of economics] on a sensible basis."[50]

In 1867, two prominent British scientists, Sir William Thomson (later Lord Kelvin) and Peter Guthrie Tait, published a new textbook titled **A Treatise on Natural Philosophy,** which consolidated recent discoveries in energy physics.[51] One of the eager readers of that book was Jevons. In Thomson and Tait's book, Jevons found new theories developed by Michael Faraday and James Clerk Maxwell for describing gravity, magnetism, and electricity as "fields of force." For example, a mass such as the sun has a gravitational field that pulls objects toward it; the bigger the mass the stronger the gravitational field of force. Jevons saw man's self-interest as a force very much like gravity: "Utility only exists when there is on the one side the person wanting and on the other the thing wanted . . . Just as the gravitating force of a material body depends not alone on the mass of that body, but upon the masses and relative positions and distances of the surrounding material bodies, so utility is an attraction between a wanting being and what is wanted."[53]

Jevons took Bentham's notion of utility, along with Gossen's theory of diminishing returns to consumption and, in his 1871 *Theory of Political Economy*, used equations derived from field theory to turn their ideas from a philosophical concept into a mathematical model.[54] In short, Jevons wanted to make human behavior as predictable as gravity. In order to predict how an object will move in a gravitational field, one must know two things: the direction gravity is acting in, and the shape of any constraints on the motion of the object. To go back to our earlier example, if we roll a ball into a bowl, gravity pulls the ball downward and the sides of the bowl constrain the motion of the ball. We can predict where the ball will eventually land (its equilibrium point) if we know which direction is "down" and the shape of the bowl constraining the motion of the ball. Likewise, we can predict the equilibrium point of a pendulum if we know which direction gravity is pulling it, and the length of the string that constrains its motion. In Jevons's conception, self-interest provides the force, like gravity, that pulls us to maximize our happiness or utility. But we also live in a world of finite resources, and this provides the constraints on our actions. The trick then is to find the combination of goods and services that maximizes our happiness within the constraints of finite resources, and as in Walras's model, we use trade to get to this state.

Let's imagine an economy with two goods, say, wine and cheese. I might generally prefer wine over cheese, but at some point the law of diminishing marginal utility says that I will have had enough wine and would rather have some cheese than another glass of wine. You, on the other hand, might generally prefer cheese to wine, but also at some point would be happy to have some wine rather than more cheese. Now let's imagine there is a finite amount of wine and cheese in this economy and we are both randomly given some of each. Just as in Walras's model, it is unlikely that we will have been given the exact amount that matches our utilities, so we will trade until we each hold an amount of wine and cheese that provides the most satisfaction possible given the total amounts available to us.

Jevons's lasting contribution was to portray the problem of economic choice as an exercise in constrained optimization. That is, given the amounts available, a consumer will calculate what quantities of various goods will make him or her the most happy. In Jevons's view, differences in individual utilities create a kind of potential energy for trade. He wrote in his *Principles* *of Economics*, "The notion of value is to our science what that of energy is to mechanics."[55] Just as a ball in a bowl seeks its minimum energy state within the constraints of the sides of the bowl, human beings will seek their maximum happiness state within the constraints of their finite resources and will trade their way to get there.

The Panglossian Economy

Adam Smith postulated that human self-interest drives markets to a form of balance, a stable state where prices are agreed on, trades are made, and the market clears. Walras demonstrated that this balanced state could be regarded as an equilibrium point that could be mathematically calculated. Jevons showed that if people attempt to maximize their happiness in a world of individually differing utilities and finite resources, they would inevitably trade their way to the market equilibrium point. Adam Smith had gone farther in his claims, however—not only would self-interest drive markets into balance, but it would result in the best possible outcome for society as a whole.

Vilfredo Pareto was an Italian contemporary of Walras and Jevons. Having been trained as an engineer and written his doctoral dissertation on "the elastic equilibrium of solid bodes," Pareto was as well or even better versed in the physics of his day than Walras and Jevons.[56] He was an eccentric personality who spent his later years as a recluse in a Swiss mountain chalet with twenty angora cats. However, he achieved immortality in the world of economics by having his name attached to one of the field's most important concepts.

Ever since Smith's *Wealth of* Nations was published, economists had wanted to determine whether competitive markets truly maximized social welfare and, if so, under what circumstances. Although Jevons had significantly advanced the theoretical treatment of utility, there was still the problem that utility was unmeasurable—one couldn't simply look inside peoples' heads, measure their utilities, and add them up. How then could one tell if social welfare had in fact gone up, or if it had been maximized.

Pareto got around this problem through an ingenious logical argument. He reasoned that there are four kinds of trades that people can make. First, there are win-win trades, in which both parties gain; in this case it is clear that welfare has gone up. Second, there are trades, in which one party gains, but no one loses, and again welfare has unambiguously gone up. Third, there are trades, in which no one gains, but someone loses, and in this case welfare has unambiguously gone down. Fourth and finally, there are trades, in which some parties win and some lose, but without the ability to directly measure utility, it is impossible to determine what the net impact is. Pareto argued that since it takes two consenting people to trade and people aren't stupid, they would only engage in trades that were either win-win or at least win-no-lose, both of which raise the total welfare of the participants. These trades later came to be called Pareto superior trades, and Pareto contended that in free markets, people would keep trading until they had exhausted all the Pareto superior trades. At that point trading would stop since any further trades would make someone worse off, and the market would reach an equilibrium point that later economists called *Pareto* optimal. The Pareto optimal is thus the point at which no further trades can be made without making someone worse off. The Pareto optimal is not necessarily the point at which value is maximized for the entire group, as there might be some trades that would harm some people for the benefit of others, but would nonetheless raise the sum total utility of the group. Without a way to precisely measure utilities and a dictator to force trades that reduce the welfare of some for the benefit of others, the Pareto optimal is the best that one can do in a free society.[57]

Thus, according to the theories of Walras, Jevons, Pareto, and the other Marginalists, in a market economy the participants freely trade their way to a state where they are as satisfied as possible, given the resources available. Through this trading the economy glides to an equilibrium, a natural resting point, where supply equals demand, where resources are put to their most efficient use, and where the welfare of society is Pareto optimal. As Voltaire's Dr. Pangloss put it, "In this best of possible worlds . . . all is for the best."[58] What was perhaps most remarkable about the Marginalists' achievement was that economics now had a mathematical theory that showed how, left to its own devices, a free-market economy would reach this Panglossian state with the inevitability of a ball rolling to the bottom of a bowl. Walras declared that his "pure theory of economics is a science which resembles the physico-mathematical sciences in every respect." Jevons believed that he had created a "calculus of moral effects." And Pareto proclaimed, "The theory of economic science thus acquires the rigor of rational mechanics."[59] In their view, the Marginalists had succeeded in their dream of turning economics into a true mathematical science.

The Neoclassical Synthesis

In the twentieth century, a pantheon of great economists consolidated and built on the foundations laid by the Marginalists. At the turn of the century, the English economist Alfred Marshall bridged Jevons's model of a single market in isolation (partial equilibrium) with Walras's model of many interlinked markets in an economy (general equilibrium). Marshall was also responsible for first drawing the crossed supply and demand curve graphs that have vexed introductory economics students ever since. In the 1930s, John Hicks (who was appropriately the Jevons Professor at the University of Manchester) synthesized the work of Walras, Marshall, and Pareto into a coherent theory in his opus Value and Capital. As Europe descended into war in the middle of the twentieth century, the locus of innovation shifted across the ocean, where a generation of Americans as well as refugees from Hitler's Europe created the modern core of economic theory that has come to be called the *Neoclassical* synthesis. Two of the most prominent figures of that era are Paul Samuelson and Kenneth Arrow.

Samuelson was a true prodigy.[60] His ambitiously titled Foundations of *Economic* **Analysis,** completed in 1941 when he was twenty-six, was written as a thesis while he was still a graduate student at Harvard. In it he essentially took Hicks's synthesized theory, added his own innovations, and turned it into a dazzling mathematical theory that become the standard model for the workings of markets.[61] One of Samuelson's key breakthroughs was solving a problem that had bedeviled economists since the days of Bentham. Utility had become a core part of economic theory, yet it was still a mysterious, unobservable, unmeasurable quantity. Pareto and Hicks had already debunked the idea that a "util" was a fixed unit of measure (like a kilogram or a watt) and argued that utility only had meaning in a relative fashion, as in "to me that apple has twice as many utils as it does relative to an orange." But that still begged the question of how one measured even relative utility. Samuelson's reply was that one didn't have to look inside people's heads and measure utility directly; rather, people would reveal their preferences through the choices they made. All one had to do was assume that people are logical and consistent in their behaviors. If, for example, you gave someone a choice between an apple and an orange and he or she chose the apple, you would predict that if next given a choice between an apple, an orange, and a banana, the person would not choose the orange (logically, he or she should still prefer the apple to the orange and thus either choose it or the banana). While such observations do not allow one to say that "an apple has twice as many utils as an orange," one could definitely say that in this case the person in question "prefers apples to oranges." Samuelson argued that this simple statement was good enough to build a theory of demand upon, and he thus replaced utility theory with a set of basic, logical rules for the ordering of people's *preferences.* These rules became the foundation for the theory of consumer behavior in Traditional Economics and the backbone of the notion that people are rational in their economic choices.[62]

Samuelson's slightly younger contemporary, Kenneth Arrow, also displayed superb mathematical skills from an early age. Arrow has made a number of fundamental contributions to the field, but one of his most famous is a theorem he proved with the French economist Gérard Debreu in 1954. Arrow and Debreu connected Walras's notion of a general equilibrium with Pareto's concept of optimality in a very general way, thus creating the Neoclassical theory of general equilibrium. Their theorem showed that all the markets in the economy together would automatically coordinate on a set of prices that was Pareto optimal for the economy as a whole, and that this would occur even when there was uncertainty in the market (Walras required in his model that everything be certain).[63] This automatic coordination occurs because markets are linked with each other by the ability of some goods to act as substitutes for others (e.g., if the price of coffee goes up, one can switch to tea) and by the tendency of other goods to be consumed together as complements (e.g., a rise in the price of gasoline can reduce the demand for large, gas-guzzling cars). Arrow and Debreu showed that prices act like a nervous system, transmitting signals about supply and demand throughout the economy, and that self-interested people react to those price signals and inevitably drive the system to its socially optimal equilibrium point—the invisible hand is powerful indeed.

Perhaps the most stunning achievement of the Arrow-Debreu general equilibrium theory was that this powerful result was built up from just a small set of axioms. Some of the assumptions were fairly uncontroversial, such as you can't have negative labor or negative consumption. However, some of the assumptions were more problematic. For example, the theorem assumed that everyone is endowed with at least some amount of every commodity, that futures markets exist for every product and service, that everyone is extremely rational in calculating decisions, and knows the probabilities of all possible future states of the world. As with Walras's original model, these assumptions were viewed as necessary simplifications, details to be addressed at another time. The important thing was that one could start with a simple set of axioms and rigorously, mathematically, build up to a very general result: rational self-interest operating in competitive markets would drive the economy to its optimal point. When the theorem was published in 1954, it was hailed by economists as a major breakthrough. At the height of the Cold War, it was eventually interpreted in the political realm (albeit incorrectly) as final mathematical proof of the superiority of market capitalism over socialism.[64] To be sure, Arrow and Debreu's model was a highly simplified picture of an economy, and it was missing real-world features such as monopolistic industries, labor unions, government regulations, taxes, and so on, but its political message was clear. The closer we reach the ideal state of perfect market competition, without distortions and interference, the closer we would be to the optimal equilibrium point.

By the 1960s, there emerged a largely complete theory that began with axiomatic assumptions about individual consumers and producers and built up to sweeping conclusions about markets and economies. Economists refer to such bottom-up theories of individuals and markets as microeconomics. Much work had also been going on during this period in *macroeconomics* as well, where economists look at the economy from the top down, and ask questions such as why unemployment exists, what causes business cycles, and how interest rates and inflation are linked. These are subjects we will return to later, but the critical point for the moment is that in the 1960s and 1970s, the Chicago economists (so called because many were on the faculty of the University of Chicago) such as Milton Friedman and Robert Lucas began to apply the techniques of Neoclassical microeconomics to macroeconomics, and concepts such as rational utility-maximizing consumers and optimal equilibriums became a core part of Traditional macroeconomic theory as well.

From Allocation to Growth

Earlier in the chapter, I noted that economics has historically been concerned with two great questions: how wealth is created and how wealth is allocated. Between the Classical era of Adam Smith and the mid-twentieth-century era of Samuelson and Arrow, the first question was largely overshadowed by the second. The models of Walras, Jevons, and Pareto began with the assumptions that an economy already exists, producers have resources, and consumers own various commodities. The models thus view the problem as how to allocate the existing finite wealth of the economy in a way that provides the maximum benefit for everyone. An important reason for this focus on allocation of finite resources was that the mathematical equations of equilibrium imported from physics were ideal for answering the allocation question, but it was more difficult to apply them to growth. Equilibrium systems by definition are in a state of rest, while growth implies change and dynamism.

An important figure who recognized the contradiction between equilibrium and growth was Joseph Schumpeter (1883–1950), often referred to as an Austrian economist, even though he was born in what today is the Czech Republic.[65] Schumpeter was a colorful character renowned for wearing riding boots to Harvard faculty meetings and formal evening dress for dinners at home. He was famed for proclaiming that he had three goals in life: to be the greatest lover in Vienna, the greatest horseman in Europe, and the greatest economist in the world. Alas, he would say, he had failed in his second goal. Schumpeter was sympathetic to the equilibrium notions of his Neoclassical contemporaries on the question of wealth allocation, but he did not believe that it was the right framework for answering the growth question. The Neoclassical view of production was very static. Firms were assumed to have fixed technologies and product sets, and all they did was calculate the quantity of production that would maximize their profits. As Schumpeter observed, however, economic growth is not just a matter of increasing the quantity of what is already produced; there must be a role for innovation: "Add successively as many mail coaches as you please, you will never get a railway thereby."[66] In the terms described in chapter 1, Schumpeter wanted to explain SKU growth as well as quantity growth.

The Neoclassicals tended to view innovation as an external, or exogenous, factor: a random variable that affected the economy—like the weather—but was outside the bounds of economic study. Schumpeter, however, believed that innovation had to be viewed as internal, or endogenous, to the economy and central to its understandmg. He insisted that for growth to occur, there must be "a source of energy within the economic system which would of itself disrupt any equilibrium that might be attained."[67] For Schumpeter, that source of energy was the figure of the entrepreneur, whom he wrote about in almost heroic terms. According to Schumpeter, technological progress occurred in a random stream of discoveries. The commercialization of new technologies, however, faced numerous barriers, ranging from the need for financing to the intransigence of old habits and mind-sets. Thus, like water behind a dam, the random rain of discoveries built up over time. In Schumpeter's theory, entrepreneurs played the role of dam breakers, unleashing a flood of innovation into the marketplace. In this way, growth comes to the economy not in a steady stream, but as Schumpeter famously put it, in "gales of creative destruction." The origin of wealth, according to Schumpeter, lies in the heroic efforts of individual entrepreneurs. Schumpterian wealth creation occurs when people like Richard Arkwright, Henry Ford, Thomas Alva Edison, and Steve Jobs battle the odds to turn the technologies of their time into successful commercial enterprises.

Schumpeter's theory was in essence a human and historical theory, and this was both its strength and its weakness. While the descriptive richness of Schumpeter's ideas still resonates today, he was never able to translate his theories into the rigorous language of mathematics. This meant that his ideas could never be reconciled with the mathematical Neoclassical framework—a shortcoming that ultimately limited their impact.[68] The lack of a mathematical approach also made growth theory something of an intellectual backwater for the next forty years, until the arrival of Robert Solow.[69]

Solow was born in Brooklyn, was trained at Harvard, and spent his career at MIT.[70] Solow did not suffer from Schumpeter's lack of mathematical acumen and sought to reconcile growth with the ball-in-the-bowl predictability of Neoclassical theory. In his 1987 Nobel Prize lecture, Solow described his motivation for developing his theory.[71] Earlier mathematical work on growth had been fairly simplistic and assumed that the productivity of capital, that is, the return one got from investing in such things as tools, machines, and equipment, was constant. This assumption was clearly unrealistic. Changes in technology through history have dramatically increased the productivity of capital—the productivity of a tractor is far higher than that of an ox-driven plough. Solow wanted to find a way to incorporate this important effect. But unlike Schumpeter, who saw innovation as a disruptive disequilibrium force, Solow wanted to account for innovation in a way that would be consistent with Neoclassical theory and maintain equilibrium in the economy.

Growth and equilibrium do not sound like very compatible concepts. The ball-in-the-bowl is not a system that grows. In a landmark paper in 1956, however, Solow reconciled the two by viewing the economy as being in a kind of dynamic equilibrium, or what he called *balanced growth*.[72] Imagine a circus act where a brave performer rides a bicycle across a high wire. In order to maintain balance and keep from falling off the wire, the performer holds a long pole extended horizontally. Even though the performer is in motion while pedaling forward across the wire, at each point in time, the rider is balanced in a kind of equilibrium. Similarly, Solow saw the economy as being balanced in equilibrium, even as it grew. He treated two key variables in the model as exogenous: the rate of population growth and the rate of technological change. These two variables drove the growth rate (you can think of these as the energy the high-wire bicycle rider is putting into pedaling). Solow then showed that other factors in the economy, such as the rate of savings and the total amount of capital in the economy, would automatically be balanced in response to changes in population growth and technology, just as our circus performer would shift the pole to stay balanced. In Solow's model, the role of the balancing bicycle rider is played by the markets for labor and capital, which work to keep everything in Pareto optimal equilibrium, even as the economy grows.

Solow's model was consistent with Adam Smith's insight that while population growth might increase the total wealth of a nation, only improvements in productivity could make a nation richer on a per capita basis—it is not how much capital a country has that makes it rich; it is how productive that capital is, and according to Solow the key to productivity is technology. Solow's model implied that the United States and other Western countries did not become rich because of a lucky endowment of natural resources or because of capital falling like manna from heaven. Rather, they became rich through a virtuous cycle in which technology improvements led to capital's becoming more productive, which in turn led to more savings, which in turn led to more capital investment. Without technology growth, capital would only grow in proportion to population, and wealth per capita would simply level off. Back in 1956, long before the term became fashionable, Robert Solow had discovered the knowledge economy.[73]

Solow's work set off renewed interest in the topic of growth. A stream of work that provided variations on his basic model soon followed. In the mid-1980s, however, a group of researchers, led by Stanford economist Paul Romer, became increasingly dissatisfied that the real driver of growth in Solow's model, technology, was exogenous, just as Schumpeter had been frustrated fifty years earlier, when economics considered innovation exogenous.[74] Like Schumpeter, Romer thought that the "energy" for growth should be considered endogenous to the economy, and in 1990, Romer published a paper that kicked off the development of what has come to be known as endogenous growth theory.[75]

Romer located the source of energy for growth not in the heroism of the entrepreneur, but in the nature of technology itself. He noted that technology has a cumulative, accelerating quality to it. The more stuff we know, the greater the base of existing human knowledge, and the greater the payoff from the next discovery. Knowledge is what economists refer to as an increasing returns phenomenon. As discussed earlier, in the eighteenth century Jacques Turgot showed that most production processes exhibit the opposite quality of decreasing returns. For most types of production processes, whether it is farming, manufacturing, or services, as one inputs more and more resources, the marginal returns get smaller and smaller. Romer argued that in the case of the production of technology (i.e., think of research and development as a process for producing technology), this logic is reversed; the more we invest in knowledge cumulatively over time, the higher the payoffs. An hour of R&D invested in microchips and biotech today has a higher payoff than an hour of R&D invested in steam locomotives and telegraphs in 1900. Romer created a positive feedback loop in lus model, a virtuous circle, in which the more society invests in technology over time, the richer the society gets, and the greater the payoffs to further investments in technology. The result is unbounded, exponential growth. If we think of the image of a bicycle rider on a high wire again, the increasing returns to investment in technology pushes the pedals of growth at an ever-faster rate.

The Legacy of Traditional Economics

By the end of the twentieth century, Traditional Economics was thoroughly dominated by the Neoclassical paradigm with its foundational notions of rational, optimizing consumers and producers making choices in a world of finite resources, and (with the exception of investments in technology) those choices being bounded by decreasing returns. This combination of self-interest and constraints then drive the economy to the Pareto optimal point of equilibrium. The methodology of economic analysis was also dominated by the use of mathematical proofs that began with a set of assumptions and then built logically up to a set of conclusions. The Neoclassical growth theory pioneered by Solow claimed to answer the great question of wealth creation, while the Neoclassical general equilibrium theory of Arrow and Debreu ostensibly answered the great question of wealth allocation. These canonical models, of course, had many variations, including models that featured uncertainty, imperfect competition, and incomplete information. But these were indeed variations on a theme rather than new symphonies themselves.

The twentieth-century economists had thus realized their ambition to create a set of rigorous, well-defined mathematical models for describing the workings of the economy. Although the dream of completely integrating the micro and macro perspectives under the Neoclassical paradigm had not been fully realized, one could nonetheless travel from the atomistic world of individual decision makers to the sweep of national economies within a logically consistent framework and set of assumptions.[76]

The Traditional paradigm has, without a doubt, had a major impact on the worlds of public policy, business, and finance. Policy makers ranging from central bankers to presidential advisers and finance ministers all rely on the concepts and models of Traditional Economics. Likewise, concepts from Traditional Economic theory are commonly used to inform decisions in the business world—decisions ranging from competitive strategy to whether to undertake a merger or an acquisition.[77] Also, it would not be an exaggeration to say that trillions of dollars are traded each day in world financial markets using calculations made from the theories of Traditional Economics. The ideas of Traditional Economics have made tremendous contributions to our understandmg of the economy and of society more generally.

Nonetheless, despite the unquestionably significant impact of Traditional Economics, the unease expressed at the beginning of the chapter remains valid. The economist Werner Hildenbrand once compared general equilibrium theory to a gothic cathedral, of which Walras and his contemporaries were the architects, and the great economists of the twentieth century were the master builders.[78] Unfortunately, as we will see in the next chapter, the cathedral was built on very shaky ground.

A Critique

CHAOS AND CUBAN CARS

DESPITE HIS OCCASIONAL frustrations with economists, John Reed maintained active connections with the academic community and served on the board of the prestigious Russell Sage Foundation, an organization that supports social science research. During a coffee break at a board meeting in New York, a fellow trustee, Bob Adams, the secretary of the Smithsonian Institution, told Reed about a radical new research organization that was being set up in the desert of New Mexico.' The group was led by a former White House science adviser and Los Alamos National Laboratory research head, George Cowan. His Co-conspirators were an A-list of scientific superstars, including Nobel Prize winner and discoverer of the quark, Murray Gell-Mann, fellow Nobel laureate Phil Anderson of Princeton University, and several Senior Fellows of the Los Alamos Lab.

The group had set itself the modest ambition of fundamentally changing the way in which scientific research is conducted. Historically, science had taken a top-down, reductionist approach, breaking the universe into ever-smaller pieces, moving from the level of galaxies to subatomic particles in search of ultimate laws. The Santa Fe scientists believed that while this approach had been extraordinarily successful, many of the hardest problems in nature are "complex systems" that have collective or emergent characteristics that are better understood though a bottoms-up, holistic approach.[2] For example, the group felt that a question such as "What is life?" would never be cracked by only looking top-down at the chemistry of organisms.[3] An organism is a complex system whose emergent whole is greater than the sum of its chemical parts. Answering the "What is life?" question would require a view of organisms as systems, and a bottoms-up understandmg of how billions of molecules interact to create the complex dance called life. The group felt that for a broad class of phenomena, including the brain, biological ecosystems, the Internet, and human society itself, the sum was in some way greater than the constituent parts, and such an approach was needed. The group also believed that such hard scientific problems require perspectives from multiple disciplines. Progress on a question such as "What is life?" would need the contributions of biologists, physicists, chemists, computer scientists, and others, working together. Yet most universities and research labs were organized in departmental silos that discouraged such collaboration. In **1984** the group created the Santa Fe Institute (SFI) as a nonprofit research organization to pursue the cross-disciplinary study of complex systems, and a short while later set up shop in a disused convent, with Cowan ensconced in the mother superior's office, and views of the Sangre de Cristo Mountains to inspire them.[4]

Reed was intrigued by Adams's description of SFI. Understandmg a system as complex as the global economy was surely a hard scientific problem, and perhaps SFI's bottoms-up, interdisciplinary approach could provide economics with a needed kick in the intellectual pants. Adams introduced Reed to SFI's founders, and in 1987, Reed and Citicorp agreed to fund a cross-disciplinary workshop on economics.

The Clash of the Titans

The meeting was set **up** like a rugby match.[5] Squaring off on one side were ten leading economists captained by Nobel Prize winner Kenneth Arrow, co-originator of the Arrow-Debreu general equilibrium theory described in the last chapter. On the other side were arrayed ten physicists, biologists, and computer scientists, captained by Phil Anderson. The economists' side had luminaries such as Larry Summers, who would later become U.S. secretary of the treasury and then president of Harvard University; Brian Arthur of Stanford University, whose theories would provide key arguments in the Microsoft antitrust trial; and José Scheinkman, who would go on to become chairman of the legendary University of Chicago economics department. The physical scientists' team was no less impressive, with scholars such as David Ruelle, one of the pioneers of chaos theory; John Holland, a researcher in artificial intelligence; Stuart Kauffman, a University of Pennsylvania biologist who had won a MacArthur Foundation "genius" award; and Doyne Farmer, a young hotshot physicist from the Los Alamos National Laboratory who was infamous for his exploits using nonlinear physics to win at roulette in Las Vegas.

Each side presented the current state of its field and then spent ten days debating economic behavior, technological innovation, business cycles, and the workings of capital markets. The economists were excited by the physical scientists' ideas and techniques, but thought the scientists were naive and even a bit arrogant about economic problems. On the other side, the physical scientists were impressed by the mathematical virtuosity of the economists and genuinely surprised by the difficulty of economic problems.

But what really shocked the physical scientists was how to their eyes, economics was a throwback to another era. One of the participants at the meeting later commented that looking at economics reminded him of his recent trip to Cuba. As he described it, in Cuba, you enter a place that has been almost completely shut off from the Western world for over forty years by the U.S. trade embargo. The streets are full of Packard and DeSoto automobiles from the 1950s and relatively few cars of more recent vintage. He noted that one had to admire the ingenuity of the Cubans for keeping these cars running for so long on salvaged parts and the odd piece of Soviet tractor. For the physicists, much of what they saw in economics had a similar "vintage" feeling to it. It looked to them as if economics had been locked in its own intellectual embargo, out of touch with several decades of scientific progress, but meanwhile ingeniously bending, stretching, and updating its theories to keep them running. What the physicists were seeing was the legacy of Walras and Jevons. The mathematical Packards and DeSotos were the equations and techniques that the Marginalists had plundered from physics textbooks a hundred years ago.

Not only did the mathematics of economics seem like a blast from the past, but the physicists were also surprised by the way the economists used simplifying assumptions in their models. Ever since the days of Galileo, scientists have used simplifications such as perfect spheres and ideal gases to make their models easier to analyze. But scientists are generally careful to ensure that while their assumptions might simplify reality, their simplifications don't actually contradict it. And scientists also carefully test whether their assumptions matter to the answers given by their theories. In the view of the scientists at the workshop, the economists had taken the use of assumptions to an extreme. One assumption that got the scientists particularly exercised was what economists refer to as perfect rationality. Traditional Economics simplifies human behavior by assuming that people know everything possible about the future and crunch all that information through incredibly complex calculations to make such basic decisions as whether to buy a pint of milk. Even without being fully aware of the long history of debate on this subject, the physical scientists vociferously objected to the use of a model so clearly at odds with day-to-day reality. The science writer Mitch Waldrop quotes one of the economists, Brian Arthur, who describes the exchange:

> The physicists were shocked at the assumptions the economists were making—that the test was not a match against reality, but whether the assumptions were the common currency of the field. I can just see Phil Anderson, laid back with a smile on his face, saying, "You guys really believe that?"
>
> The economists backed into a corner would reply, "Yeah, but this allows us to solve these problems. If you don't make these assumptions, then you can't do anything."
>
> And the physicists would come right back, "Yeah, but where does that get you—you're solving the wrong problem if that's not reality."[6]

In this chapter, I will argue that despite the field's many successes, the concerns of the scientists at the Santa Fe meeting were valid. When Walras imported the concept of equilibrium from physics into economics, he gained mathematical precision and scientific predictability. But he paid a high price for that gain—realism. The mathematics of equilibrium required Walras and later economists to make a set of highly restrictive assumptions that have increasingly detached theoretical economics from the real world. Traditional Economics has what computer programmers call a "garbage in, garbage out" problem. If you feed a computer bad inputs, it will with absolute precision and flawless logic grind out bad outputs. Likewise, most Traditional Economic models begin with unrealistic assumptions and then, with mathematical inevitability, work their way to equally unrealistic conclusions. As we will see, this is why there is little empirical support for many core ideas of Traditional Economics, and in some cases empirical evidence directly contradicts the theory's predictions. We will look at the assumptions that so vexed the Santa Fe scientists, and then move on to an examination of the empirical record of Traditional Economics. We will close with a return to the history of economics and see how a historical accident sent Traditional Economics down a century-long wrong turn.

Unrealistic Assumptions

The Santa Fe meeting was not the first time economists and physical scientists had clashed over the use of assumptions. In 1901, Léon Walras sent Henri Poincaré, the legendary French mathematician, a copy of his *Elements of Pure Economics*, asking him for his opinion. Poincaré replied, "*A priori*, I am not hostile to the application of mathematics to the economic sciences, as long as one does not go beyond certain limits." In a follow-up letter, the mathematician made clear what those limits were by noting that Walras's theory contained a number of "arbitrary functions" (referring to Walras's use of assumptions). Poincaré commented that the conclusions drawn from Walras's equations were mathematically correct, but "if the arbitrary functions reappear in these consequences," the conclusions of the theory will be "devoid of all interest.'" Just like the Santa Fe scientists a century later, Poincaré was particularly concerned about Walras's assumption of the unlimited foresight of economic actors. As Poincaré put it, "you regard men as infinitely selfish and infinitely farsighted. The first hypothesis may perhaps be admitted in a first approximation, the second may call for some reservations."'

During this period, there was quite a lot of correspondence between economists and the leading scientists of the day, including the French physicists Joseph Bertrand and Hermann Laurent, the American pioneer of thermodynamics J. Willard Gibbs, and the great Italian mathematician Vito Volterra. All echoed Poincaré's complaint that, while it was laudable for economics to become more mathematical and rigorous, throwing out reality for the convenience of making the equations solvable was not the way to go about it.[9] For the most part, however, the economists ignored these criticisms, and the program of building the Neoclassical theory of economics continued apace. The controversy over assumptions didn't go away, but for many decades bubbled along in the field at a low level.

Then in 1953, the University of Chicago's Milton Friedman brought the debate back up to a full boil when he published an essay titled "The Methodology of Positive Economics."" The essay argued that unrealistic assumptions in economic theory simply do not matter so long as the theories make correct predictions. If the economy behaves "as if" people were perfectly rational, then it really doesn't matter whether people are perfectly rational or not. Assumptions need no further justification as long as the results are correct. In other words, if it wasn't "garbage out" it didn't matter what was going "in." The essay was widely read and immediately controversial." At a meeting of the American Economic Association several years later, Herbert Simon of Carnegie Mellon University delivered the counterargument.[12] He noted that the purpose of scientific theories is not to make predictions, but to explain things—predictions are then tests of whether the explanations are correct. But one has to test the whole logical chain of explanation, not just the conclusion reached at the end.

I will use a simple example to illustrate Simon's point. One could propose a theory that would explain that the sky is blue by assuming the existence of giants who paint it blue every night while we are sleeping.[13] Taken to an extreme, Friedman's logic would say that the assumption of giants is irrelevant as long as the theory makes the correct prediction, that the sky is blue, which it does. Simon would argue, however, that one can't just test the correctness of the conclusion. Rather, to accept such a theory, one would also have to observe the giants in action. As the economic philosopher Daniel Hausman has put it, one must "look under the hood of a theory to see that the causal chain of explanation is valid as well.[14]

What, then, is the proper role of assumptions in theory? Why can Galileo and Newton get away with perfect vacuums and idealized spheres while Walras cannot get away with perfectly rational people and godlike auctioneers? Philosophers of science generally agree that there are two golden rules for the use of assumptions.[15] First, the assumptions must be appropriate for the purpose of the model, and second, they must not affect the answers the model provides for that purpose. The source of these two rules comes down to what philosophers of science call *fine* versus coarse graining.

A good way to illustrate this is to imagine scientific theories as being like maps.[16] Maps are approximate pictures of an underlying reality; a map of Oskaloosa, Iowa, is only an approximate representation of the real Oskaloosa. The only perfect map of Oskaloosa is Oskaloosa itself, which is too big to fit in the glove compartment of your car and thus not very useful. Just as map makers idealize and leave out certain features of the terrain, scientists simplify and idealize their theories. What is included or left out will depend on the purpose of the map or theory. If you are driving across the country, you might need just a coarse-grained map that shows the major highways. If, on the other hand, you were going to visit your great-aunt on Ford Avenue in Oskaloosa, you would need a fine-grained map that shows the street grid of Oskaloosa, but not all the highways in the country. Likewise, a cosmologist might be looking at the universe at the level of galaxies while a chemist might be looking at it at the level of atoms; each researcher needs different types and amounts of idealization. The key is that both the coarse- and fine-grained maps (and theories) must agree with *each* other and the observations *of underlying* reality. If a highway map places a river in a particular location, the river must be in the same location on the local map, and must agree with observations of where the river actually is. Likewise, even though the models of the cosmologist and the chemist may focus on different things, the models should not contradict each other, and both should be consistent with empirical and experimental evidence. In map making, one cannot just move roads and rivers around for the purpose of making the maps easier to draw. To many critics, the assumptions of Traditional Economics do not look like a legitimate case of coarse graining. Instead, it appears that beginning with Walras and Jevons, economists began arbitrarily making up assumptions about perfect rationality, godlike auctioneers, and so on, with the sole purpose of making the equilibrium math work. We will now take a closer look at some of the most troubling assumptions in Traditional theory.

Incredibly Smart People in Unbelievably Simple Worlds

Of all the assumptions in Traditional Economics, perhaps the strongest and most obviously unrealistic is its model of human behavior, a topic we will discuss in detail in chapter 6. The standard model, often referred to as *perfect rationality,* is built on two fundamental assumptions. The first is that people pursue their self-interest in economic matters. Economists recognize that in the real world, people occasionally do engage in acts of genuine altruism (though this is notoriously tricky to define), but argue that as a simplification, it is reasonable to assume that people will generally do whatever is in their economic self-interest. The second part of the assumption is that people pursue their self-interest in fantastically complex and calculating ways. Economists regularly assume that we take into account factors such as inflation rates, estimates of future government spending, and the trade deficit in our daily decision making. Economists also assume that we process all this information using equations and calculations that they themselves find difficult to solve.

Furthermore, in order to make human behavior predictable, economists traditionally assume that these superhuman robots live in theoretical worlds that are much simpler than the real world people actually inhabit. For example, to take into account projected interest rates for the rest of your life when deciding whether to put your money into a savings account or buy a six-pack of beer, you need information about what those rates are likely to be. Traditional models typically assume that all the information needed to make decisions is completely and instantly available for free. The reality, of course, is that we often have to make decisions with incomplete or ambiguous information, or if we wanted more information, it would cost us time and money to get it. Other typical assumptions about the world we live in include:

- There are no transaction costs (e.g., no fees, taxes, legal restrictions, or other costs or barriers to buying and selling)
- *All* products are pure commodities sold only on price (e.g., no brands or differences in product quality)
- Companies are always working as efficiently as possible
- Consumers can purchase insurance for any possible eventuality
- Economic decision makers only interact with each other through price, usually through an auction mechanism (when was the last time your supermarket held an auction?)

This combination of assumptions has caused Axel Leijonhufvud, a macroeconomist at the University of California, Los Angeles, to comment that

Traditional Economics models "incredibly smart people in unbelievably simple situations," while the real world is more accurately described by "believably simple people [coping] with incredibly complex situations."" There is a mountain of evidence to support Leijonhufvud's claim (which, again, we will review in chapter 6). Behavioral economists such as Herbert Simon, Daniel Kahneman, and Amos Tversky have shown that while people are intelligent in their decision making, they are intelligent in ways very different from the picture presented by Traditional Economics.[18] Real people are actually quite poor at complex logical calculations, but are very good at quickly recognizing patterns, interpreting ambiguous information, and learning. Real people are also fallible and subject to biases in their decision making. Finally, they engage in what Herbert Simon called satisficing, whereby one looks for a result that is "good enough rather than the absolute best. For example, Traditional Economics would assume that the moment you need gas for your car, you drive to every gas station in your area in search for the one with the lowest price. Simon, on the other hand, would argue that you simply have a rough idea of what gas costs and pull into the nearest station that appears to have a reasonable price." It makes sense that in a world where information is costly, incomplete, and rapidly changing, our brains would be wired to make fast decisions that are "good enough" rather than perfectly optimal.

In recent years, mainstream economists have begun to accept the unreality of these Traditional assumptions. In 2001 the Nobel Prize was awarded to George Akerlof, Michael Spence, and Joseph Stiglitz, whose models recognize that not everyone has access to perfect dormation. Then in 2002 the Nobel went to Daniel Kahneman and Vernon Smith for their work on more realistic theories of behavior. There has also been much work on "non-Walrasian markets" (i.e., markets without auctioneers) by researchers such as Frank Hahn and Takashi Negishi. Despite these advances, models that incorporate all these effects simultaneously and thus portray realistic people in a realistic environment have remained elusive.[20] Equilibrium is a strict master, and while economists are able to relax one or two assumptions at a time, the limitations of equilibrium mathematics mean that truly realistic models require a more radical break from the Traditional framework.

Time Waits for No One

One of the other prices that Traditional Economics has paid for its reliance on equilibrium is a strange view of time. Most Traditional Economic models don't actually consider time; instead they simply assume that the economy clicks along instantly from one equilibrium to another and that the transient conditions between equilibrium states do not matter. If a model does have time, it is typically a "short run" and a "long run," or an imaginary index time (e.g., rounds in game-theory models, or generations in many macroeconomic models). Few models actually have time in the normal sense of minutes, hours, days, and weeks.[21] Yet, time is undoubtedly important in real-world economic phenomena. It takes time to design things, make things, transport things, sell things, get information, and make decisions. How much time these things take matters in understandmg the dynamics of the economy.

This can be illustrated using a well-worn joke about an old economist and a young economist walking down the street. The young economist looks down and sees a $20 bill on the street and says, "Hey, look a twenty-dollar bill!" Without even looking, his older and wiser colleague replies, "Nonsense. If there had been a twenty-dollar bill lying on the street, someone would have already picked it up by now."

In the Traditional Economics view, when a $20 bill hits the street, the world is suddenly out of equilibrium. As rational, self-interested people have an incentive to pick up $20 bills, someone will come along, pick up the bill, and move the world back to equilibrium. What matters is that we know what the equilibrium state is—one with no $20 bills lying on the streets—how long it takes to find and scoop up the bill and the specific path the world follows as it moves between equilibrium states are of no real concern.

In the real world, of course, there is a time delay between a $20 bill's landing on the sidewalk and someone's seeing it and picking it up. It then stands to reason that at any point in time, there are at least some undiscovered $20 bills lying on sidewalks somewhere. It is important to be explicit about the timescales in this process, because the amount of money lying on the streets will be a function of the rate at which bills are dropped and the average time to discovery. By varying the timescales, one can paint scenarios in which the streets are littered with money (rapid rate of loss, long delay until discovery) or in which $20 bills are very rare (slow rate of loss, short delay until discovery) or any scenario in between. One can even construct scenarios in which the world oscillates wildly between piles of money lying around and none.[22] The point is that unless we know the relative timescales involved, we can't say much about how the system will behave.

This lack of explicit timescales was one of Alfred Marshall's favorite complaints about economics a hundred years ago. During the intervening century, there have been some important attempts to introduce dynamics into Traditional theory, including work by Richard Day of the University of Southern California and macroeconomic models that feature time lags.[23] But, as with the assumptions on behavior, it is all but impossible to create models that combine equilibrium with complex dynamics and real-world timescales.[24]

Making the Interesting Exogenous

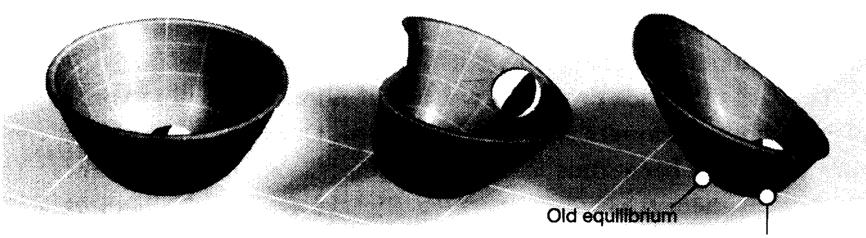
If Traditional models don't typically include explicit notions of time, then it is reasonable to ask just how they handle change in the economy. Returning to our image of Traditional theory as like a ball in a bowl, every time we try to roll the ball somewhere else in the bowl, the ball returns to the same equilibrium point it started from. But we know that economies are highly dynamic phenomena; things change all the time as production goes up and down, prices fluctuate, tastes and technologies change, and so on. How do we get this kind of dynamism into the inherently static picture of equilibrium? How do we get the ball-in-the-bowl to move over time?

What if we picked up our ball-in-the-bowl and gave it a good shake, bent one of the bowl's sides, and disturbed its equilibrium? The shock would initially send the ball out of its equilibrium point rolling around the bowl. As we bent the bowl's sides (imagine the bowl is made of rubber) and changed the shape of the constraints, eventually the ball would settle down into a new equilibrium point based on the reshaped bowl (figure 3-1).

In effect, this is what economists do to their models when they introduce exogenous shock. All models have boundaries. If one tries to incorporate too much into a model, it will become so large and complex that it loses its usefulness. For example, population growth clearly affects economic systems, but it might not make sense to have a model of birth and death built into an economic model. Instead, for simplicity, one might just take a table of projected

FIGURE 3-1

Equilibrium, Shock, New Equilibrium



population figures as an external input. As mentioned earlier, variables outside the bounds of a model are known as exogenous ***variables,*** while variables inside the bounds of a model are endogenous ***variables.*** Typical examples of exogenous variables include changes in consumer tastes, technological innovations, government actions, and the weather. For example, a change in technology, such as the invention of the Internet, can be seen as an exogenous shock to the economic system. This change affects both producer costs (e.g., Dell can sell computers more cheaply by taking orders online) and consumer preferences (e.g., consumers like the convenience of buying books online from Amazon.com). Such changes affect the constraints in the system (i.e., the shape of the bowl) and thus the location of the equilibrium point. As the economy is buffeted by shocks from exogenous variables, the equilibrium point moves over time. Thus the dynamism of the economy comes from a process of equilibrium, then shock, then new equilibrium, then shock, then new equilibrium, and the economy moves from one *temporary equilibrium* to another.

The problem with this approach is that it gives economists an escape hatch and allows them to put the most difficult and often most interesting questions outside the bounds of economics. For example, if technological change is treated as a random, outside force (like the weather), then one doesn't need a fundamental theory of the interaction between technological change and changes in the economy.[25] Likewise, one can attribute the waves of the business cycle to mysterious outside forces such as changes in consumer confidence, or crashes in the stock market to news. There is a parallel to this approach in biology. For years, evolutionary theorists pondered the puzzle of mass-extinction events. Our natural instinct is to look for a proximate and proportionate cause; that is, a big event must have had a big cause. For example, in the 1980s the geologist Walter Alvarez and his father, Nobel Prize laureate physicist Luis Alvarez, proposed a theory that the dinosaurs were wiped out by a massive asteroid colliding with the earth at the end of the Cretaceous period, and indeed, some evidence supports this hypothesis. Yet when other researchers stepped back and examined the long-term fossil record, they found that while the asteroid theory might explain the particular mass extinction event of the Late Cretaceous, it did not account for the ten other major extinction spasms (some much bigger) evident in the fossil record. More recent work has shown that extinction spasms are probably caused by the internal dynamics of evolution itself, without a major external event.[26] As we will see in chapter 8, in complex adaptive systems, small, innocuous events can occasionally set off avalanches of change.

In economics, exogenous "asteroids" do sometimes hit the economy, such as the worldwide economic impact of the September 11 terrorist attacks. But what about the stock market crash of October 19, 1987, when the market plummeted 20 percent? The *New York Times* headline that day was "Worry over dollar decline and trade deficit"; surely such a headline could have been written on many other days when major crashes did not happen.[27] Or what about the recession of 1982, when unemployment jumped from 7.5 percent to 11 percent in twelve months? Throughout the year, a panel of twenty leading economists consistently made forecasts that unemployment would decline. If some major exogenous event that could cause a recession had been going on at that time, wouldn't the forecasters have predicted that unemployment would grow?[28] In each case, it seems that endogenous factors are driving the truly interesting economic behavior—that some incompletely understood internal dynamic is causing stock market crashes and recessions.[29]

Again, one must draw model boundaries somewhere, but for a science to progress, it must extend its scope of explanation over time. In Traditional Economics, the straitjacket of equilibrium has forced the models to put some of the field's most interesting and fundamental questions outside the exogenous wall.

Keeping a Lid on Things

Many people have had the embarrassing situation of stepping up to a microphone to speak and being greeted by a loud squealing sound—the result of positive feedback. Positive feedback happens when a microphone is held too close to a loudspeaker and the sound bounces between the mike and loudspeaker in an amplifying cycle until the result is an earsplitting screech. Positive feedback is an accelerating, amplifying, self-reinforcing cycle. Negative feedback is the opposite: a decelerating, dampening, self-regulating cycle. A classic example of negative feedback is a thermostat. If your house gets cold, the thermostat switches on the heat. As the heat rises past a set point, the thermostat switches off, until the house cools back down below the set point. The thermostat dampens the fluctuations of heat in the house, keeping the temperature close to the set point.

Traditional Economics assumes that economic processes are dominated by dampening, negative feedback. This is the decreasing, or diminishing, returns to production and consumption that we discussed earlier. As we noted, Traditional Economics assumes that the twentieth worker on the production line is incrementally less productive than the tenth, and the fifth doughnut incrementally less desirable than the first. Like the sides of a bowl, negative feedback keeps things contained, keeps things heading toward equilibrium, and prevents the world from being awash in infinite quantities of cars and doughnuts.

The real world clearly does exhibit decreasing returns. But as former Stanford and SFI economist Brian Arthur has argued, the real world also exhibits positive feedback, or increasing returns.[30] As more teenagers wear a trendy pair of sneakers, the shoes become more desirable. As more information becomes available on the Web, the more useful the Web becomes. And sometimes, the more people who buy a stock, the more other people pile in to catch its rise. All these increasing-returns phenomena eventually peter out. The hot trend today is tomorrow's fashion blunder, the Web runs into information overload, and stock-market bubbles inevitably pop. But again, timing is everything. Traditional Economic theory tends to assume a long run, in which all increasing returns have exhausted themselves and the economy can safely go to equilibrium. But what if the long run never arrives? What if before one fashion peters out another starts to rise? What if someone invents Google to help us navigate the Web? What if some investors still believe they can beat the market, even after seeing a bubble pop? In a system such as the economy, there are always new sources of positive feedback to liven things up. There is no long run in the real world, or as John Maynard Keynes famously put it: "This long run is a misleading guide to current affairs. In the long run we are all dead. Economists set themselves too easy, too useless a task if in tempestuous seasons they can only tell us that when the storm is long past the ocean is flat again."[31]

In his novel Crotchet Castle, the nineteenth-century English satirist Thomas Love Peacock describes a debate between two gentlemen on whether the world has progressed or gone backward since the days of the ancient Greeks. One of the gentlemen cites as evidence of progress the invention of economics, "the science of sciences," as he puts it. His opponent replies that economics is "a hyperbarbarous technology, that no Athenian ear could have borne. Premises assumed without evidence, or in spite of it; and conclusions drawn from them so logically, that they must necessarily be erroneous."[32]

In order to fit the complex, dynamic world economy into the simple, static equilibrium box, economists have been forced to make "premises without evidence," and these premises raise serious questions about the results of the models built with them. Without these assumptions, the neat ball-in-the-bowl model degenerates; the smooth bottom of the bowl sprouts bumps, the ball never settles down, the equations cannot be solved, and the predictability of equilibrium is lost. A Traditional economist might justifiably reply that a great deal of effort has been expended over the years building models that add a dose of reality by relaxing some of these assumptions.

Economists have built models with less-than-perfect rationality, with imperfect information, with market frictions, with dynamics, and with endogenous treatments of formerly exogenous variables. But one can ask where in Traditional Economics are the models that relax *all* of these assumptions *at* once and therefore actually look something like a real economic system? To do this, one has to give up on the idea that the economy is an equilibrium system, something that until recently Traditional Economics has not been ready to do.

Reality Test

But let's say we give Milton Friedman the benefit of the doubt and imagine that we don't need to "look under the hood at the assumptions in Traditional Economics. How does Traditional theory fare against Friedman's empirical test?

Many noneconomists are skeptical of the scientific credentials of economics because of its notoriously bad record at predicting things such as economic growth, interest rates, and inflation. We should keep in mind, however, that the hallmark of a science is not its ability to forecast the future, but its ability to *explain* things—to increase our understanding of the workings of the universe.[33] As mentioned before, the role of prediction in science is to help us distinguish between competing explanations. A well-formulated theory will have logical implications that can be tested. For example, meteorologists and climatologists can tell us quite a lot about the chemistry of the atmosphere, and their theories can be tested by drilling ice cores in the Arctic and sending weather balloons into the upper atmosphere. However, this does not mean that anyone can tell you with certainty whether it will rain on your barbecue next Sunday. This is because the earth's atmosphere, like the economy, is a complex, highly dynamic system that is far from equilibrium. In fact, meteorology and climate science can explain why weather forecasting is so inherently inaccurate. Science is full of examples of fields where researchers can explain phenomena and test the validity of their explanations, without necessarily being able to make accurate forecasts. For example, biologists can explain but not forecast the folding of proteins, and physicists can explain but not forecast the exact motion of a turbulent fluid.

Science is a continuous learning process in which the logical implications of competing explanations are tested and a body of evidence is accumulated over time. As Sir Karl Popper showed in the 1930s, there is no "final proof" that a theory is correct, but one can say whether a theory is disproved by data, whether one theory fits the data better than another, and whether a theory has yet to be contradicted by data.[34] For example, one cannot say that Einstein's theory of relativity has been proven, but one can say that its predictions have been well tested, it has yet to be contradicted, and it fits the data better than any alternative explanation proposed thus far. Science thus goes through a process of proposing various explanations, rigorously articulating them in ways that can be tested, eliminating theories that fail the tests, and building on the ones that succeed.[35]

Given this standard, we can then ask, how well are the predictions of Traditional Economics supported by data? The answer is ‘hot well.” As the highly respected microeconomist Alan Kirman, director of studies at L’Écoles des Hautes Études en Sciences Sociales in France, observes:

> Much of the elegant theoretical structure that has been constructed over the last one hundred years in economics will be seen over the next decade to have provided a wrong focus and a misleadmg and ephemeral idea of what constitutes an equilibrium. If we consider two standard criteria for a scientific theory—prediction and explanation—economic theory has proved to say the least, inadequate. On the first count, almost no one contests the poor predictive performance of economic theory. The justifications given are many but the conclusion is not even the subject of debate. On the second count, there are many economists who would argue that our understandmg of how economies work has improved and is improving and would therefore contest the assertion that economic theory, in this respect, has proved inadequate. The evidence is not reassuring, however. The almost pathological aversion to facing economic theory with empirical data at anything other than the most aggregate level is indicative of the extent to which “explanation” is regarded as being a self-contained rather than a testable concept.[36]

As Kirman points out, not only is there a problem with data that contradicts Traditional theories, but many theories have simply never been properly tested. One branch of economics, called econometrics, deals with data analysis.[37] Rather than testing theoretical models, however, much econometric work is devoted to finding statistical relationships between variables (often for public policy or other applied purposes). Unfortunately, statistical correlations don’t provide a causal explanation of the phenomena. Furthermore, as many economists would point out, there is often a lack of readily available data to test theories with, and even data that is available is frequently noisy or otherwise problematic (though economists would find little sympathy from physicists or biologists, who have to build particle colliders and space telescopes and map the human genome to get data for their theories).

In two areas, however, Traditional theory has undergone rigorous testing. The first is finance theory, for which the availability of minute-by-minute data from financial markets and huge amounts of computing power have enabled an unprecedented level of testing of Traditional theory. Unfortunately for Traditional Economics, this encounter with data has produced a steady stream of work refuting many of the theory's most basic predictions, a topic we will return to in chapter 17.[38] The second area of rigorous testing is experimental economics. There is a popular perception that economics is different from other sciences in that one cannot readily carry out controlled experiments to test hypotheses. The Federal Reserve, for example, can't radically raise interest rates just to see at what point they would trigger a recession. While it may be challenging to conduct experiments on the economy as a whole, it is, however, possible to conduct experiments on economies in miniature. Researchers take groups of people and have them bargain with each other, bid in auctions, play economic games, invest in simulated stock markets, go shopping in fake stores, and participate in all sorts of contrived situations to capture specific aspects of economic behavior. This has produced a rich body of work, some of which we will review in chapter 6. Again, the encounter with data has generally not been kind to many of the core ideas of Traditional Economics.[39]

Naturally, much of the work testing Traditional Economics has been highly technical (and those interested can refer to the notes). Nevertheless, over the next few sections, we will look at a few intuitive examples for which the key predictions of Traditional theory do not meet the standards of a scientific reality test.

The "Law" of Supply and Demand

As discussed in the previous chapter, one of the oldest principles of Traditional Economics is the law of supply and demand. A basic prediction of this "law" is that the counterbalancing forces of supply and demand will drive a market to an equilibrium price and quantity level where the market clears. As a first approximation, this theory works pretty well. For example, if a car company introduces a new model that suddenly becomes popular, the company will typically raise the price while demand exceeds supply, expand production, and then lower the price once demand has cooled off and supply has caught up. AU just as the theory would predict.

If, however, we zoom into a more he-grained level, we see that real-world markets are almost never in equilibrium, supply rarely equals demand, and markets rarely come into balance. In fact, virtually all markets are built around the assumption of disequilibrium rather than equilibrium. Most markets have stocks of inventory, order backlogs, slack production capacity, and middlemen to help smooth out the disequilibria. Your local car dealer has a parking lot full of vehicles that are slower selling and an order backlog of "hot" vehicles that customers are waiting for. Your local supermarket is rarely in equilibrium, as its inventory stock floats up and down soaking up the imbalances between the supply of food being delivered through the back door and the demand being carried out through the front door. Service businesses such as lawyers and accountants rarely utilize their professionals at 100 percent, thus keeping some swing capacity available for fluctuations in demand. Even financial markets, which are viewed as the closest markets to the theoretical ideal, have mechanisms for dealing with inevitable supply-demand imbalances. The New York Stock Exchange has "specialists," and the NASDAQ exchange has "market makers," both of whom stand between supply and demand to smooth things out.

The law of supply and demand isn't a law after all (at least not in any scientific sense); rather, it is more appropriately "the rough approximation of supply and demand." Some Traditional economists might argue that the existence of inventories and slack production capacity doesn't matter, that they are just noise in the supply-demand balance. This is actually wrong. As we will discuss later in the book, the dynamics of inventories and production capacity can help explain phenomena such as price fluctuations and business cycles—phenomena that Traditional Economics usually looks to exogenous forces to explain.[40] And as we will see in chapter 18, the existence of inventories in stock markets may even help explain stock market volatility.[41]

The Law of One Price

The second most famous "law" in Traditional microeconomics is the law of one price, which states, "In the absence of transportation costs and trade barriers, identical goods must sell at the same price in all markets."[42] For example, the price of gold in New York should be the same as that in London, and any difference should be accounted for by the cost of shipping it from one market to the other (plus import duties, taxes, and any other transaction costs). Otherwise, one could arbitrage the difference and make a risk-free profit by buying gold in the low-price market and selling it in the high-price market. The buying and selling of arbitrageurs would then bring the price of the two markets back to equilibrium. Like supply and demand, the law of one price does often work as a first approximation. Highly liquid commodities such as gold rarely do show significant "arbitrageable" deviations in prices across markets.

Nonetheless, it is an approximation that often breaks down, both at the macro level of economies as a whole, as well as at the more micro level of individual products and services. For example, an important test of the theory has been the integration of the majority of European economies into the European Union and in particular the introduction of the euro currency. The theory predicts that this large-scale dropping of trade barriers, increased mobility of people, reduction in currency transaction costs, and greater price transparency should have led to a greater convergence of prices across the European Union. But in fact the opposite has happened. According to Eurostat, the EU's statistical agency, price differences have widened since the euro was introduced in 1999. The standard deviation of prices within the euro zone rose from 12.3 percent in 1998 to 13.8 percent in 2003, the exact opposite of the theory's prediction. Francisco Caballero-Sanz, head of economic analysis at the EU internal market &rectorate, attributed the lack of convergence to consumers being "not as 'rational' as economic theory would like them to be."[43]

Zooming in to a more fine-grained level, we often see a wide &vergence in the prices of individual goods and services. For example, James Montier, the head of global equity strategy at the investment bank Dresdner Kleinwort Wasserstein, conducted a somewhat whimsical study of the London ketchup market and found that the price of the same bottle of ketchup could vary widely at area supermarkets.[44] He found deviations of up to 43 percent from the theoretically predicted price. There are thus opportunities for risk-free profits in the London ketchup market. In the theoretical world of Traditional microeconomics, such an opportunity would be arbitraged away instantly. But in the real world, arbitrage opportunities take time to be discovered, come and go, may or may not be worth exploiting, and may have various barriers to being exploited.

Again, some Traditional economists might ask, does it matter if the law of one price is an idealization? To most scientists, however, a 13.8 percent standard deviation across the euro zone, or a 43 percent error in ketchup prices, sound like pretty big idealizations. The point is not that the basic idea behind the law of one price is wrong; of course people have incentives to arbitrage price differences "in the absence of barriers." But in the real world, barriers of some kind almost always exist, whether it is the fact that no one has the time to search all the stores in an area for the lowest-priced ketchup, or whether there are still various transaction costs and transport, legal and other issues affecting trade in the European Union. In fact, the scientifically interesting question around price convergence is the dynamic interplay over time between the incentives to arbitrage and the changing nature of the various barriers. Yet, the mathematical requirements of the equilibrium framework force economists to strip away this complexity, leaving a "law" whose predictions are of questionable value. More useful would be a theory that could handle the complexity of prices in the real world.[45]

Equilibrium in a Few Quintillion Years

Perhaps the most fundamental prediction of Traditional Economics is that the economy as a whole must at some point reach equilibrium (this is a prediction made by both the general equilibrium theory of microeconomics, as well as by standard macroeconomics).[46] As noted earlier, Traditional Economics does not imagine equilibrium as a permanent state, but describes the economy as going through a sequence of shock, temporary equilibrium, shock, temporary equilibrium over time. Again, we can imagine whacking our ball-in-the-bowl, watching the ball settle back down, whacking it again, and so on. But for the system to reach equilibrium, the time in between shocks to the bowl must be long enough for the ball to settle. If that isn't the case, and we keep hitting the bowl with rapid shocks, then the ball will simply rattle around forever, randomly buffeted and never reaching equilibrium.

An important question, then, is, How long does it take for the economy to reach equilibrium? What is its "settling" time? In the 1970s, the Yale economist Herbert Scarf determined that the time to equilibrium scales exponentially with the number of products and services in the economy to the power of four.[47] The intuition behind this relationship is straightforward: the more products and services, the longer it takes for all the markets to interact with each other, and the longer it takes for all the prices and quantities to adjust. If we take the rough estimate from the first chapter that a modern economy has something on the order of 10^{10} SKUs in it, and if we optimistically assume that ***every*** decision in the economy is made at the speed of the word's fastest supercomputer (currently IBM's Blue Gene, at 70.72 trillion floating-point calculations per second), then using Scarf's result, it would take a mere 4.5 quintillion years (4.5×10^{18}) for the economy to reach general equilibrium after each exogenous shock. Given that shocks from factors such as technology change, political uncertainty, weather, and changes in consumer tastes buffet the economy every second, and the universe is only about 12 billion years old (1.2×10^{10}), this clearly presents a problem.[48]

Nonrandom Walks

As mentioned earlier, perhaps the area of Traditional Economics with the best opportunity to empirically test its theories is finance. But again, while the predictions of Traditional finance are not bad as a first approximation, they break down under closer examination.

One of the best known predictions of Traditional finance is that stock prices should follow a "random walk." We will look at this in more detail later in the book, but briefly, a random walk implies that there should be no patterns in the movement of prices, and that looking at past prices should not provide any clues about future prices. At first glance, stock prices do look very much like a random walk, particularly when they are relatively quiet and behaving "normally." For decades, researchers believed that the prices were, in fact, random. More recent analyses with better data and more powerful tools, however, have shown conclusively that prices do not follow a random walk. For example, Andrew Lo of the Massachusetts Institute of Technology (MIT) and Craig MacKinlay of the Wharton School at the University of Pennsylvania put the random-walk hypothesis through a series of tests on a 1,216-week sample of stock prices from 1962 to 1985; they tested individual stocks, portfolios of stocks, and stock indices, and in all cases rejected the random-walk hypothesis.[49] Numerous other studies using different samples and different techniques have also rejected the random-walk hypothesis.[50]

Interestingly, the departure of stocks from a random walk is statistically clearest when markets are making major moves, in other words, when they are the farthest from equilibrium.” There is also clear dynamic structure and information in stock price data, and while it is debatable whether anyone can systematically make money from that information, the fact that the prediction of random walks is wrong certainly does little to enhance Traditional finance's scientific credibility.[52]

The predictions of Traditional Economic theory are usually not completely crazy. Supply does roughly, approximately, equal demand. Prices do sometimes (but not always) converge. Markets may never actually reach equilibrium, but can act as if they are in a form of equilibrium. And, financial markets do superficially appear as if they follow a random walk when they are quiet and well behaved, that is, until they are no longer quiet and well behaved. If these statements don't sound very scientific, it is because they are not. As Friedman's nemesis, Herbert Simon, put it: "To be sure, economics has evolved a highly sophisticated body of mathematical laws, but for the most part these laws bear a rather distant relation to empirical phenomena, and usually imply only qualitative relations among observables."[53]

Traditional Economics is built on a shaky foundation of assumptions that has led to equally shaky conclusions. The next logical question is to ask why the field has ended up in this position. The explanation for the troubles with Traditional Economics goes back to over a hundred years ago, to the crucial step Walras took when he imported the concept of equilibrium into economics from physics. Without realizing it, Walras fundamentally misclassified the economy

Misused Metaphors

Human beings are skillful pattern recognizers and use metaphors to help them understand and reason about the world. Saying that something resembles or has qualities of something else enables us to quickly, and in just a few words, grasp the essence of a complex phenomenon. Shakespeare could have given us a long passage about how Juliet was central to Romeo's life, brought him happiness, and so on. Instead, with the simple phrase "Juliet is the sun!" Shakespeare conveyed those meanings in a far richer and more powerful way.

Science uses metaphor as well, both to inspire creativity and to help communicate complex ideas. For example, the metaphor of tiny, vibrating loops of string has helped inspire the physicists who are developing string theory (an attempt to unify the fundamental forces of the universe and explain the origins of subatomic particles) to think in radically different ways from their predecessors.[54] Likewise, the phrase **loops** of string helps metaphorically communicate the key idea of string theory to a lay audience more easily than does "eleven-dimensional Calabi-Yau space." But while metaphor is useful in inspiring and communicating science, science itself is based on more than metaphor. Scientific theories do not merely make claims that one thing resembles another. As discussed in chapter 1, scientists make claims that something literally is a member of a universal class of phenomena. Similarity is not sameness. When a cosmologist says our sun is a star, the scientist doesn't just mean it is similar in some way to a star. Rather, our sun is a member of a universal class of phenomena, which are called stars, that share certain empirically observable characteristics.[55]

There is no doubt that when Walras read Poinsot's physics textbook, he was metaphorically inspired by the similarity between notions of balancing forces in physical systems and notions of balancing forces in economic systems.[56] This similarity motivated him to apply the mathematical tools of equilibrium analysis to economic systems. A hundred years later, at the meeting of scientists and economists in Santa Fe, the key question on the table was, is the concept of equilibrium in economics based merely on superficial similarities between physical and economic systems, or are economic systems literally equilibrium systems, which thus share the universal properties of such systems?[57] In other words, is the equilibrium framework in Traditional Economics a metaphor or science?

To Walras and his Marginalist compatriots, such a question would not have occurred to them. First, at that point in time, the philosophy of science and an understanding of the legitimate and illegitimate roles of metaphor were not as well understood as they are today. Second, the question begs another question. If economic systems are not equilibrium systems, then what are they? This second question would have baffled Walras as well. To the physicists of Walras's time, there were simply equilibrium systems, which could be mathematically analyzed, and "other" systems, some of which could be analyzed, but most of which could not. There weren't many alternative ways one could categorize a phenomenon such as the economy. Given Walras's goal of bringing mathematical rigor and predictability to economics, it is not surprising he went down the well-trodden path of equilibrium analysis.

Half-Baked Physics

Unfortunately, Walras was on his mission to turn economics into a science when science itself was at a peculiar point in its development and missing a critical concept. All science is a work in progress, and the physics that the Marginalists knew was not yet the classical thermodynamics that one would see in a textbook today; in fact, one could say it was only half-baked. The physics that the Marginalists borrowed included the First Law of Thermodynamics, but was missing the Second Law.

The ***First Law** of Thermodynamics*, which states that energy is neither created nor destroyed and is otherwise known as the *Conservation of Energy Principle,* had been developed in the early to mid-nineteenth century and was clearly spelled out in the texts that Walras, Jevons, and the others read. To see how the First Law works, imagine that a ball is held high on the side of our now familiar bowl. It has potential *energy* that can be released when the ball is dropped. If you put your hand at the bottom of the bowl, you would feel the ball whack into it as gravity pulls it down and its energy is released into your hand. That release of energy is referred to as ***work*** (because it potentially could be used to do something useful, like drive a machine). When the ball is let go and begins to roll around, it also encounters friction from the side of the bowl, and that friction generates heat. The potential energy of the ball is thus turned into work and heat. The great English physicist James Prescott Joule showed that nature is very parsimonious with energy and that energy is neither created nor destroyed, but merely converted from one form into another. If one added up the amount of potential energy stored in the ball at the top of the bowl and the amount of work plus heat released as it rolled down, the two amounts would be equal. Likewise, if one measured the amount of energy stored in a lump of coal and then burned the coal to do some work (e.g., propel a steam locomotive), the energy stored in the coal would equal the energy used to do the work plus the waste heat going up the locomotive smokestack.[58]

One of the properties of the First Law is that if the total energy in a system is fixed, that is, "conserved," then the system is *guaranteed* to eventually reach equilibrium. Once the potential energy of the ball is done turning into work and heat, and the ball is resting at its minimum energy state at the bottom of the bowl, it is in equilibrium. Likewise, once the burning coal has been turned into work and waste heat, it will stop burning and reach an equilibrium state. Only by *adding energy from* **the outside,** for example, by shaking the bowl or adding another lump of coal, can we keep the system out of equilibrium.

As Philip Mirowski of Notre Dame has pointed out, one of the consequences of Walras's borrowing equilibrium is the mathematical need for fixed or conserved quantities in Traditional models. This is why Traditional Economics typically portrays value as a fixed quantity that is converted from one form to another (i.e., resources are turned into goods, which are exchanged for money, which is exchanged back for goods, which are consumed, creating utility).[59] New wealth isn't actually created; rather, the world begins with a finite set of resources that are allocated among producers who in turn create a finite set of commodities that are allocated among consumers. One can allocate that wealth in ways that are more or less efficient, just as one can burn a lump of coal in ways that are more or less efficient, but in general equilibrium models the economy can't create new wealth any more than a lump of coal can reproduce.[60] This emphasis on a fixed pie of wealth caused the English economist Lionel Robbins in 1935 to famously call economics "the science of scarcity."[61] This is still reflected in modern economics textbooks, for example, Paul Samuelson and William Nordhaus's widely used book defines economics as "the study of how societies use scarce resources to produce valuable commodities and distribute them among different people."[62] The legacy of the First Law that metaphorically inspired Walras and Jevons lives on in Traditional Economics today.

However, the First Law is only half of the thermodynamic story. The Second Law, which was missing from the physics Walras and Jevons knew, states that **entropy,** a measure of disorder or randomness in a system, is always increasing. The Second Law says that the universe as a whole is inevitably drifting from a state of order to a state of disorder—the ultimate end point of the universe is a random, featureless miasma of perfectly even temperature. Over time, **all** order, structure, and pattern in the universe breaks down, decays, and dissipates. Cars rust, buildings crumble, mountains erode, apples rot, and cream poured into coffee dissipates until it is evenly mixed. Entropy is what gives time its arrow. The great physicist Murray Gell-Mann, one of the founders of SFI, illustrates this by noting that if you have young children (or in his case, grandchildren), you are likely to have jars of both peanut butter and jelly in the cupboard. Over time, the peanut butter eventually gets in the jelly and jelly gets in the peanut butter as the children make sandwiches. Gell-Mann notes that if he showed you a time-lapse movie of the peanut butter jar getting progressively more and more flecks of jelly in it, and then showed a movie where the flecks disappear as the peanut butter spontaneously cleaned itself up, you would immediately know which was the forward and which was the backward version.[63] Without entropy and the inevitable drift from order to disorder, there would be no way to tell what was the past, present, or future. Since its discovery, entropy has become a central concept in the way physicists view the universe.[64]

Unfortunately for Walras, Jevons, and the other builders of Traditional Economics, this supreme law of nature was missing from their framework. The Second Law was one of those scientific concepts that had a long gestation and was built through the work of a number of people, including Sadi Carnot, Rudolph Clausius, and Sir William Thomson (a.k.a. Lord Kelvin), over the period 1824 to **1865.** Its significance, however, was not fully appreciated until the end of the nineteenth century, and many of its important implications were not worked out until well into the twentieth century (and indeed are still being worked out today). Entropy would have been considered still too new and too poorly understood to be put into introductory texts that inspired Walras and Jevons at the time.[65]

Open Sesame

With an understandmg of both the First and Second Laws of Thermodynamics, we can move on to another concept that would have been unavailable to Walras and Jevons at the time: that of closed and open systems (these terms have another meaning in economics relating to whether an economy engages in international trade, but we will use them in the physicists' sense). First, a thermodynamic *system* is any defined set of space, matter, energy, or information that we care to draw a box around and study The universe itself is a system, and within that largest of all systems, one can define any number of smaller systems. For example, our planet is a system, as is your body, your house, or a bathtub full of water. A *closed* system is a system having no interaction or communication with any other system—no energy, matter, or information flowing into or out of it. The universe itself is a closed system. There is no "outside" the universe, no other system beyond its boundaries that it can interact with.[66] Energy might be converted into matter, and vice versa, and energy might be converted into different forms within the system, but the total amount is constant, according to the First Law. In addition, the total entropy in a closed system is always increasing to its maximum level, as order decays into disorder and the system eventually comes to rest.

The second type of system is an open system, with energy and matter flowing into and out of it. Such a system can use the energy and matter flowing through it to temporarily fight entropy and create order, structure, and patterns for a time. Our planet, for example, is an open system; it sits in the middle of a river of energy streaming out from the sun. This flow of energy enables the creation of large, complex molecules, which in turn have enabled life, thus creating a biosphere that is teaming with order and complexity. Entropy has not gone away; things on the earth do break down and decay, and all organisms eventually die. But the energy from the sun is constantly powering the creation of new order. In open systems, there is a never-ending battle between energy-powered order creation and entropy-driven order destruction. Nature's accounting rules are very strict, and there is a price to be paid when order is created in an open system. For order to be created in one part of the universe, order must be destroyed somewhere else, because the net effect must always be increasing entropy (decreasing order). Thus, as the sun powers order creation on earth, all of that life and activity creates heat, which is radiated back into space. The heat has a randomizing effect wherever it ends up, thereby increasing entropy. The earth thus imports energy and exports entropy.

For an example closer to home, let's imagine you've been very busy at work and the Second Law has driven your house from a state of order to one of disorder. You decide to invest some energy to fight entropy and clean it up. You input energy into your house through the calories you burn scrubbing and picking things up, and you use electricity to power your vacuum cleaner, dishwasher, and washing machine. In addition, matter flows into your house in a highly ordered state in the form of food, clothing, cleaning products, and so forth. The universe gets its entropy payback, however, when you and all the devices you use radiate heat back into the environment. Moreover, the electricity you use also causes waste heat and smokestack emissions at the generating plant, and matter flows back out of your house into the world in a disordered state in the form of trash. Thus the system of your house imports energy and matter, which is then used to create the order within its confines, and then sends back into the universe heat and disordered matter, thereby exporting its entropy.

Closed systems always have a predictable end state. Although they might do unpredictable things along the way, they always, eventually, head toward maximum entropy equilibrium. Open systems are much more complicated. Sometimes they can be in a stable, equilibrium-like state, or they can exhibit very complex and unpredictable behavior patterns that are far from equilibrium—patterns such as exponential growth, radical collapse, or oscillations. As long as an open system has free energy, it may be impossible to predict its ultimate end state or whether it will ever reach an end state.

In chapter 1, I defined a complex adaptive system as a system of interacting agents that adapt to each other and their environment. Complex adaptive systems are a subcategory of open systems. It takes energy to process information, sustain order, and create complex patterns. For example, an ant colony takes in energy and matter through the food and material it brings into the nest; it uses that energy and material to fight entropy as the colony builds its nest and organizes its activities. The presence of free energy is what enables a complex adaptive system such as an ant colony to stay away from equilibrium, create order, and be dynamic over time. If you remove that energy, then entropy takes over and the system decays and eventually reaches a state of stasis or equilibrium. As one of the participants at the SFI meeting, University of Michigan theorist John Holland, once put it, "in fact, if the system ever does reach equilibrium, it isn't just stable. It's dead."[67]

The Misclassification of the Economy

Walras and Jevons were not familiar with the Second Law and thus were not aware of the distinction between open and closed systems, or the existence of complex adaptive systems. In fact, a detailed understandmg of open systems emerged only gradually during the twentieth century, accelerating with the work of the Russian-born chemist Ilya Prigogine in the 1960s and 1970s. The Traditional model, then, was created with the implicit assumption that the economy is a thermodynamically closed equilibrium system, even though, at the time, Walras, Jevons, and their fellow Marginalists did not know that they were building this assumption into their theories. For the next one hundred years, as economics and physics each went their separate ways, this assumption lay buried in the mathematical heart of Traditional Economics.[68]

Unfortunately for economic theory, this unawareness of the Second Law meant that the Marginalists and their successors fundamentally (though unwittingly) misclassified the economy. The economy is not a closed equilibrium system; it is an open disequilibrium system and, more specifically, a complex adaptive system. The proof for this lies just outside your window, right under your nose. It is so obvious, in fact, that it has escaped the attention of most economists until relatively recently.[69] If the economy were a closed equilibrium system, its defining characteristic would be a trend toward *less* order, complexity, and structure over time, as entropy sends any closed equilibrium system inevitably toward a featureless stasis. Closed equilibrium systems do not spontaneously self-organize; they do not generate patterns, structures, and complexity; and above all, they do not create novelty over time.[70] All the movement, buzz, organization, and activity of the economy outside your window cannot be the product of a closed equilibrium system. As we saw in the first chapter, the defining characteristic of the economy has been an immense rise in economic complexity throughout its journey from the

10^1 SKU economy of *Horno habilis* to the 10^{10} SKU economy of the modern world. The growth of economic activity from the Stone Age until now has been one long story of fighting entropy on a grand scale—something that could only happen in an open disequilibrium system.

A Traditional economist might well ask what all this physics of open and closed systems has to do with economics. Open and closed systems are physical concepts, while the economy is a social phenomenon. Am I engaging in the kind of inappropriate metaphorical reasoning I have accused Walras of using? The answer is no. We have to remember that social systems are not just abstract mathematical models that exist in the minds of economists or in the equations of textbooks. They are real physical systems made of matter, energy, and information; they are made up of people and all of that stuff outside your window, and they are just as subject to the laws of physics as any other phenomenon. Real, physical economies have enormous amounts of real, physical energy pouring into them every day—that is what makes them tick.[71] Our hunter-gather ancestors powered their economies with the food they ate and the firewood they collected. Modern economies power themselves with Big Macs and microwavable ready-meals, as well as with oil, natural gas, coal, hydropower, nuclear power, and any other energy source we can get our hands on. Energy comes into economies to power the fight against entropy and create order. Likewise, economies obey the Second Law and export disorder back into the universe around them as they throw off waste, pollution, greenhouse gases, and heat.

Economies are not just metaphorically **like** open systems; they literally and physically *are* a member of the universal class of open systems. If one were to cut off the supply of energy to an economy—shut off the food, oil, gas, and coal—then entropy would be unopposed, and the economy would drift toward a true equilibrium. Sadly, we see something like this when a country has been wracked by war, such as in the Democratic Republic of Congo, or is isolated by its political leaders, such as in North Korea. Such economies inevitably decline as entropy begins to win and they head toward a literal equilibrium of misery and starvation, whereas a growing, vibrant economy is by definition far from equilibrium.

Even a market that is "pureinformation" such as the NASDAQ stock market, which exists only on the computer screens of traders, still has a basis in the physical world. There was a surprising reminder of this a number of years ago, when a squirrel burrowed its way into **an** electricity transformer near the NASDAQ's main computer center in Connecticut. The creature got zapped, knocked out the power, and briefly shut down the market.[72] As we will discuss in chapter 14, all wealth creating economic activities require some form of energy and involve manipulations of matter and/or information (although the reverse is not true, not all energy using, matter and information manipulating activities are wealth creating). Economic activity is firmly rooted in the real, physical world, and thus economic theory cannot escape the laws of thermodynamics.

A Traditional economist might concede that economies are real physical systems and even open systems, but argue that the physics of open and closed systems does not matter because economists model economies at a higher level of abstraction than their physical basis (in other words, economic models are more coarse-grained than physical science models). Just as a biologist might model a cell without reference to subatomic physics, an economist might model an economy without explicit reference to physical thermodynamics. Economics has its own concepts, such as preferences, prices, and production functions, that exist as abstractions in the social realm, just as biologists have their own high-level abstractions (e.g., the gene) that are relevant to the biological realm. A Traditional economist might argue that by borrowing some math tricks from physics textbooks, all Walras and Jevons were guilty of was trying to make the abstractions of economics more rigorous. Equilibrium analysis is just a math technique, nothing more. Both physics and economics also use algebra—why is equilibrium such a problem?[73]

There are actually two points embedded in this pro-equilibrium argument. The first is the "different levels of abstraction" point; the second is the "it's just math" point. Certainly, science requires different levels of abstraction for different phenomena. As we noted before, scientific theories can be big picture and coarse grained like a highway map, or fine grained like a local street map. Both are equally valid; they just need to agree with each other and conform with reality. Thus, it is fine for economics to have its own high-level, coarse-grained concepts that are not addressed in physics and that may omit explicit references to physical laws. However, economic theories cannot be inconsistent with basic physical laws. A claim that the economy is a closed equilibrium system would be in obvious violation of basic physical laws. Thus, for the "levels of abstraction" response to be valid, we must believe that, even though the economy is in reality an open disequilibrium system, it is for some reason better to model it as a closed equilibrium system. In fact, the reverse is true. As we will see in part 2, the problems of unrealistic assumptions and lack of empirical validation stem from the mis-modeling of the open disequilibrium economy using closed equilibrium techniques.[74]

The second part of the pro-equilibrium argument—"it's just math"—misunderstands both what equilibrium is about and what math is about. Math is a form of language, it is a symbolic system that we use to describe and explain our world.[75] It is a special language because of the high degree of agreement on what its various symbols mean and the rules for manipulating those symbols. There have been various attempts to create a "pure" mathematics, which is just an abstract language whose symbols are purely logical constructs with no connection to the real world.[76] While these exercises have been valuable in pushing the boundaries of the field, the current consensus among mathematicians and philosophers is that one cannot separate mathematics fi-om its meaning in the physical world.[77] Of course, mathematicians can create mathematical fantasy worlds that do not exist in physical reality, including forty-three-dimensional objects that one cannot see or touch. But we do this with natural language as well—we write novels or make movies about things that do not exist in the real world. Yet our interpretation of these fantasy objects, whether the latest Hollywood blockbuster, or a forty-three-dimensional hypersphere, is unavoidably tied to our experience with the real world.[78] There is no such thing as "just math."

If "economic equilibrium" does have a meaning in the real world, the next question is, What does it mean? There is no rule that says researchers in two fields must use their terminology in the same way. We can thus ask whether the term *equilibrium* means the same thing in economics as it does in physics? Perhaps the economists mean something completely different by *equilibrium* and the problem I've pointed out is just a case of confused terminology. If *equilibrium* were being used to mean different things in different fields, then we should be able to translate fi-om one definition to the other. Yet, I know of no definition of *equilibrium* in economics that defines it in any way that is distinct fi-om what physicists mean by it. On the contrary, the two fields use the word in precisely the same way. The *Oxford Dictionary of Physics* defines equilibrium as "[a] state of a system in which forces, influences, reactions, etc. balance each other out so that there is no net change."[79] Meanwhile the *Collins Dictionary of Economics* defines equilibrium as "a state of balance with no tendency to change."[80] In addition, the mathematical techniques used by economists and physicists for equilibrium analysis are identical.

This leads to some uncomfortable questions for economics. Does Traditional Economics claim that economies and markets *literally* are equilibrium systems? Is this a case of legitimate theory extension, in which we have a universal class, called equilibrium systems, that includes things like weights hanging off springs and the market for pork bellies? Yet, how can the economy be a closed equilibrium system when it has energy and matter pouring in one end and entropy leaking out the other? Wouldn't this claim violate the laws of physics? Or, are economies and markets merely *like* equilibrium systems? Is it all just a misused metaphor arising fi-om the peculiar history of economics?[81]

The answer, I believe, is yes; the Neoclassical model that lies at the heart of Traditional theory was built on a misused metaphor. Without realizing it and with the best intentions, the late-nineteenth-century economists borrowed from physics a set of ideas that fundamentally misclassified the economy as a closed equilibrium system. This approach set the framework for the Traditional Economics we see today. Unfortunately, this misclassification has acted as a straitjacket, forcing economists to make highly unrealistic assumptions and limiting the field's empirical success.

Beyond Walras's Cathedral

When the Santa Fe meeting ended after ten days, there was a sense of both exhilaration and exhaustion.[82] Despite the intensity of debate and occasional clashing of egos, the meeting ended with a profound sense of mutual respect. The economists had seen some of their own doubts about Traditional economic theory reinforced and had their eyes opened to new ways of thinking about long-standing economic problems. The physical scientists, for their part, had gotten a glimpse into a phenomenon as fascinating, complex, and challenging as anything in nature. Many of the connections and collaborations forged at the meeting continued, and SFI launched an interdisciplinary program in economics, initially cochaired by Brian Arthur and John Holland and funded by Citicorp. Like a snowball starting down a hill, the idea of viewing the economy as a complex adaptive system gathered pace. SFI remained a central driving force, hosting a variety of workshops and conferences over the years on topics ranging from finance to economic inequality, including a sequel to the original conference a decade later.[83] Perhaps even more importantly, the network of researchers working on these issues spread dramatically. Today, virtually every major economics department has at least one or two people working on some aspect of what I will define in the next chapter as Complexity Economics. And the interdisciplinary collaborations have grown as well; it is not uncommon now to see economics papers in journals such as *Physical Review Letters*, *Nature*, and even the *Journal of Theoretical Biology*.

The critique presented in this chapter is not intended as a broadside at economics or economists generally. Rather it has been a critique of the specific theories that comprise Traditional Economics. Economics is a broad church, and within the field there has been a wide variety of work outside the Traditional Economics orthodoxy and much recent work pushing the Traditional boundaries. As we will see in part 2, many economists themselves have left the Traditional fold and are taking the lead in developing the new theories of Complexity Economics, oftentimes alongside colleagues from other disciplines. Nor am I criticizing economics' aspirations as a science, or the use of mathematics by the field. There are many critics who pine for the simpler pre-Walrasian days, when economics was a branch of political and moral philosophy and one did not need sophisticated mathematical skills to be an economist. While economics undoubtedly has a number of unique characteristics as a science, it would have little hope of creating scientifically credible explanations without the precision and rigor of mathematics.[84] The issue I have raised is whether economics is using the right math.

This critique also does not in any way take away from the accomplishments of the field over the past century. As discussed earlier, scientific theories are always approximations of the underlying reality they attempt to describe. In part 2, I will argue that Complexity Economics is a better approximation of economic reality than Traditional Economics, just as Einstein's relativity is a better approximation of physical reality than Newton's laws. Nonetheless, I believe that Traditional Economics has been at least approximately or directionally right on many important issues, and its ideas have helped improve the lives of billions of people. In addition, the theories of Traditional Economics have a true intellectual beauty to them and have been developed by some of the finest minds to grace the sciences. Science progresses by the ideas of one generation building on, and occasionally replacing, the ideas of another. Nothing would better honor the legacy of the builders of Walras's cathedral than to see the field progress beyond the paradigm that they constructed.

NOTES

Chapter One

1. From Smith (1776), ch. 4, p. 25.

2. The question of what makes people happy is studied by a subfield in psychology called *hedonic psychology*. Researchers have found that while one's absolute level of wealth is not a strong determinant of happiness compared with other factors such as genetics, relationships, and career fulfillment, the rate of change of wealth over time is indeed an important factor. See Kahneman, Diener, and Schwarz (1999) for a survey.

3. Krugman (1992), preface.

4. Stuart Kauffman opens his wonderful book *At Home in the Universe* (1995) with a look out his window in Santa Fe and asks the question "where does all of the order come from?" I am indebted to Stuart for helping me appreciate the centrality of this question in economics. Kauffman (2000), 211–241, discusses his views on the question of order in economics.

5. My example is inspired by the question "how does New York manage to feed itself?" which was raised as an example of self-organization in economics in the 1987 economics meeting at the Santa Fe Institute, a meeting that we will discuss later in the book. See Anderson, Arrow, and Pines (1988).

6. The technical definition of the word *complex* and measures of complexity are topics that we will discuss later in the book. Meanwhile, my usage is the term's common meaning. For a general discussion of definitions and measures of complexity, see Gell-Mann (1994) and Flake (1998). For a technical discussion, see Haken (2000).

7. Seabright (2004), pp. 13–26.

8. For detailed accounts of humankind's long-term economic history, see Diamond (1997), Wright (2000), Landes (1998), Jay (2000), Cameron and Neal (2003), and Seabright (2004).

9. The dates in this section are all highly approximate, as estimates vary significantly and new evidence is constantly causing researchers to reconsider elements of the chronology. The sources for this section were Jones et al. (1992) and Diamond (1997).

10. Horan, Bulte, and Shogren (2005).

11. Seabright (2004). Other species do have "economies" featuring colonies of individuals living together, divisions of labor, and trade in nutrients. These species range from social insects, to the creature Physalis physalis (known as a Portuguese man-of-war), which is not a single organism but rather a colony of single-celled organisms. Many of these species are haplodiploids, and the female members of the colony are all sisters. True sociality among nonrelatives is not unknown; as Seabright notes, it has been seen in sticklebacks, vampire bats, and other species. However, the sociality tends to be around specific tasks, within very small groups, and for limited periods. Extensive cooperation among large numbers of nonrelatives persisting over long periods does appear to be unique to humans. Nonetheless, the study of other social species and superorganisms provides fascinating insights into the dynamics and evolution of cooperation—insights that may be applicable to human economies as well. See, for example, Bonabeau, Dorigo, and Theraulaz (1999).

12. Horan, Bulte, and Shogren (2005).

13. This description of the Yanomamö is drawn from Chagnon (1992).

14. The $90 figure is based on an estimate of very long-run world GDP, by J. Bradford DeLong of the University of California–Berkeley (see DeLong's Web site, www.j-bradford-delong.net, for a description of the data and methodology). Although I could not find GDP figures specific to the Yanomamö, the Yanomamö live a lifestyle roughly typical of 10,000 to 15,000 years ago. According to DeLong's figures, this would place the Yanomamö at around $93 in GDP per capita (in constant 1990 dollars), but we should not put too fine a point on it and I have thus rounded the figure to $90. I have used GDP per person as a proxy for income, as the Yanomamö have very little savings and no government, so what is produced is consumed. As another reference point, the World Bank estimate of gross national income per capita for the worlds least developed countries in the world is $280. Some example indicators of the relative development levels of these countries are 11.9 telephone lines per 1,000 people, 2.8 computers per 1,000, and 14 percent of roads paved. Estimating Yanomamö income at approximately one-third of this level, which also gives us $93 per capita, while not precise, is probably not unreasonable. New York City average income data is from New York State government statistics. Median income, however, is probably more informative than average, and the U.S. Census Bureau reports median household income in New York State averaged $43,160 for 2001–2003. But we know even less about income distribution in Yanomamö society, so I have simply compared averages.

15. Chapon (1992) does much to explode the myth that life before the advent of technology was a kind of innocent Eden. For example, one-quarter of all Yanomamö males die violently, and the Yanomamö people also suffer from very high infant mortality. The overall mortality data for the Yanomamö averages 6.5 percent (calculated from the data given in ibid., p. 268, for the years 1987 to 1991). I have used the data for the most remote villages with the least modern contact, because this better approximates the ancestral hunter-gatherer lifestyle. The comparable figure for New Yorkers is 0.84 percent (from the 2002 U.S. Census). This rough comparison actually understates the difference, as Yanomamö demographics are significantly younger than the New Yorker demographics.

16. I am paraphrasing DeLong's statement from his study of long-run GDP. DeLong's actual words were these: "I know I at least would be extremely unhappy if I were handed my current income, told that I could spend it on goods at current prices, but that I was prohibited from buying anything not made before 1800." See www.j-bradford-delong.net.

17. Schwartz (2004) points out that such a wide array of choice does not, as economists have long assumed, necessarily mean an increase in welfare. I have used some of Schwartz's examples from pp. 9–22.

18. I was unable to find an exact measure of SKUs in any research on the Yanomamö. However, an informal counting of the items mentioned in Chagnon (1992) and some assumptions yielded an estimate of around 300 SKUs. As a further reference, I informally counted items on my visit to a Maasai village, a significantly more advanced society with far more contact with the modern world, and came up with approximately 800 SKUs.

19. Although I have not found any reliable estimates of the number of unique products and services on offer in a modern economy, one data point is at least instructive in the likely order of magnitude: the universal product code (UPC) system. The UPC system is an inaccurate measure itself, because not all final products have UPC codes, the vast majority of services (which in turn account for most consumption

in developed countries) do not, and UPC codes are also used for intermediate goods. Nonetheless, the code does give us one measure of product diversity. The current UPC system has twelve digits, of which two are administrative, meaning the unique product part of the code is ten digits. The manager of the system, the Universal Code Council, is running out of codes and recently moved to a thirteen-digit system. A full UPC system with ten numerically identifying digits implies 10 billion products. The hierarchical structure of the system, however, means that not all codes are available for all products. For example, if Pepsi runs out of its unique codes, it cannot use a code with digits assigned to Coke. Let's assume that the code utilization is 50 percent and, for sake of argument, that the number of false codes and number of uncoded products roughly cancels out and that the ratio of product SKUs to service SKUs in the economy is proportional to the ratio of product to service consumption (services were 59 percent of U.S. 2002 total consumption). Under these assumptions, we would have about 12 billion SKUs, or in the range of 10^{10}. A further cross-check is that if world GDP is $36.5 trillion, then this would imply an average of $3,650 in GDP per SKU, which seems to be about the right order of magnitude. Petroski (1992), 23, cites a few other numbers that help us get a sense of the magnitude of SKU diversity. He notes that 5 million patents have been issued in the United States alone and the Chemical Society's database contains over 10 million human-made chemical substances. Likewise, Schwartz (2004), pp. 9–22, gives a sampling of the staggering array of items found just in his local environment in Philadelphia. Whatever the true number of SKUs, it would clearly be very large. My calculation is intended merely to illustrate the complexity of the modern economy. A serious analysis of this topic would undoubtedly yield some very interesting results.

20. It is difficult to place the lifestyle of the Yanomamö exactly in our crude timeline. There is much controversy between researchers on the date of the first human colonization of the Americas, but it ranges from 10,000 to 35,000 years ago, with evidence of settlements in South America from about 15,000 years ago (Diamond, 1997, pp. 45–50). There is evidence of settled agriculture in various parts of the world starting around 10,000 years ago (p. 100). Given that the Yanomamö are descendents of people who migrated into the Americas, but that their economy is not one of settled agriculture, their lifestyle is probably typical of people living 10,000 to 15,000 years ago. Again, this observation is intended to be more illustrative than exact.

21. DeLong constructed this estimate out of seven data sets: a long-term estimate of population *size* by Kremer, three long-term series on GDP per capita, and three series on world GDP. The data and a description of how DeLong constructed the series are published under the title "Estimating World GDP, One Million B.C. to Present" on DeLong's Web site, www.j-bradford-delong.net. For the period from 2.5 million BC (roughly the appearance of the first tools) to the beginning of DeLong's series at 1 million BC (for which period he estimates GDP per capita at $92), I have simply assumed a linear extrapolation from zero. Naturally, any specific estimates over such a long period are highly speculative, but economic historians have significant evidence regarding the overall pattern that the data shows.

22. In looking at the curves for GDP per capita growth, one might initially (and not unreasonably) think that the sudden near-vertical bend in the curve is simply the result of exponential growth viewed over a very long period. However, plots of log GDP per capita reveal a nearly identical shape. Doyne Farmer of the Santa Fe Institute analyzed DeLong's data for his 2003 Ulam Lecture and concluded that the data exhibited double exponential growth (www.santafe.edu/~jdf). Given the degree to which the data series is an estimate, one cannot be conclusive regarding its functional form, but there is significant evidence that the rate of growth has been accelerating over time. See Bernstein (2004), pp. 17–23, for further discussion and data.

23. Ormerod (1994), p. 10, cites a 1982 study by Angus Maddison showing a related statistic, that Western economies grew as much in percentage terms between 1950 and 1970 as they did between 500 and 1500. Bernstein (2004) also discusses the Maddison data.

24. Landes (1969), p. 5.

25. I have borrowed the term *econosphere* from Stuart Kauffman; see Kauffman (2000), p. 211.

26. Darwin was, of course, the first to see evolution as an algorithm, although he did not articulate it in that specific way and did not have the later mathematical discoveries of Alan Turing, Kurt Gödel, or Alonzo Church to help him see the broader implications (Dennett, 1995, pp. 48–50). For popular expositions on the idea of evolution as an algorithm, see Dawkins (1976) and (1982) and Dennett (1995), in particular ch. 2, section 4, from which I have borrowed the term ***substrate.*** For a mathematical treatment, see Landweber and Winfree (2002).

27. See Paul Krugman's critique of the book ***Bionomics,*** by Michael Rothschild (Rothschild, 1990): "The Power of Biobabble," published on the *Slate* Web site, October 23, 1997.

28. See, for example, Holland (1975), Whitley (1993), Mitchell (1996). Landweber and Winfree (2002), and Crutchfield and Schuster (2003).

29. Hodgson (1993), p. 81, notes that it was actually the sociologist Herbert Spencer, not Darwin, who coined the term *survival of the fittest.* Hodgson goes on to defend Spencer's economic ideas, which he contends were insightful for their time. However, Spencer's ideas increasingly became hijacked at the turn of the century by Social Darwinists with political and racist agendas.

30. Dennett (1995), pp. 28–34 and 48-60. Richard Dawkins also eloquently made this point in 1986 in *The Blind Watchmaker.*

31. For a review of debates on Darwinism versus theories of "intelligent design" (creationism by another name), see Dembski and Ruse (2004).

32. Increasing complexity is not a *guaranteed* result of the evolutionary process. Rather, it is dependent on the implementation of the system and the tuning of its parameters. Kauffman (1993) argues that biological evolution has self-tuned its parameters to enable growth in complexity. However, while biological evolution has increased the average complexity of the biosphere and the complexity of the most complex organisms, that increase has been far from monotonic, as the various crashes of extinction and bursts of speciation in the fossil record show. Likewise, although the overall trend in economic evolution has been toward greater order and complexity, the historical record too shows it has been far from monotonic. See Wright (2000) and Cameron and Neal (2003).

33. Dennett (1995) and Kauffman (1995a), pp. 149–189, also make this point.

34. Paul Seabright, in his fascinating 2004 book *The Company of Strangers: A Natural History of Economic Life,* also uses the example of a shirt in his first chapter, although his purpose is to illustrate the intricate cooperation involved in the manufacture of even the most prosaic products in the global economy My purpose is different and is to make a point about the evolution of designs. I only became aware of Seabright's book and his shirt example late in the process of editing and thus happened on shirts as my choice of illustration independently Furthermore, during final editing Pietra Rivoli published her *The Travels of a T-Shirt in the Global Economy: An Economist Examines the Markets, Power, and Politics of World Trade* (John Wiley & Sons, 2005). Perhaps shirts will become the standard example of economic evolution and globalization, much as Adam Smiths pins have become the canonical example of the division of labor.

35. My use of the labels *Physical Technology* and *Social Technology* are from Nelson (2003) and will be defined more fully later in the book.

36. Social Technologies are similar but not identical to what economists refer to as institutions. I will more fully define Social Technologies in chapter 12 and make this distinction clearer.

37. Freeman and Soete (1997).

38. See Hodgson (1993) for an excellent history of evolutionary theory in economics.

39. Charles Darwin's *Autobiography,* p. 120, as quoted in Plotkin (1993), pp. 28–29.

40. Alfred Russell Wallace deserves credit for independently coming to many of the same insights that Darwin had. While Darwin was generous in recognizing Wallace's contributions (and afraid of being scooped), the historical record shows that Darwin did indeed get there first (Browne, 2002).

41. Thorstein Veblen, "Why Is Economics Not an Evolutionary Science?" *Quarterly Journal of Economics* 12 (1898), pp. 373–397, reprinted in Gherity (1965).

42. There has been controversy about Marshall's intent with this passage, but he repeated it in every edition of *Principles,* starting with the fifth. See Hodgson (1993), ch. 7, for a discussion of Marshall's thoughts on economics and evolution.

43. Hayek wrote repeatedly about linking evolution and what he called "spontaneous order." He was probably the first economist to look seriously at theories of self-organization developed by the chemist Ilya Prigogine. See Hodgson (1993), ch. 12, for a discussion. Also see Vriend (2002) on Hayek and complexity, and Colander (2000) for a historical survey of complexity thinking in economics.

44. Nelson and Winter (1982).

45. See Waldrop (1992), p. 82.

46. For a highly readable introduction to complex adaptive systems, see Waldrop (1992). There are also several other excellent popular books on the subject, including Gell-Mann (1994), Kauffman (1995a), Holland (1998), and Johnson (2001). Flake (1998) provides a nicely written and illustrated introductory text. For a comprehensive technical introduction, see Bar-Yam (1997). For a compendium of early papers and discussion, see Cowan, Pines, and Meltzer (1994).

47. For examples. see Anderson, Arrow, and Pines (1988), and Cowan, Pines, and Meltzer (1994).

48. I first heard Brian Arthur use the term "complexity economics" in a lecture in 1994. The first printed reference is in Arthur (1999) in *Science:* "Complexity economics is not a temporary adjunct to static economic theory, but theory at a more general, out-of-equilibrium level."

49. The notion of scientific programs was developed by the philosopher of science Imre Lakatos in the late 1960s. For an application to economic methodology, see Mark Blaug's essay in Hausman (1994), pp. 348–375. See Hands (2001) for further discussion.

Chapter Two

1. This account is adapted from various sources, including Waldrop (1992), news reports from the period, personal discussions with founding members of the Santa Fe Institute, and the Citigroup Web site.
2. Waldrop (1992), p. 91.
3. See, for example, Ormerod (1194), Keen (2001), and Fullbrook, ed. (2004).
4. Cassidy (1996). The article was widely discussed at the December 1996 annual meeting of the American Economics Association as well as at a subsequent meeting of over sixty leadmg economists at Stanford in January 1997.
5. See, for example, Colander, Holt, and Rosser (2004).
6. Quoted in Cassidy (1996).
7. Alan Greenspan, quoted in Andrews (2005).
8. At this point, I will not delve into a philosophical debate about whether economics is a science in the same way that, say, physics is. But I will contend that economics has aspirations to be scientific in the sense that the fields goals are to provide an understanding of human economic phenomena through explanations that are rigorous, logically consistent, and backed by empirical observation. For discussions of the status of economics as a science, see Hausman (1994) and Hands (2001). Evidence for economics' scientific aspirations can be found in virtually any economics textbook, or in the acceptance criteria for any refereed journal in the field.
9. For histories of economics, see Niehans (1990) and Backhouse (2002). For classic introductory textbooks, see Samuelson and Nordhaus (1998) and Stiglitz (1997). For a managerially oriented text, see Mansfield (1999).
10. Some readers will note that my characterization of the Traditional Economics consensus has a distinctly Anglo-American Neoclassical bias. This is because of the global dominance of those ideas, particularly in recent decades. Continental academics have typically given more prominence to historical and institutional views of economics than have their British and American counterparts. I will later discuss the relevance of those views to Complexity Economics.
11. Nelson and Winter (1982), pp. 6–11. I have added survey articles to my definition to admit more advanced material. I have also not followed Nelson and Winter's lead on their use of the label ***orthodox economics*** because I do not believe that Traditional Economics represents an orthodoxy anymore; as we will see, numerous economists and physical scientists disagree with many elements of the historical paradigm. For now, "Traditional" is a more accurate term. Nonetheless, Nelson and Winter's description of the strengths and weaknesses of their term orthodox economics holds for my definition of Traditional Economics as well.
12. Everyone has his or her favorite textbooks, but examples include, for microeconomics, Samuelson and Nordhaus (1998), Stiglitz (1997), and Mas-Colell, Whinston, and Green (1995). For macroeconomics examples, see Dornbusch and Fischer (1990), Mankiw (1994), Krugman and Obstfeld (1991), D. Romer (1996), Blanchard and Fischer (1989), and Heijdra and Van Der Ploeg (2002). For an example of the type of survey article I am referring to, see ***Quarterly Journal of Economics*** 115, nos. 1 and 4 (2000), in which, in celebration of the millennium, Harvard University's prestigious journal commissioned a series of six essays by leadmg economists on the question "What do we know about economics today that Marshall did not?" Examples of some recent survey monographs include Aghion et al. (2003) and Szenberg and Ramrattan (2004).
13. Baumol (2000), pp. 3–4, also notes that textbooks are a useful gauge of the state of the field because "the material selected for such a book can therefore be expected to focus on subjects deemed to shed light on the workings of the economy and the design of policy. They are intended to sum up the contributions of economics that really matter to others, and not just to those who labor at the frontiers of our disapline, sometimes perhaps, as Marshall put it, largely '. . . for the purpose of mathematical diversion' . . . It follows that the textbook criterion can indicate what economists believe others should glean from the work of our profession . . . that is, what [is] ***useful.***"
14. There are, of course, exceptions. See, for example, Szenberg and Ramrattan (2004).
15. Not all Nobel laureates fall into what I have labeled the Traditional camp. For example, the work of Herbert Simon, Friedrich Hayek, Douglass North, and Daniel Kahneman have all provided critical foundations for the work of the Complexity economists.

16. In a review article, Colander (1999), pp. 6–7, provides a nice summary of what I am referring to as Traditional Economics: "Through the 1990s, economic researchers typically started with a set of principles: for example, utility-maximizing by consumers and profit-maximizing for firms, far-sighted individual rationality, and a belief in equilibrium, which meant that structurally, individual's decisions in the models fit reasonably well together. These principles were probably best embodied in Debreu's 1959 *Theory of Value*. During the second half of the 1900s, they first became comprehensively embedded in microeconomic models, and then, as Keynesian economics declined and New Classical macroeconomics became dominant in the 1980s, they spread to macroeconomics as well. By the late twentieth century, these principles formed the core of economist' vision of reality, in the sense that all economic models were built on these principles, or around variations of these principles like assumptions of bounded rationality or imperfect information."

17. See Backhouse (2002), pp. 13–17, for an overview of Xenophon's work.

18. Biographical details about Adam Smith are from Ross (1995), Niehans (1990), and Backhouse (2002). The origin of the term classical economics comes from Marx (Niehans, 1990, pp. 9–13). Marx himself is now commonly placed in this period, though he probably would have vociferously objected to being put in the same category as Adam Smith.

19. There are, of course, many important questions that economics has wrestled with. However, questions of the nature of economic value and its ultimate source, growth, and allocation have dominated the Classical, Marginalist, and Neoclassical periods (Niehans, 1990). More specific questions such as the role of money, the setting of prices, and the gains from exchange have typically been placed within the framework of these larger questions. A possible exception is phenomenological questions of the macroeconomy, such as the nature of unemployment. But the longtime quest of macroeconomics has been to integrate such questions into a more fundamental framework based on value, growth, and allocation.

20. Smith's intention to explicitly address both questions is clearly spelled out in the title of the first part of *The Wealth of Nations*: "Of the Causes of Improvement in the productive Powers of Labour [i.e., the origin of wealth], and of the Order according to which its Produce is naturally distributed among the different Ranks of the People [i.e., the allocation of Wealth]." Smith (1776), p. ix.

21. Smith also acknowledged the importance of technology and capital in boosting productivity, but saw those as ultimately driven by the &vision of labor; for example, the amount and type of machinery required would be determined by the organization of labor. See Backhouse (2002), p. 124.

22. Smith (1776), book 1, ch. 1, p. 4.

23. Niehans (1990), p. 60.

24. Smith (1776), book 1, ch. 2, p. 15.

25. Ibid., book 4, ch. 2, p. 482.

26. Ibid., p. 485.

27. For brevity, I have greatly simplified my description of Smith's view of supply and demand. Although Smith can be credited with the first clear articulation of the role of price in equilibrating supply and demand, his portrayal was not the modern form we are accustomed to. Smith postulated a "natural price" based on factor costs plus a "natural rate" of return on capital. If the market price were above the natural price, then consumers would reduce their demand, driving the price back to its "natural" level. Although the idea of a "natural" rate of return in the form of the zero-profit condition did survive in production theory, Smith had no theory of utility and budgets to provide constraining conditions on the demand side. Not until seventy-two years later, when John Stuart Mill published his *Principles of Political Economy*, would there be a complete theory of supply and demand, and then Marshall provided the famous X diagram in 1890. See Niehans (1990) and Backhouse (2002).

28. According to Niehans (1990), pp. 24–36, Cantillon was very specific and calculated this balancing point at 1.5 acres of land per head. At this point, according to Cantillon, wages would be at subsistence levels and the population neither starving nor growing.

29. For a description of Quesnay's *Tableau Économique*, see ibid., pp. 37-48. As an eighteenth-century physician, Quesnay believed that the health of the body depended on a balance of circulatory flows of humors (blood, bile, lymph, and phlegm), and there is a clear metaphorical connection between his medical views of bodily health and his views of economic health. For a discussion of the metaphor of the economy as circulatory system, see Mirowski (1989).

30. The term *lassez-faire*, however, is attributable to Pierre de Boisguilbert, a critic of the government of Louis XIV. See Backhouse (2002), p. 91.

31. Ibid., pp. 104–108, and Niehans (1990), pp. 73–76.

32. We will discuss theories of increasing returns in the next chapter, as well as in the context of positive feedback dynamics in part 2.

33. Turgot's work would later be extended and given analytical footing by Antoine Augustin Cournot and Johann Heinrich von Thünen. See Niehans (1990), pp. 164–187.

34. Ibid., pp. 123–126.

35. The notion of utility was first articulated by the Dutch mathematician Daniel Bernoulli in 1738. Bentham independently rediscovered it sixty years later and, unlike Bernoulli, did not give it a mathematical form. Bernoulli's discovery, however, failed to have a significant impact until much later, whereas Bentham's writings were highly influential on a subsequent generation of economists, including Mill and Ricardo and the later Neoclassicists. See ibid., pp. 118–137, and Backhouse (2002), pp. 132–165.

36. Backhouse (2002), p. 136.

37. While Bernoulli and Bentham had both postulated a diminishing marginal utility of income, neither had extended the concept to consumption or given it an analytic treatment. Thus, Niehans (1990), pp. 187–196, credits Gossen for the concept of diminishing marginal utility. For convenience, I have discussed Gossen's work in the section with Classical economists such as Smith, Turgot, and Bentham. However, on the basis of Gossen's analytic treatment of utility and as a contemporary of Cournot and von Thünen, Niehans properly classifies Gossen as an early Marginahst.

38. An autobiographical note by Walras on this incident is given in Ingrao and Israel (1990), p. 87.

39. Quoted in ibid., p. 88.

40. Mirowski (1989), Niehans (1990), and Backhouse (2002).

41. On the use of numerical examples in Classical economics, see Backhouse (2002), pp. 237–240. Prior to Walras and the Neoclassicists, early-nineteenth-century economists such as Antoine Cournot, Johann Heinrich von Thünen, and Hermann Heinrich Gossen used basic algebraic techniques and differential calculus. See ibid., pp. 166–168.

42. Stewart (1989).

43. Ingrao and Israel (1990).

44. Stewart (1989), p. 60.

45. Walras noted in various letters and articles the significant influence of Poinsot's book and other writings on rational mechanics in the development of his theories. See Ingrao and Israel (1990), p. 88, and Mirowski (1989), pp. 219–220.

46. Ingrao and Israel (1990), p. 88.

47. Walras never actually proved either the existence, the uniqueness, or the stability of his equilibrium; rather, he merely worked through the equations until he found one that satisfied the conditions. Such formal and general proofs would have to wait until the twentieth century, when von Neumann introduced fixed-point techniques to the field. See Mas-Colell, Whinston, and Green (1995), pp. 584–598, for existence and uniqueness proofs for Walrasian equilibria.

48. Mirowski (1989), pp. 243–248, provides an account of Walras's reactions to early criticisms about these assumptions.

49. Niehans (1990), pp. 197–207.

50. Quoted in ibid., pp. 197, 198.

51. Mirowski (1989), pp. 217, 256–257, notes the popularity of this text in spreading the key ideas of Lagrange, Maxwell, and Faraday within England. Jevons was known to have attended Faraday's lectures at the Royal Institution and followed the writings of Thomson, Maxwell, and Joule closely.

52. According to Mirowski (1989), p. 257, Jevons's initial metaphor of choice was a lever in equilibrium, a metaphor he used to derive his initial equations of exchange. Later, he broadened his conception to a more general notion of energetics and the mathematical use of field theory.

53. Quoted in ibid., p. 219.

54. Ibid., pp. 217–222. Niehans (1990), pp. 189, 201, notes that in the first edition of Jevons's **Principles,** it is not clear whether Jevons got his notion of diminishing marginal utility directly from Gossen, as Jevons merely notes that the principle is implied in the writings of a number of economists and refers only specifically to Richard Jennings. In the second edition, however, Jevons devotes six pages of the preface to Gossen and credits Gossen's originality.

55. Quoted in Mirowski (1989), p. 219.

56. Niehans (1990), pp. 259–266.

57. Niehans (1990), p. 265, notes that Pareto argued that in the absence of fixed costs, a central planner could only equal the market outcome, but with fixed costs, a central planner could achieve a superior outcome. As Niehans adds, this argument would be further developed by Hotelling's analysis of monopolistic competition in 1938.

58. From Voltaire's **Candide,** 1759, ch. 1.

59. Mirowski (1989), pp. 219–221.

60. Niehans (1990), pp. 420–444.

61. As Samuelson himself commented on the relationship between Hicks's book and his own, "Value and Capital was an expository tour de force of great originality, which built up a readership for the problems Foundations grappled with and for the expansion of mathematical economics that soon came." Quoted in Backhouse (2002), p. 259.

62. For an exposition of Samuelson's revealed preference theory, see Mas-Colell, Whinston, and Green (1995), pp. 5–16.

63. For an exposition of Arrow-Debreu general equilibrium, see ibid., pp. 691–693.

64. The debate over the efficiency of allocation in market economies versus centrally planned ones has a long history going back to Pareto and Enrico Barone. They each concluded that a central planner could do at least as well as a market since both the central planner and the market were simply solving a Walrasian system of equations. Oskar Lange argued that all that mattered from a soaal-welfare perspective is that the correct prices are used he said it was irrelevant whether those prices were discovered by a market or by a central planner. Friedrich Hayek countered that in practical terms, it was impossible for any central planner to acquire all the information needed to calculate correct prices. The Soviet Union actually attempted to adopt Lange's technique and created massive mathematical models to calculate prices. History, however, would seem to have proven Hayek right. As we will discuss later, in developing his arguments on socialism, Hayek anticipated many of the key themes of Complexity Economics. See Niehans (1990) and Backhouse (2002) for histories of this debate, and Hayek (1988), Bernstein (2001), and Caldwell (2004) for discussions of Hayek's views.

65. Niehans (1990), pp. 445–451, and John Elliot's introduction in the 1983 edition of Schumpeter (1934).

66. Quoted by John Elliot in Schumpeter (1934), p. xix.

67. Ibid., p. xxiv.

68. Although it is fair to say that Neoclassical growth models, exemplified by the later work of Robert Solow and Paul Romer, dominated Traditional Economics at the end of the century, the Schumpeterian tradition of growth theory has also continued into the modern era. See Nelson (1996), Scherer (1999), and Helpman (2004) for discussions.

69. Niehans (1990), pp. 451–456, notes, however, the contributions of Roy Harrod during this period. Although Harrod was largely concerned with extending Keynes's theory of the business cycle and his mathematical skills were limited, he was an important transitional figure between Schumpeter and Solow.

70. In the spirit of full disclosure, Robert Solow has on occasion served as an adviser to McKinsey & Company, a firm I am associated with as well.

71. Solow (2000). pp. ix–xxvi.

72. The balanced-growth concept was introduced in an earlier *Econometrica* paper in 1953 coauthored with Paul Samuelson, but the full "Solow model," with exogenous population growth, was first described in Solow (1956).

73. For expositions of Solow's model, see Solow (2000), Barro and Sala-i-Martin (1995), and D. Romer (1996).

74. See P. M. Romer (1994), Aghion and Howitt (1998), and Barro and Sala-i-Martin (1995) for reviews.

75. P. M. Romer (1990).

76. Heijdra and Van Der Ploeg (2002).

77. For example, Michael Porter's widely used work on strategy has its roots in Neoclassical microeconomics. See Porter (1980) and (1985).

78. Niehans (1990), p. 491.

Chapter Three

1. This account is drawn from Waldrop (1992).

2. Anderson (1972).

3. In 1944, the physicist Erwin Schrödinger wrote 'What Is Life?" a provocative essay that wrestles with these issues. For a modern discussion, see Haynie (2001).

4. In the spirit of full disclosure, the firm I am affiliated with, McKinsey & Company, has been a financial supporter of research at the Santa Fe Institute since 1994.

5. My description of this meeting is drawn from Waldrop (1992), pp. 136–197, Anderson, Arrow, and Pines (1988), and personal discussions with various of the meeting's participants.

6. Waldrop (1992). p. 142.

7. Quoted in Ingrao and Israel (1990), p. 158.

8. Ibid., p. 159.

9. Mirowski (1988), pp. 241-265, and Ingrao and Israel (1990), pp. 148-173, give accounts of the scientific critiques of the Marginalist program.

10. Friedman (1953).

11. Hands (2001), p. 53, notes the impact of the essay as "it is cited in almost every economics textbook." According to economic philosopher Daniel Hausman (1994), the essay is, half a century later, "the only essay in methodology that a large number of, perhaps majority of, economists have ever read."

12. H. Simon, "Problems of Methodology—Discussion," **American Economic** Review: Papers *and Proceedings* 53 (1963): 229-31, reprinted in Hausman (1994), pp. 214-216.

13. I am, of course, simplifying, but the logic is the same as Simon's example: "X-businessmen desire to maximize profits; Y-businessmen can and do make the calculations that identify the profit-maximizing course of action . . . [therefore] 2-prices and quantities are observed at those levels which maximize the profits of the firms in the market." Simon noted that Nagel had shown the fallacy of using the validity of Z to support X and Y, and further argued that one would need to observe X and Y to support the theory, even if Z were observed. Ibid.

14. D. M. Hausman, "Why Look Under the Hood?," in Hausman (1994), pp. 217-221.

15. For a summary of critiques of Friedman, see Hands (2001), pp. 53-60. I am greatly simplifying here. For a review and detailed references on the role of assumptions in science and economics, see ibid., and for an anthology of classic articles, see Hausman (1994). In the course of my discussion on economic methodology and philosophy of science, I will draw on various models, including Hempel's deductive-nomological (D-N) model, post-Kuhnian sociology of scientific knowledge (SSK), Lakatos's methodology of scientific research programs (MSRP), and Campbell's evolutionary epistemology.

16. The originator of the theory-as-map analogy is the philosopher of science Ronald Giere (Hands, 2001, p. 311). My explanation is drawn from Holland (1998), pp. 28-33. Also see Sterman (2002) for a discussion of models as approximations.

17. Axel Leijonhufvud, "Towards a Not-Too-Rational Macroeconomics," in Colander (1996), pp. 39-55.

18. See, for example, Kahneman, Slovic, and Tversky (1982).

19. Technology, of course, plays a role in establishing the bounds of "satisficing" behavior. For example, someday we might have the price of all nearby gas stations beamed to our cars via the wireless Internet and then be directed to the cheapest one via GPS, and the on-board computer might calculate the trade-off between gallons used in driving the extra distance and the cost saved. But even with more information available, people still engage in "satisficing," for example, you might switch the computer off because you can't be bothered to go the extra distance to save a few dollars and you think a nearer station might have cleaner bathrooms.

20. Behavioral game theory probably comes closest to incorporating behavioral, informational, and market-structure effects in an equilibrium setting. See Camerer (2003) for a survey. However, as Camerer notes (pp. 473–476), there is still some distance to go before all these effects are simultaneously incorporated in a realistic way.

21. Kirman and Gérard-Varet (1999) p. 10. There are exceptions. Kirman notes that the non-*tâtonnement* models of Hahn and Negishi explicitly deal with time. Steve Smale worked with dynamic models in the 1970s, and Richard Day in the 1980s and 1990s. I view concepts such as the Hicksian "week" as arbitrary index times that don't relate to real-world timescales (despite the name *week*), something that Hicks himself admitted (see Hicks, 1939, p. 122).

22. Imagine a process that randomly rains $20 bills on a geographic area. Also imagine that the population of that area is not evenly distributed, but clustered in an area we will call A. At some point, by random chance, there will be an accumulation of bills in a relatively unpopulated area (call it B). Once that accumulation is discovered, people will rush to area B to pick the bills up. But since this takes time, while they are gone, bills will pile up in area A. They will rush back to A. The macro pattern will be fluctuating stocks of bills in areas A and B.

23. For example, Richard Day (1994) and (1999) has done much to bring a dynamic perspective to the field (though his work is arguably in the gray zone between Traditional and Complexity Economics). Some might also argue that game theory and many macroeconomic models are dynamic, but again, in the majority of these models, the dynamics are paths to a preassumed equilibrium and there is no explicit recognition of either absolute or relative timescales. See Fudenberg and Tirole (1991) and Heijdra and Van Der Ploeg (2002) for examples.

24. See Anderson, Arrow, and Pines (1988), Arthur, Durlauf, and Lane (1997), Sterman (2000), and Durlauf and Young (2001) for discussions.

72. I was told this story while visiting the NASDAQ computer center in 1996. The center naturally has backup generators, but apparently the squirrel created a chain reaction of problems that caused a modest delay in getting the backup power on. But any stoppage in the market, even a small one, is taken very seriously. The market has since apparently been made squirrel-proof.

73. For example, Robert Solow has voiced this view: "It will occasionally turn out that some piece of economics is mathematically identical to some piece of utterly unrelated physics. (This has actually happened to me although I know absolutely nothing about physics.) I think this has no methodological significance but arises because everyone playing this sort of game tends to follow the line of least mathematical resistance." From T. Bender and C. Schorske, *American Academic Culture in Transformation* (Princeton, NJ: Princeton University Press, 1997), pp. 73–74, quoted in Mirowski (2002), p. 8n3.

74. While I will argue that the economy is best modeled as an open disequilibrium system, this does not mean that equilibrium techniques will not have their uses. Equilibrium analysis remains a very powerful tool and will undoubtedly continue to be useful to model special cases **within** the more general case of a complex adaptive economy. As we will see, just as game theory and certain equilibrium techniques have been very useful in understandmg biological evolutionary systems (see Maynard Smith, 1982), they can be highly useful in Complexity Economics as well. The key distinction between Complexity and Traditional approaches is knowing that one is modeling an equilibrium as a special case or as an approximation of a more general disequilibrium setting, and thus knowing the limits of that special case or approximation.

75. For a discussion of the philosophy of mathematics and its properties as a language, see Devlin (2000), and Lakoff and Núñez (2000).

76. The most famous of these is the Bourbaki School, a French movement started in 1939 and active through the 1950s. The logical positivists also attempted to prove the pure objectivity of mathematics at about the same time, but that effort was subsequently abandoned. The peak of economics' flirtations with Bourbakism was Debreu's brilliant *Theory of Value* in 1959. See Ingrao and Israel (1990), pp. 280–288. The physical sciences largely abandoned Bourbakism in the 1950s and 1960s, but its influence in economics can continue to be seen in the purely axiomatic style of much work even in recent years. Alan Kirman, in Kirman and Gérard-Varet (1999), ch. 1, provides a critique of the "self-contained" yet "empirically empty" nature of much recent theoretical work in economics.

77. For a good nontechnical discussion of this issue, see Deutsch (1997), ch. 10.

78. This does not imply that only intuitive math objects are real. Physicists create all sorts of bizarre math objects that are not intuitive but have a real physical meaning. For example, superstring theory postulates eleven or maybe more dimensions in the universe. But again, the categorization and interpretation ultimately ties back to some interaction with the physical world, whether it is a sophisticated physics experiment or a child counting pebbles.

79. *Oxford Dictionary of Physics* (2000), pp. 158–159.

80. *Collins Dictionary of Economics* (2000), p. 164. Another example is from Stiglitz (1997), p. 88: "Physicists also speak of equilibrium in describing a weight hanging from a spring. Two forces are working on the weight. Gravity is pulling it down; the spring is pulling it up. When the weight is at rest, it is in equilibrium, with the two forces just offsetting each other . . . An economic equilibrium is established in just the same way"

81. This point about the contradiction between Neoclassical economics and the physical energy characteristics of the economy was first made by Nicholas Georgescu-Roegen in his 1971 masterwork, *The Entropy Law and the Economic* Process, a book we will discuss at length later. Daly (1999), pp. 75–88, provides a fascinating account of a debate between Georgescu-Roegen and Robert Solow on this issue.

82. This description is drawn from Anderson, Arrow, and Pines (1988), Waldrop (1992), and personal discussions with several of the participants.

83. See Arthur, Durlauf, and Lane (1997), Durlauf and Young (2001), Bowles, Gintis, and Osborne Groves (ZOOS), Gintis et al. (2005), and the Santa Fe Institute Web site (www.santafe.edu) for examples.

84. For a discussion, see Krugman (1998).