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Preface

Shortly after 9/11, a Russian scientist named Dmitri Gusev proposed an explanation for the origin of the name Al Gavastie suggested that the terrorist organization toolaat name from Isaac Asimov's famous 1950s science fiction robers known as the foundation Trilogy. After all the robustoned, the Arabic Atore Gaeda" means somethin Cike base or "foundation. After the first novel in Asimov's tillogy, *Foundation*, apparently was talled "al-Qaida" in an Arabic translation.

In Asimov's books, "Foundation" referred to an organization dedicated to salvaging a decaying galactic empire. The empire was hopeless, destined to crumble into chaos, leaving civilization in ruins for 30,000 years. Foreseeing the inevitability of the empire's demise, one man devised a plan to truncate the coming era of darkness to a mere millennium. His strategy was to establish a "foundation" of scholars who would preserve human knowledge for civilization's eventual rebirth.

At least that's what he told the empire's authorities.

In fact, Asimov's hero, a mathematician named Hari Seldon, created a community of scientists devoted to manipulating the future. Seldon actually formed two foundations—one in a remote but known locale (sort of like Afghanistan), the other in a mystery location referred to only with riddles. Foundation I participated openly in the affairs of the galaxy. Foundation II operated surreptitiously, intervening at key points in history to nudge events along Seldon's chosen path.

Seldon's plan for controlling human affairs was based on a

Preface

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links with the physical sciences as well, and ultimately, I suspect, it will forge a merger of all the sciences in the spirit of Asimov's psychohistory. At least that is the prospect that I explore in this book.

Game theory is a rich, profound, and controversial field, and there is much more to it than you could find in any one book. What follows is in no way a textbook on game theory. Nor do I attempt to give any account of its widespread uses in economics, the realm for which it was invented, or the many variants and refinements that have been developed to expand its economic applications. My focus is rather on how various manifestations of game theory built on Nash's foundation are now apple On a vast range of other scientific disciplines with solution to those arenas where game theory illuminates human nature and ophivio (and where it connect with other fields seeking similar insights). I view these flows on the context of the area for a "Code of Nature describing the "laws" of human behavior, a historical precursor to Asimov's notion of psychohistory.

As with all my books, I try to give any interested reader a flavor of what scientists are doing at the frontiers of knowledge, where there are no guarantees of ultimate success, but where pioneers are probing intriguing possibilities. There are scientists who regard some of this pioneering work as at best misguided and at worst a fruitless waste of time. Consequently, there may be objections from traditionalists who believe that the importance of game theory is overstated or that the prospects for a science of society are overhyped. Well, maybe so. Time will tell. For now, the fact is that game theory has already established itself as an essential tool in the behavioral sciences, where it is widely regarded as a unifying language for investigating human behavior. Game theory's prominence in evolutionary biology builds a natural bridge between the life sciences and the behavioral sciences. And connections have been established between game theory and two of the most prominent pillars of physics: statistical mechanics and quantum theory. Certainly many physicists, neuroscientists, and social scientists from various disciplines are indeed pursuing the dream of a quantitative

quantifying human experience," says neuroscientist Read Montague, "in the same way we quantify airflow over the wings of a Boeing 777."⁵

In short, Nash's math—with the rest of modern game theory built around it—is now the weapon of choice in the scientist's arsenal on a wide range of research frontiers related to human behavior. In fact, Herbert Gintis contends, game theory has become "a universal language for the unification of the behavioral sciences."⁶

I think it might go even farther than that. Game theory may become the language not just of the behavioral sciences, buy Silo the sciences.

As science stands today, that claim is httpe bold. It might ever be wrong. But game theory dready has conquere belowed of a sciences and invaded boorgy. And it is now in the works of a few pioneeting scientists, forming a power in alliance with physics. Physicists, of course, have always sought a unity in the ultimate description of nature, and game theory may have the potential to be a great unifier.

That realization hit me in early 2004, when I read a paper by physicist-mathematician David Wolpert, who works at NASA's Ames Research Center in California. Wolpert's paper disclosed a deep connection between the math of game theory and statistical mechanics, one of the most powerful all-purpose tools used by physicists for describing the complexities of the world.

Physicists have used statistical mechanics for more than a century to describe such things as gases, chemical reactions, and the properties of magnetic materials—essentially to quantify the behavior of matter in all sorts of circumstances. It's a way to describe the big picture when lacking data about the details. You can't track every one of the trillion trillion molecules of air zipping around in a room, for instance, but statistical mechanics can tell you how an air conditioner will affect the overall temperature.

It's no coincidence that statistical mechanics (which encompasses the kinetic theory of gases) is the math that inspired Asimov's heroic mathematician, Hari Seldon, to invent psycho-

Smith's Hand

Searching for the Code of Nature



-Roger Smith, The Norton History of the Human Sciences

Colin Camerer was a child prodigy, one of those kids who skipped several grades of school and enrolled in a special program for the gifted. By age 5, he was reading *Time* magazine (even though no one had taught him to read), and at 14 he entered Johns Hopkins University. He graduated in three years, then went to the University of Chicago to earn an M.B.A. and, for good measure, a Ph.D. He joined the faculty at Northwestern University's graduate school of management by the age of 22.

Today, he's a full-fledged adult on the faculty at Caltech, where he likes to play games. Or more accurately, he likes to analyze the behavior of other people during various game-playing experiments. Camerer is one of the nation's premier behavioral game theorists. He studies how game theory reveals the realities of human economic behavior, how people in real life depart from the purely rational choices assumed by traditional economic theory.

lectual leap to make his system fly. "In order to discover such a science as economics," they wrote, "Smith had to posit a faith in the orderly structure of nature, underlying appearances and accessible to man's reason."¹

Viewed in these terms, Smith's book was an important thread in a fabric of thought seeking a Code of Nature, a system of rules that explained human behavior (economic and otherwise) in much the same way that Newton had explained the cosmos. First philosophers, and then later sociologists and psychologists, tried to articulate a science of human behavior based on principles "underlying appearances" but "accessible to man's reason." Smith's of the reflected the influence of his friend and fellow the straan David Hume, the historian-philosopher who are fulled a "science of man" as the ultimate goal of the scientific emerprise. "There is the protion of importance whose decision is not comprised on the science of man" Hune wrote, "and the environe, which can be decided with any certainty, before we become acquainted with that science."² In the attempt "to explain the principles of human nature, we in effect propose a compleat system of the sciences."

Today, game theory's ubiquitous role in the human sciences suggests that its ambitions are woven from that same fabric. Game theory may, someday, turn out to be the foundation of a new and improved 21st-century version of the Code of Nature, fulfilling the dreams of Hume, Smith, and many others in centuries past.

That claim is enhanced, I think, with the realization that threads of Smith's thought are entangled not only in physical and social science, but biological science as well. Smith's ideas exerted a profound influence on Charles Darwin. Principles describing competition in the economic world, Darwin realized, made equal sense when applied to the battle for survival in the biological arena. And the benefits of the division of labor among workers that Smith extolled meshed nicely with the appearance of new species in nature. So it is surely no accident that, today, applying economic game theory to the study of evolution is a major intellectual industry. promoted by many of Smith's disciples—that Smith had revealed "a natural order of things," an "offshoot of the ancient fiction of a Code of Nature."

This idea of a "code of natural law" had been around since Roman times, with possible Greek antecedents. The Roman legal system recognized not only Roman civil law (*Jus Civile*), the specific legal codes of the Romans, but a more general law (*Jus Gentium*), consisting of laws arising "by natural reason" that are "common to all mankind," as described by Gaius, a Roman jurist of the second century A.D.

Apparently some Roman legal philosophers regarded *Jer on* **3** *tium* as the offspring of a forgotten "natural law" in *eventment* or "Code of Nature"—an assumed primortial "overnment-free"elegal code shared by all nations and herpes. Human politic (1) ntitutions, in this view, differ a beneficial and harrow out an atural order of folgs. So as near as I apper One of Nature" is what people commonly refer to today us the law of the jungle.⁹ (Perhaps the FOX network will develop it as the next new reality-TV series.) "The belief gradually prevailed among the Roman lawyers that the old *Jus Gentium* was in fact the lost code of Nature," English legal scholar Henry Maine wrote in an 1861 treatise titled *Ancient Law*. "Framing . . . jurisprudence on the principles of the *Jus Gentium* was gradually restoring a type from which law had only departed to deteriorate."¹⁰

In any event, as Cliffe Leslie recounted, the "Code of Nature" idea was, in Smith's day, one of two approaches to grasping "the fundamental laws of human society." The Code of Nature method sought to reason out the laws of society by deducing the natural order of things from innate features of the human mind. The other approach "induced" societal laws by examining history and features of real life to find out how things actually are, rather than some idealized notion of how human nature should be.

In fact, Smith's work did express sentiments favorable to the Code of Nature view; his statement that eliminating governmental preferences and restraints allows "the obvious and simple system of natural liberty" to establish itself clearly resonates with the conOf course, he accomplished plenty anyway. Von Neumann produced the standard mathematical formulation of quantum mechanics, for instance. He didn't exactly invent the modern digital computer, but he improved it and pioneered its use for scientific research. And, apparently just for kicks, he revolutionized economics.

Born in 1903 in Hungary, von Neumann was given the name Janos but went by the nickname Jancsi. He was the son of a banker (who had paid for the right to use the honorific title *von*). As a child, Jancsi dazzled adults with his mental powers, telling jokes in Greek and memorizing the numbers in phone books. Later the on rolled in the University of Budapest as a math more out than't bother to attend the classes—at the same side he was majoring in chemistry at the University of Burlin He waveled back to Budapest for exams, aced them and continued his chemical entration, first at Berlin in the dater at the University of Zarich.

I've recounted some of von Neumann's adult intellectual escapades before (in my book *The Bit and the Pendulum*), such as the time when he was called in as a consultant to determine whether the Rand Corporation needed a new computer to solve a difficult problem. Rand didn't need a new computer, von Neumann declared, after solving the problem in his head. In her biography of John Nash, Sylvia Nasar relates another telling von Neumann anecdote, about a famous trick-question math problem. Two cyclists start out 20 miles apart, heading for each other at 10 miles an hour. Meanwhile a fly flies back and forth between the bicycles at 15 miles an hour. How far has the fly flown by the time the bicycles meet? You can solve it by adding up the fly's many shorter and shorter paths between bikes (this would be known in mathematical terms as summing the infinite series). If you detect the trick, though, you can solve the problem in an instant—it will take the bikes an hour to meet, so the fly obviously will have flown 15 miles.

When jokesters posed this question to von Neumann, sure enough, he answered within a second or two. Oh, you knew the trick, they moaned. "What trick?" said von Neumann. "All I did was sum the infinite series." Bentham, utility was roughly identical to happiness or pleasure in "maximizing their utility," individual people would seek to increase pleasure and diminish pain. For society as a whole, maximum utility meant "the greatest happiness of the greatest number."³ Bentham's utilitarianism incorporated some of the philosophical views of David Hume, friend to Adam Smith. And one of Bentham's influential followers was the British economist David Ricardo, who incorporated the idea of utility into his economic philosophy.

In economics, utility's usefulness depends on expressing it quantitatively. Happiness isn't easily quantifiable, for example the (as Bentham noted) the *means* to happiness can also be norrected as a measure of utility. Wealth, for example, provides a meane of enhancing happiness, and wealth it easier to measure. So meaonomics, the usual approach is to measure self intersect terms of money. Its Norwment medium of exchange for comparing the value of different things. But in most walks of life (except perhaps publishing), money isn't everything. So you need a general definition that makes it possible to express utility in a useful mathematical form.

One mathematical approach to quantifying utility came along long before Bentham, in a famous 1738 result from Daniel Bernoulli, the Swiss mathematician (one of many famous Bernoullis of that era). In solving a mathematical paradox about gambling posed by his cousin Nicholas, Daniel realized that utility does not simply equate to quantity. The utility of a certain amount of money, for instance, depends on how much money you already have. A million-dollar lottery prize has less utility for Bill Gates than it would for, say, me. Daniel Bernoulli proposed a method for calculating the reduction in utility as the amount of money increased.⁴

Obviously the idea of utility—what you want to maximize can sometimes get pretty complicated. But in many ordinary situations, utility is no mystery. If you're playing basketball, you want to score the most points. In chess, you want to checkmate your opponent's king. In poker, you want to win the pot. Often if the *Minnow* had beached on Crusoe's island, each new player would have brought an additional set of variables of his or her own into the game. Then Crusoe would need to take all of those new variables into account, too.

On top of all that, more players means a more complex economy, more kinds of goods and services, different methods of production. So the social economy rapidly becomes a mathematical nightmare, it would seem, beyond even the ability of the know-Notesale.C 8. of 273 it-all Professor to resolve. But there is hope, for economics and for understanding society, and it's a hope that's based on the simple idea of taking a temperature.

TAKING SOCIETY'S EVILE AT

In drawing analogits ween economics and ysics, von Neumann and Morgenstern talk 1 P but the theory of heat (or, as it is more pretentiously nown, thermodynamics). They pointed out, for instance, that measuring heat precisely did not lead to a theory of heat; physicists needed the theory first, in order to understand how to measure heat in an unambiguous way. In a similar way, game theory needed to be developed first to give economists the tools they needed to measure economic variables properly.

The example of the theory of heat played another crucial role—in articulating a basic issue within game theory itself. At the outset, von Neumann and Morgenstern made it clear that they did not want to venture into the philosophical quagmire of defining all the nuances of utility. For them, to develop game theory for use in economics, it was enough to equate utility with money. For the businessman, money (as in profits) is a logical measure of utility; for consumers, income (minus expenses) is a good measure of utility, or you could think of the utility of an object as the price you were willing to pay for it. And money can be used as a currency for translating what anyone wants into more specific objects or events or experiences or whatever. So equating utility with money is a convenient simplifying assumption, allowing the theory to focus

does. And Bob will choose the bus also, because it minimizes his losses, no matter what Alice does. Walking can do no better and might be worse.

Of course, you didn't need game theory to figure this out. So let's look at another example, from real-world warfare, a favorite of game theory textbooks.

In World War II, General George Kenney knew that the Japanese would be sending a convoy of supply ships to New Guinea. The Allies naturally wanted to bomb the hell out of the convoy. But the convoy would be taking one of two possible routes--one to the north of New Britain, one to the south.

sale.c Either route would take three days, so in prin could get in three days' worth of hombing time against the con voy. But the weather could interfere horecasters said the not route would be rainy place. the days, limiting the building time to a max m n c two days. The part of Nate would be clear, providing visibility for three days of bombing. General Kenney had to decide whether to send his reconnaissance planes north or south. If he sent them south and the convoy went north, he would lose a day of bombing time (of only two bombing days available). If the recon planes went north, the bombers would still have time to get two bombing days in if the convoy went south.

So the "payoff" matrix looks like this, with the numbers giving the Allies' "winnings" in days of bombing:

		Japanese	
		North	South
Allies	North	2	2
	South	1	3

fied with the strategy they've adopted, in the sense that no other strategy would do better (as long as nobody else changes strategies, either). Similarly, in social situations, stability means that everybody is pretty much content with the status quo. It may not be that you like things the way they are, but changing them will only make things worse. There's no impetus for change, so like a rock in a valley, the situation is at an equilibrium point.

In a two-person zero-sum game, you can determine the equilibrium point using von Neumann's minimax solution. Whether using a pure strategy or a mixed strategy, neither player has anything to gain by deviating from the optimum strategy that same theory prescribes. But von Neumann did not player has similarly stable solutions could be found whet you moved from the Robinson Crusoe–Friday, coolomy to the Gilligar (s) plant economy or Manhittan shand economy. And at you'll recall, von Neuman incorpt the way to an alwel large economies (or games) was by considering coalitions among the players.

Nash, however, took a different approach—deviating from the "party line" in game theory, as he described it decades later. Suppose there are no coalitions, no cooperation among the players. Every player wants the best deal he or she can get. Is there always a set of strategies that makes the game stable, giving each player the best possible personal payoff (assuming everybody chooses the best available strategy)? Nash answered yes. Borrowing a clever piece of mathematical trickery known as a "fixed-point theorem," he proved that every game of many players (as long as you didn't have an infinite number of players) had an equilibrium point.

Nash derived his proof in different ways, using either of two fixed-point theorems—one by Luitzen Brouwer, the other by Shizuo Kakutani. A detailed explanation of fixed-point theorems requires some dense mathematics, but the essential idea can be illustrated rather simply. Take two identical sheets of paper, crumple one up, and place it on top of the other. Somewhere in the crumpled sheet will be a point lying directly above the corresponding point on the uncrumpled sheet. That's the fixed point. If you don't believe it, take a map of the United States and place it

Von Neumann and Morgenstern, Nash politely noted in his paper, had produced a "very fruitful" theory of two-person zerosum games. Their theory of many-player games, however, was restricted to games that Nash termed "cooperative," in the sense that it analyzed the interactions among coalitions of players. "Our theory, in contradistinction, is based on the *absence* of coalitions in that it is assumed that each participant acts independently, without collaboration or communication with any of the others."¹⁵ In other words, Nash devised an "every man for himself" version of manyle.c player games-which is why he called it "noncooperative" game theory. When you think about it, that approach pretty much for up many social situations. In a dog-eat-dog work, housh equilibrium describes how every dog car have as best possible day "The distinction between not-cooperative and cooperative rames that Nash made is de i fre to this day," wrote ga n ecorist Harold Kuhn.

To me, the really key point about the Nash equilibrium is that it cements the analogy between game theory math and the laws of physics—game theory describing social systems, the laws of physics describing natural systems. In the natural world, everything seeks stability, which means seeking a state of minimum energy. The rock rolls downhill because a rock at the top of a hill has a high potential energy; it gives that energy away by rolling downhill. It's because of the law of gravity. In a chemical reaction, all the atoms involved are seeking a stable arrangement, possessing a minimum amount of energy. It's because of the laws of thermodynamics.

And just as in a chemical reaction all the atoms are simultaneously seeking a state with minimum energy, in an economy all the people are seeking to maximize their utility. A chemical reaction reaches an equilibrium enforced by the laws of thermodynamics; an economy should reach a Nash equilibrium dictated by game theory.¹⁷

Real life isn't quite that simple, of course. There are usually complicating factors. A bulldozer can push the rock back up the hill; you can add chemicals to spark new chemistry in a batch of at maximizing their food intake. So he cut up some white bread into precisely weighed pieces and enlisted some friends to toss the pieces onto the pond.

The ducks, naturally, were delighted with this experiment, so they all rapidly paddled into position. But then Harper's helpers began tossing the bread onto two separated patches of the pond. At one spot, the bread tosser dispensed one piece of bread every five seconds. The second was slower, tossing out the bread balls just once every 10 seconds.

Now, the burning scientific question was, if you're a duck, what do you do? Do you swim to the spot in front of the factor tosser or the slow tosser? It's not an easy question. When I ask people what they would do, I inevitably genamix of answers (and some keep changing their mind as they think aborpit longet).

Perhaps (if you we calcuck) your first thought would be to go for the 90 yth owing the breaching a text. But all the other ducks might have the same idea. You's get more bread for yourself if you switched to the other guy, right? But you're probably not the only duck who would realize that. So the choice of the optimum strategy isn't immediately obvious, even for people. To get the answer you have to calculate a Nash equilibrium.

After all, foraging for food is a lot like a game. In this case, the chunks of bread are the payoff. You want to get as much as you can. So do all the other ducks. As these were university ducks, they were no doubt aware that there is a Nash equilibrium point, an arrangement that gets every duck the most food possible when all the other ducks are also pursuing a maximum food-getting strategy.

Knowing (or observing) the rate of tosses, you can calculate the equilibrium point using Nash's math. In this case the calculation is pretty simple: The ducks all get their best possible deal if one-third of them stand in front of the slow tosser and the other two-thirds stand in front of the fast tosser.

And guess what? It took the ducks about a minute to figure that out. They split into two groups almost precisely the size that game theory predicted. *Ducks know how to play game theory!*

When the experimenters complicated things—by throwing bread chunks of different sizes—the ducks needed to consider both the rate of tossing and the amount of bread per toss. Even then, the ducks eventually sorted themselves into the group sizes that Nash equilibrium required, although it took a little longer.¹

Now you have to admit, that's a little strange. Game theory was designed to describe how "rational" humans would maximize their utility. And now it turns out you don't need to be rational, or even human.² The duck experiment shows, I think, that there's more to game theory than meets the eye. Game theory is not just a clever way to figure out how to play poker. Game theory corrections something about how the world works.

At least the biological world. And it multiplies the realization that game theory describes biology that gave it its first major symmetrific successes. Game theory inturns out, captures that realized on the second of biological evolution. Many expense on visual explains the mystery of human cooperation, how civinization itself could emerge from individuals observing the laws of the jungle. And it even seems to help explain the origin of language, including why people like to gossip.

LIFE AND MATH

I learned about evolution and game theory by visiting the Institute of Advanced Study in Princeton, home of von Neumann during game theory's infancy. Long recognized as one of the world's premier centers for math and physics, the institute had been slow to acknowledge the ascent of biology in the hierarchy of scientific disciplines. By the late 1990s, though, the institute had decided to plunge into the 21st century a little early by initiating a program in theoretical biology.

Just as the newborn institute had reached across the Atlantic to bring von Neumann, Einstein, and others to America, it recruited a director for its biology program from Europe—Martin Nowak, an Austrian working at the University of Oxford in England. Nowak was an accomplished mathematical biologist who had mixed biosites and their hosts to out-and-out altruism that people often exhibit toward total strangers. Human civilization could never have developed as it has without such widespread cooperation; finding the Code of Nature describing human social behavior will not be possible without understanding how that cooperation evolved. And the key clues to that understanding are coming from game theory.

GAMES OF LIFE

In the 1960s, even before most economists took game theory seriously, several biologists noticed that it might prove useful in the seriplaining aspects of evolution. But the man was welly put evolutionary game theory on the science hap was the British 2

He was "an opplotenable man with usual) Onite hair and thick glaste," of or his obituate Bud, temembered by colleagues and friends as a charismalic speaker but deadly debater, a lover of nature and an avid gardener, and a man who enjoyed nothing better than discussing scientific ideas with young researchers over a glass of beer in a pub."⁴ Unfortunately I never had a chance to have a beer with him. He died in 2004.

Maynard Smith was born in 1920. As a child, he enjoyed collecting beetles and bird-watching, foreshadowing his future biological interests. At Eton College he was immersed in mathematics and then specialized in engineering at Cambridge University. During World War II he did engineering research on airplane stability, but after the war he returned to biology, studying zoology under the famed J. B. S. Haldane at University College London.

In the early 1970s, Maynard Smith received a paper to review that had been submitted to the journal *Nature* by an American researcher named George Price. Price had attempted to explain why animals competing for resources did not always fight as ferociously as they might have, a puzzling observation if natural selection really implied that they should fight to the death if only the fittest survive. Price's paper was too long for *Nature*, but the issue remained in the back of Maynard Smith's mind. A year later, while of players. Further studies suggest why the human race might have evolved to include punishers.

In one such test of a public goods game,¹⁸ most players began by giving up an average of half their points. After several rounds, though, contributions dropped off. In one test, nearly three-fourths of the players donated nothing by round 10. It appeared to the researchers that people became angry at others who donated too little at the beginning, and retaliated by lowering their own donations—punishing everybody. That is to say, more of the players became reciprocators.

But in another version of the game, a researcher annuares each player's contribution after every round and which the comments from the rest of the group. When hev-annount donors were ridiculed, the cheapskates conched up more generative on tributions in later rounds. When about the low aloners, later contributions drupped. Shame appare the tribution of the proved behavior.

Other experiments consistently show that noncooperators risk punishment. So it may have been in the evolutionary past that groups containing punishers—and thus more incentive for cooperation—outsurvived groups that did not practice punishment. The tendency to punish may therefore have become ingrained in surviving human populations, even though the punishers do so at a cost to themselves. ("Ingrained" might not be just in the genes, though—many experts believe that culture transmits the punishment attitude down through the generations.)

Of course, it's not so obvious what form that punishment might have taken back in the human evolutionary past. Bowles and Gintis have suggested that the punishment might have consisted of ostracism, making the cost to the punisher relatively low but still inflicting a significant cost on the noncooperator. They show how game theory interactions would naturally lead societies to develop with some proportion of all three types noncooperators (free riders), cooperators, and punishers (reciprocators)—just as other computer simulations have shown. The human race plays a mixed strategy. As the 20th century progressed, both Freudianism and behaviorism faded. The black box concealing the brain turned translucent as molecular medicine revealed some of its inner workings. Nowadays the brain is almost transparent, thanks to a variety of scanning technologies that produce images of the brain in action. And so the infant neuroscience that Freud abandoned over a century ago has now matured, nearly to the point of fulfilling his original intention.

Freud could not have dreamed about merging neuroscience with economics, though, for he died before the rise of game theory. And even though they regarded game theory as a wintlow how human behavior, game theory's originators thread vis did not imagine that their math would someday at write the cause of frain science. The original game theorist would not have pedicted that game theory could to recay partner with neuroscience, or that such a battlet op would facilitate gime theory is quest to conquer economics.¹ But in the late 1990s, game theory turned out to be just the right math for bringing neuroscience and economics together, in a new hybrid field known as neuroeconomics.

BRAINS AND ECONOMICS

One of the appealing features of game theory is the way it reflects so many aspects of real life. To win a game, or survive in the jungle, or succeed in business, you need to know how to play your cards. You have to be clever about choosing whether to draw or stand pat, bet or pass, or possibly bid nillo. You have to know when to hold 'em and know when to fold 'em. And usually you have to think fast. Winners excel at making smart snap judgments. In the jungle, you don't have time to calculate, using game theory or otherwise, the relative merits of fighting or fleeing, hiding or seeking.

Animals know this. They constantly face many competing choices from a long list of possible behaviors, as neuroscientists Gregory Berns and Read Montague have observed (in language

FREUD'S DREAM

human civilization, to explain how selfish individuals manage to cooperate sufficiently well to establish elaborate functioning societies. Smith's basic answer was the existence of sympathy—the ability of one human to understand what another is feeling. Modern neuroscience has begun to show how sympathy works, by identifying "mirror neurons," nerve cells in the brain that fire their signals both in performing an action and when viewing someone else performing that same action.

Other neuroscientific studies have identified the neural basis of both individual behavioral propensities and collective and cooperative human behavior. Scientists scanning the brains of the ers participating in a repeated Prisoner's Dilented vane, for instance, have identified regions in the brain that are active in platers who prefer cooperating rather than the "purely rational" choice to defect.¹⁴

Another successed a version of the true game to examine the brains of people who punish those who play uncooperatively (by keeping all the money instead of returning a fair share). In this game, players who feel cheated may assess a fine on the defector (even though they must pay the price of reducing their own earnings by half the amount of the fine they impose). People who choose to fine the defector display extra activity in a brain region associated with the expectation of reward. That suggests that some people derive pleasure from punishing wrongdoers—the payoff is in personal satisfaction, not in money. In the early evolution of human society, such "punishers" would serve a useful purpose to the group by helping to ostracize the untrustworthy noncooperators, making life easier for the cooperators. (Since this punishment is costly to the individual but beneficial to the group as a whole, it is known as "altruistic punishment.")¹⁵

Such studies highlight an essential aspect of human behavior that a universal Code of Nature must accommodate—namely that people do not all behave alike. Some players prefer to cooperate while others choose to defect, and some players show a stronger desire than others to inflict punishment. A Code of Nature must accommodate a mixture of individually different behavioral ten-

A Beautiful Math

CULTURAL DIVERSITY

This cross-cultural game theory research clearly shows that people in many cultures do not play economic games in the selfish way that traditional economic textbooks envision. And it appears that the differences in behavior are indeed rooted in culture-specific aspects of the group's daily life. Individual differences among the members of a group—such as sex, age, education, and even personal wealth—did not affect the likelihood of rejecting an offer very much. Such choices apparently depend not so much on individual idiosyncrasies as on the sorts of economic activity a society a engages in. In particular, average offers seemed to real coast every s amount of commerce with other groups. More experience particing pating in markets, the research enggetted, produces not controat competition, but a green these of fairness.

The ting e Michiguenga, for instance, are economically detached from most of the work-or iso, they hardly ever interact with anyone outside their own families. So their market-based economic activity is very limited, and their behavior is selfish. In cultures with more "market integration," such as the cattle-trading Orma in Kenya, ultimatum game offers are generally higher, averaging 44 percent of the pot and often are as much as half.

Orma average offers are similar to those found with American college students. But sometimes students make low offers, and the Orma rarely do. College students find their low offers are usually rejected, but in some societies any offer is accepted, no matter how low. Among the Torguud Mongols of western Mongolia, for example, a low offer is rarely refused. Even so, Torguud offers averaged between 30 and 40 percent—despite the fact that the offerer would surely get more by offering less. Apparently the local Mongolian culture values fairness more than money. At the same time, inflicting punishment (by rejecting an offer) is not highly regarded there, either.

In society after society, the anthropologists discovered different ways in which cultural considerations dictated unselfish behavior. Among the Aché of Paraguay, for example, hunters often leave (That just means that certain conditions influenced some genetic strains but not others.)

Mogil and collaborators concluded that the laboratory environment plays an important role in the way mice behave, either masking or exaggerating the effects under genetic control. And since tail-flipping is such a simple behavior—basically a spinal cord reflex—it's unlikely that the environment's influence in this case is a fluke. More complicated behaviors would probably be even more susceptible to environmental effects, the researchers observed.

Results such as these strike me as similar to findings about 500 humans play economic games in different ways Gere, environment, and culture interact to produce conductivity of behaviors in mice, and in people. The human face has adopted a nixed strategy for surviving in the work. With a diverse blend of Dihavioral types. It should "becurprising there uses offer around the world as well, that the planet is populated by a "inixed strategy" of cultures, rooted in a mixture of influences on how behavior evolves.

A MIXED HUMAN NATURE

So what of human nature, and game theory's ability to describe it? There is a human nature, but it is not the simplistic consistent human nature described by extreme evolutionary psychologists. It is the mixed human nature that, on reflection, should be obvious in a world ruled by game theory. Evolution, after all, is game theory's ultimate experiment, where the payoff is survival. As we've seen, evolutionary game theory does not predict that a single behavioral strategy will win the game. That would be like a society populated by all hawks or all doves—an unstable situation, far from Nash equilibrium. Game theory's rules induce instead a multiplicity of strategies, leading to a diverse menagerie of species practicing different sorts of behaviors to survive and reproduce.

Seen through the lens of game theory, evolution's role in human psychology is still important, but it operates more subtly than

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While Asimov's vision remains a science fiction dream, it is now closer to reality than probably even he would have thought possible. The statistical approach inaugurated by Maxwell has today become physicists' favorite weapon for invading the social sciences and describing human actions with math. Physicists have applied the statistical approach to analyzing the economy, voting behavior, traffic flow, the spread of disease, the transmission of opinions, and the paths people take when fleeing in panic after somebody shouts Fire! in a crowded theater.

But here's the thing. This isn't a new idea, and physicists didn't have it first. In fact, Maxwell, who was the first to devise the state tical description of molecules, got the idea to use statistics in physics from social scientists applying multiply society! So before statistical physicists congratulate themselves for showing the way to explaining the spill eccences, they should path to reflect on the his physicist field. As the set metrum alist Philip Ball has observed, "by seeking to unrove, the rules of collective human activities, statistical physicists are aiming to return to their roots."³

In fact, efforts to apply science and math to society have a rich history, extending back several centuries. And that history contains hints of ideas that can, in retrospect, be seen as similar to key aspects of game theory—foreshadowing an eventual convergence of all these fields in the quest for a Code of Nature.

STATISTICS AND SOCIETY

The idea of finding a science of society long predates Asimov. In a sense it goes back to ancient times, of course, resembling at least partially the old notion of a "natural law" of human behavior or a Code of Nature. In early modern times, the idea received renewed impetus from the success of Newtonian physics, stimulating the efforts of Adam Smith and others as described in Chapter 1. Even before Newton, though, the rise of mechanistic physical science inspired several philosophers to consider a similarly rigorous approach to society.

In medieval times, the importance of the mechanical clock to

pretty much the same from one year to the next, and even the murderer's methods showed a similar distribution.

"The actions which society stamps as crimes," Quetelet wrote, "are reproduced every year, in almost exactly the same numbers; examined more closely, they are found to divide themselves into almost exactly the same categories; and if their numbers were sufficiently large, we might carry farther our distinctions and subdivisions, and should always find there the same regularity."¹² Similarly, the rate of crimes for different ages displayed a constant distribution, with the 21–25 age group always topping the list. "Crime pursues its path with even more constancy than death," Concert observed.¹³

He warned, though, of the danger considery interpreting such statistics without sufficiently car full mought. Another releasener, for instance, had show that property crime in France was higher in products where more children over sent to schools, and concluded that education caused erime. It's the sort of reasoning you hear today on talk radio. Quetelet correctly chastised such stupidity.

Quetelet also repeatedly emphasized that the statistical approach could not be used to draw conclusions about any given individual (another obvious principle that is often forgotten by today's media philosophers). The insurance company's mortality tables cannot forecast the time of any one person's death, for instance. Nor can any single case, however odd, invalidate the general conclusions drawn from a statistical regularity.

Quetelet's exposition of social statistics attracted a great deal of attention among scientists and philosophers. Many of them were aghast that he seemed to have little regard for the supposed free will that humans exercised as they pleased. Quetelet responded not by denying free will, but by observing that it had its limits, and that human choice was always influenced by conditions and circumstances, including laws and moral strictures. In making the simplest of choices, Quetelet noted, our habits, needs, relationships, and a hundred other factors buffet us from all sides. This "empire of causes" typically overwhelms free will, which is why, with using a fair coin). But there are many conceivable combinations of totals that would give that average. Half the trials could turn up 10 heads, for instance, while the other half turned up zero every time. Or you could imagine getting precisely 5 heads in every 10-flip trial.

What actually happens is that the number of trials with different numbers of heads is distributed all across the board, but with differing probabilities—about 25 percent of the time you'll get 5 heads, 20 percent of the time 4 (same for 6), 12 percent of the time 3 (also for 7). You would expect to get 1 head 1 percent of the time (and no heads at all out of a 10-flip run about 0.1 percent of the time, or once in a thousand). Coin tossing, that is words, produces a probability distribution of consumes not merely some average outcome. Maxwell's intight was that the carn kind of probability distribution generates the possible allocators of energy among a most of molecules. And can's theory's triumph was in showing that a probability distribution of pure strategies—a mixed strategy—is usually the way to maximize your payoff (or minimize your losses) when your opponents are playing wisely (which means they, too, are using mixed strategies).

Imagine you are repeatedly playing a simple game like matching pennies, in which you guess whether your opponent's penny shows heads or tails. Your best mixed strategy is to choose heads half the time (and tails half the time), but it's not good enough just to average out at 50-50. Your choices need to be made randomly, so that they will reflect the proper probability distribution for equally likely alternatives. If you merely alternate the choice of heads or tails, your opponent will soon see a pattern and exploit it; your 50-50 split of the two choices does you no good. If you are choosing with true randomness, 1 percent of the time you'll choose heads 9 times out of 10, for instance.

In his book on behavioral game theory, Colin Camerer discusses studies of this principle in a real game—tennis—where a similar 50-50 choice arises: whether to serve to your opponent's right or left side. To keep your opponent guessing, you should serve one way or the other at random.²² Amateur players tend to

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Bacon's Links

Networks, society, and games



Modern science owes a lot to a guy named Bacon.

If you had said so four centuries ago, you would have meant Francis Bacon, the English philosopher who stressed the importance of the experimental method for investigating nature. Bacon's influence was so substantial that modern science's birth is sometimes referred to as the Baconian revolution.

Nowadays, though, when you mention Bacon and science in the same breath you're probably talking not about Francis, but Kevin, the Hollywood actor. Some observers might even say that a second Baconian revolution is now in progress.

After all, everybody has heard by now that Kevin Bacon is the most connected actor in the movie business. He has been in so many films that you can link almost any two actors via the network of movies that he has appeared in. John Belushi and Demi Moore, for instance, are linked via Bacon through his roles in Animal House (with Belushi) and A Few Good Men (with Moore). Actors who never appeared with Bacon can be linked indirectly: Penelope Cruz has no common films with Bacon, but she was in *Vanilla Sky* with Tom Cruise, who appeared with Bacon in *A Few Good Men.* By mid-2005, Bacon had appeared in films with nearly 2,000 other actors, and he could be linked in six steps or fewer to more than 99.9 percent of all the linked actors in a database dating back to 1892. Bacon's notoriety in this regard has become legendary, even earning him a starring role in a TV commercial shown during the Super Bowl.

Bacon's fame inspired the renaissance of a branch of mathematics known as graph theory—in common parlance, **abs** math of networks. Bacon's role in the network of a cost motivated mathematicians to discover new properties (but an sorts of networks that could be described with the tools of statistical plysic. In particular, modern Bharitan science has turned the attention of statistical physic sr to social networks (providing a new mode of attack on the problem of forecasting collective human behavior.

In fact, the new network math has begun to resemble a blueprint for a science of human social interaction, a Code of Nature. So far, though, the statistical physics approach to quantifying social networks has mostly paid little attention to game theory. Many researchers believe, however, that there is—or will be—a connection. For game theory is not merely the math for analyzing individual behavior, as you'll recall—it also proscribes the rules by which many complex networks form. What started out as a game about Kevin Bacon's network may end up as a convergence of the science of networks and game theory.

SIX DEGREES

In the early 1990s, Kevin Bacon's ubiquity in popular films caught the attention of some college students in Pennsylvania. They devised a party game in which players tried to find the shortest path of movies linking Bacon to some other actor. When a TV talk show publicized the game in 1994, some clever computer science students at the University of Virginia were watching. They soon (actor or airport) is as likely to be linked as much as any other, so most of them are linked to about the same degree. Only a few would have a lot more links than average, or a lot less. If actors were linked randomly, their rankings by number of links would form a bell curve, with most of them close to the middle. But in many small-world networks, there is no such "typical scale" of the number of links.

Such distributions—with no typical common size—are known as "scale free." In scale-free networks, many lonely nodes will have hardly any connections at all, some nodes will be moderately well connected, and a few will be superconnected hubs. To mathematical cians and physicists, such a scale-free distribution is convergent of a "power law."

In a groundbreaking paper pit listed in *Science* in 1999 Héka Albert and Albert-Irácz Barabási of Notre Dahe University noted the scare in ensure of many kinds of a tworks, and consequently the userulness of power laws for describing them. The revelation that networks could be described by power laws struck a responsive chord among physicists. (They "salivate over power laws," Strogatz says—apparently because power law discoveries in other realms of physics have won some Nobel Prizes.)

Power laws describe systems that include a very few big things and lots of little things. Cities, for example. There are a handful of U.S. cities with populations in the millions, a larger number of medium-sized cities in the 100,000 to a million range, and many, many more small towns. Same with earthquakes. There are lots of little earthquakes, too weak to notice; a fewer number of middling ones that rattle the dishes; and a very few devastating shocks that crumble bridges and buildings.

In their *Science* paper, Barabási and Albert showed how the probability that a node in a scale-free network is linked to a given number of other nodes diminishes as the number of links increases. That is to say, scale-free networks possess many weakly linked nodes, fewer with a moderate number of links, and a handful of monsters—like Google, Yahoo, and Amazon on the World Wide Web. Nodes with few links are common, like small earthquakes;

Asimov's Vision

Psychohistory, or sociophysics?

"Humans are not numbers." Wrong; we justice of tesale. want to be treated like numbers. —Dietrich stanter 07273 Preview Page In 1951—the same year that John Nash published his famous paper on equilibrium in game theory—Isaac Asimov published the novel *Foundation*. It was the first in a series of three books (initially) telling the story of a decaying galactic empire and a new science of social behavior called psychohistory. Asimov's books eventually became the most famous science fiction trilogy to appear between Lord of the Rings and Star Wars. His psychohistory became the model for the modern search for a Code of Nature, a science enabling a quantitative description and accurate predictions of collective human behavior.1

Mixing psychology with math, psychohistory hijacked the methods of physics to forecast-and influence-the future course of social and political events. Today, dozens of physicists and mathematicians around the world are following Asimov's lead, seeking the equations that capture telling patterns in social behavior, trying to show that the madness of crowds has a method.

As a result, Asimov's vision is no longer wholly fiction. His psychohistory exists in a loose confederation of research enterprises that go by different names and treat different aspects of the Fortunately, the collisions of molecules have their counterpart in human interaction. While molecules collide, people connect, in various sorts of social networks. So while the basic idea behind sociophysics has been around for a while, it really didn't take off until the new understanding of networks started grabbing headlines.

Social networks have now provided physicists with the perfect playground for trying out their statistical math. Much of this work has paid little heed to game theory, but papers have begun to aple.c pear exploring the way that variants on Nash's math become important in social network contexts. After all, von Neuran 550 Morgenstern themselves pointed out that statistical obvics provided a model giving hope that game the overcould describe arge social groups. Nash saw his concept of game theory equilibrium in the same terms as the first in chemical reactions, which is also describ 2017 etistical mechanics And eme theory provides the proper mathematical framework for describing how competitive interactions produce complex networks to begin with. So if the offspring of the marriage between statistical physics and networks is something like Asimov's psychohistory, game theory could be the midwife.

SOCIOCONDEMNATION

Network math offers many obvious social uses. It's just what the doctor ordered for tracking the spread of an infectious disease, for instance, or plotting vaccination strategies. And because ideas can spread like epidemics, similar math may govern the spread of opinions and social trends, or even voting behavior.

This is not an entirely new idea, even within physics. Early attempts to apply statistical physics to such problems met with severe resistance, though, as Serge Galam has testified. Galam was a student at Tel-Aviv University during the 1970s, when statistical mechanics was the hottest topic in physics, thanks largely to some Nobel Prize–winning work by Kenneth Wilson at Cornell University. Galam pursued his education in statistical physics but with a to find a similar analogy between particles and people that will lead to an improved knowledge of the functioning of society.

SOCIOMAGNETISM

One popular example of such an approach appeared in 2000 from Katarzyna Sznajd-Weron of the University of Wroclaw in Poland. She was interested in how opinions form and change among members of a society. She reasoned that the global distribution of opinions in a society must reflect the behavior and interactions of individuals—in physics terms, the macrostate of the system Pass reflect its microstate (like the overall temperature or pressure of a container of gas reflects the speed and all bioms of individual molecules).⁶ "The question is furthelaws on the microscopic scale of a social system conversion phenomene on the macroscopic scale, phenomene that sociologism is now wise," she wrote.⁷

Sznajd-Weron was well aware that people recoil when told they are just like atoms or electrons rather than individuals with feelings and free will. "Indeed, we are individuals," she wrote, "but in many situations we behave like particles." And one of those common properties that people share with particles is a tendency to be influenced by their neighbors. Sometimes what one person does or thinks depends on what someone else is doing, just as one particle's behavior can be affected by other particles in its vicinity.

Sznajd-Weron related an anecdote about a New Yorker staring upward at the sky one morning while other New Yorkers pass by, paying no attention. Then, the next morning, four people stare skyward, and soon others stop as well, all looking up for no reason other than to join in the behavior of the crowd. Such pack behavior suggested to Sznajd-Weron an analogy for crowd behavior as described by the statistical mechanics of phase transitions, the sudden changes in condition such as the freezing of water into ice. Another sort of phase transition, of the type that attracted her attention, is the sudden appearance of magnetism in some materials cooled below a certain temperature. patterned, contextual, and sometimes suboptimal behavior we think of as culture."¹³

But game theory has a remarkable resilience against charges of irrelevance. It's explanatory power has not yet been exhausted, even by the demands of explaining the many versions of human culture. "Surprisingly," Bednar and Page declare, "game theory is up to the task."¹⁴

The individuals, or agents, within a society may very well possess rational impulses driving them to seek optimum behaviors, Bednar and Page note. But the effort to figure out optimal behaviors in a complicated situation is often considerable. In any graph game, a player has to consider not only the payof of the "best" strategy, but also the cost of calculating the bist moves to achieve that payoff. With limited brain power (and everybed as is Con can't always afford the cost of calculating the not profitable response.

Even more important, in real like yea are never playing only one game. You are in fact engaging in an ensemble of many different games simultaneously, imposing an even greater drain on your brain power. "As a result," write Bednar and Page, "an agent's strategy in one game will be dependent upon the full ensemble of games it faces."

So Alice and Bob (remember them?) may be participating in a whole bunch of other games, requiring more complicated calculations than they needed back in Chapter 2. If they have only one game in common, the overall demand on their calculating powers could be very different. Even if they face identical situations in the one game they play together, their choices might differ, depending on the difficulty of all the other games they are playing at the same time. As Bednar and Page point out, "two agents facing different ensembles of games may choose distinct strategies on games that are common to both ensembles."

In other words, with limited brain power, and many games to play, the "rational" thing to do is not to calculate pure, ideal game theory predictions for your choices, but to adopt a system of general guidelines for behavior, like the Pirate's Code in the Johnny Shubik. "Almost certainly, 'physical' aspects of theories of social order will not simply recapitulate existing theories in physics."¹⁶

Yet there are areas of overlap, they note, and "striking empirical regularities suggest that at least some social order . . . is perhaps predictable from first principles." The role of markets in setting prices, allocating resources, and creating social institutions involves "concepts of efficiency or optimality in satisfying human desires." In economics, the tool for gauging efficiency and optimality in satisfying human desires is game theory. In physics, analogous concepts correspond to physical systems treated with statistical mechanical math. The question now is whether that analogous powerful enough to produce something like Astrony psychohistory, a statistical physics approach to for the statistics human social interaction, a true Code of Nature.

One possible weakings in the analogy between physics and game theor, though, is that physical three than just statistical mechanics. Physics is supposed to be the science of physical reality, and physical reality is described by the weird (yet wonderful) mathematics of quantum mechanics. If the physics—game theory connection runs deep, there should be a quantum connection as well. And there is. When it comes to making bets, Pascal observed, it is not enough to know the odds of winning or losing. You need to know what's at stake. You might want to take unfavorable odds if the payoff for winning would be really huge, for example. Or you might consider playing it safe by betting on a sure thing even if the payoff was small. But it wouldn't seem wise to bet on a long shot if the payoff was going to be meager.

Pascal framed this issue in his religious writings, specifically in the context of making a wager about the existence of God. Choosing to believe in God was like making a bet, he said. If you believe in God, and that belief turns out to be wrong, you haven bottomuch. But if God does exist, believing wins you and termity of heavenly happiness. Even if God is a hwyprobability deity, the payoff is so great (basically infinite) that He's a good betary vay. "Let us weigh the gun ord the loss in wagering that God is," Pascal wrote. Ut us estimate these two charters of you gain, you gain all; if you lose, you lose nothing Wager, then, without hesitation that He is,"²

Pascal's reasoning may have been theologically simplistic, but it certainly was mathematically intriguing.³ It illustrated the kind of reasoning that goes into calculating the "mathematical expectation" of an economic decision—you multiply the probability of an outcome by the value of that outcome. The rational choice is the decision that computes to give the highest expected value. Pascal's wager is often cited as the earliest example of a mathbased approach to decision theory.

In real life, of course, people don't always make their decisions simply by performing such calculations. And when your best decision depends on what other people are deciding, simple decision theory no longer applies—making the best bets becomes a problem in game theory. (Some experts would say decision theory is just a special case of game theory, in which one player plays the game against nature.) Still, probabilities and expected payoffs remain intertwined with game theory in a profound and complicated way.

For that matter, all of science is intertwined with probability theory in a profound way—it's essential for the entire process of Wolpert is one of those creative thinkers who refuse to be straitjacketed by normal scientific stereotypes. He pursues his own intuitions and interests along the amorphous edges separating (or connecting) physics, math, computer science, and complexity theory. I first encountered him in the early 1990s while he was exploring the frontiers of interdisciplinary science at the Santa Fe Institute, discussing such issues as the limits of computability and the nature of memory.

In early 2004, Wolpert's name caught my eye when I noticed a paper he posted on the World Wide Web's physics preprint page.⁴ His paper showed how to build a bridge between game theory and statistical physics using information theory (providing finctionally, one of the key inspirations for writing that book). In fact, as Wolpert showed in the paper that attracted my ettention to this issue in the first place, reparticular approach to statistical mechanics turks but house math theories of the ert to the math for noncooperative games.

Wolpert's paper noted that the particles described by statistical physics are trying to minimize their collective energy, like the way people in a game try to reach the Nash equilibrium that maximizes their utility. The mixed strategies used by players to achieve a Nash equilibrium are probability distributions, just like the distribution of energy among particles described by statistical physics.

After reading Wolpert's paper, I wrote him about it and then a few months later discussed it with him at a complexity conference outside Boston where he was presenting some related work. I asked what had motivated him to forge a link between game theory and statistical physics. His answer: rejection.

Wolpert had been working on collective machine learning systems, situations in which individual computers, or robots, or other autonomous devices with their own individual goals could be coordinated to achieve an objective for the entire system. The idea is to find a way to establish relationships between the individual "agents" so that their collective behavior would serve the global goal. He noticed similarities in his work to a paper published in *Physical Review Letters* about nanosized computers. So Wolpert sent off one of his papers to that journal. and subjective probability theory does not really differ in any fundamental respect other than its interpretation. It's just that in some cases it seems more convenient, or more appropriate, to use one rather than another, as Jaynes pointed out half a century ago.

INFORMATION AND IGNORANCE

In his 1957 paper,⁷ Jaynes championed the subjectivity side of the probability debate. He noted that both views, subjectivist and objectivist, were needed in physics, but that for some types of probables only the subjective approach would do.

He argued that the subjective approach can be set theven when you know nothing about the system you'r initerested in to begin with. If you are given a bay full of particles but know nothing about them—porther trass, not their composition not their internal structure—there's not made out can be about their behavior. You know the laws of physics, but you don't have any knowledge about the system to apply the laws to. In other words, your ignorance about the behavior of the particles is at a maximum.

Early pioneers of probability theory, such as Jacob Bernoulli and Laplace, said that in such circumstances you must simply assume that all the possibilities are equally likely—until you have some reason to assume otherwise. Well, that helps in doing the calculations, perhaps, but is there any real basis for assuming the probabilities are equal? Except for certain cases where an obvious symmetry is at play (say, a perfectly balanced two-sided coin), Jaynes said, many other assumptions might be equally well justified (or the way he phrased it, any other assumption would be equally arbitrary).⁸

Jaynes saw a way of coping with this situation, though, with the help of the then fairly new theory of information devised by Claude Shannon of Bell Labs. Shannon was interested in quantifying communication, the sending of messages, in a way that would help engineers find ways to communicate more efficiently (he worked for the telephone company, after all). He found math that

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mittee of supercomputers to calculate what all the players' mixed strategies would have to be.

In turn, that crack is exacerbated by a weakness in the cardinal assumption underlying traditional game theory—that the players are rational payoff maximizers with access to all the necessary information to calculate their payoffs. In a world where most people can't calculate the sales tax on a cheeseburger, that's a tall order. In real life, people are not "perfectly rational," capable of figuring out the best money-maximizing strategy for any strategy combination used by all the other competitors. So game theory appears to assume that each player can do what supercomputers can't, another fact, almost everybody recognizes that such totanet to fairly is unachievable. Modern approaches to game theory often assume, therefore, that rationality is limited on "bounded."

Game theorists have devided various ways to deal with these limitation of the highest caliber, has modified and elaborated game theory's original formulations into a system that corrects many of these initial "flaws." Much work has been done on understanding the limits of rationality, for instance. Nevertheless, many game theorists often cling to the idea that "solving a game" means finding an equilibrium—an outcome where all players achieve their maximum utility. Instead of thinking about what will happen when the players actually play a game, game theorists have been asking what the individual players should do to maximize their payoff.

When I visited Wolpert at NASA Ames, a year after our conversation in Boston, he pointed out that the search for equilibrium amounts to viewing a game from the inside, from the viewpoint of one of the participants, instead of from the vantage point of an external scientist assessing the whole system. From the inside, there may be an optimal solution, but a scientist on the outside looking in should merely be predicting what will happen (not trying to win the game). If you look at it that way, you know you can never be sure how a game will end up. A science of game theory should therefore not be seeking a single answer, but a probability distribution of answers from which to make the best possible prediction of how the game will turn out, Wolpert insists. "It's going to be the case that whenever you are given partial information about a system, what must pop out at the other end is a distribution over possibilities, not a single answer."¹¹

In other words, scientists in the past were not really thinking about the game players as particles, at least not in the right way. If you think about it, you realize that no physicist computing the thermodynamic properties of a gas worries about what an indile.c vidual molecule is doing. The idea is to figure out the bulk features of the whole collection of molecules. You can't know where the molecule is up to, but you can calculate, statistical one macroscopic behavior of all the molecules could ined. The paraller between games and gases should be clear. Statistical providests studying gases don't low what individual molecules are doing, and gane the wass don't knew what it widual players are thinking. But physicists do know how of molecules are likely to behave-statistically-and can make good predictions about the bulk properties of a gas. Similarly, game theorists ought to be able to make statistical predictions about what will happen in a game.

This is, as Wolpert repeatedly emphasizes, the way science usually works. Scientists have limited information about the systems they are studying and try to make the best prediction possible given the information they have. And just as a player in a game has incomplete information about all the game's possible strategy combinations, the scientist studying the game has incomplete information about what the player knows and how the player thinks (remember that different individuals play games in different ways).

All sciences face this sort of problem—knowing something about a system and then, based on that limited knowledge, trying to predict what's going to happen, Wolpert pointed out. "So how does science go about answering these questions? In every single scientific field of endeavor, what will come out of such an exercise is a probability distribution."¹²

From this point of view, another sort of mixed strategy enters

probability distribution of grades in a class, the maximum entropy approach says all grade distributions are possible. But if you know something about the students—maybe all are honors students who've never scored below a B—you can adjust the probability distribution by adding that information into the equations. If you know something about a player's temperature—the propensity to explore different possible strategies—you can add *that* information into the equations to improve your probability distribution. With collaborators at Berkeley and Purdue, Wolpert is beginning to test that idea on real people—or at least, college students.

unat idea on real people—or at least, college students. "We've just run through some experiments on under we're where we're actually looking at their temperatures is a set of repeated games—voting games in this card—and seeing thingclike how does their temperature change with time. Do the pact ally get more rational or lets reporter? What are the corrections between different infinite runs' temperature? On the correctional as you get less rational?"

If, for instance, one player is always playing the exact same move, that makes it easier for opponents to learn what to expect. "That suggests intuitively that if you drop your temperature, mine will go up," Wolpert said. "So in these experiments our intention is to actually look for those kinds of effects."

VISIONS OF PSYCHOHISTORY

Such experiments, it seemed to me, would add to the knowledge that behavioral game theorists and experimental economists had been accumulating (including inputs from psychology and neuroeconomics) about human behavior. It sounded like Wolpert was saying that all this knowledge could be fed into the probability distribution formulas to improve game theory's predictive power. But before I could ask about what was really on my mind, he launched into an elaboration that took me precisely where I wanted to go.

"Let's say that you know something from psychology, and you've gotten some results from experiments," he said. "Then you

A Beautiful Math

Peter could delay any desire as long as he needed to; he could conceal any emotion. And so Valentine knew that he would never hurt her in a fit of rage. He would only do it if the advantages outweighed the risks. . . . He always, always acted out of intelligent self-interest.¹

Ender himself represents the social actor who plays games with a combination of calculation and intuition, more in line with the notion of game theory embraced by today's behavioral game theorists:

"Every time, I've won because I could understand the way my enemy thought. From what they did. I could tell what they thoughed was doing, how they wanted the battle to take shape. An evelopee off of that. I'm very good at that. Understanding h women people think."

That is, after all vice to e-modern science of gemetheory is all about-storter provide the provide the provide the second state of the second stat

The modern search for a Code of Nature began in the century following Newton's Principia, which established the laws of motion and gravity as the rational underpinning of physical reality. Philosophers and political economists such as David Hume and Adam Smith sought a science of human behavior in the image of Newtonian physics, pursuing the dream that people could be described as precisely as planets. That dream persisted through the 19th century into the 20th, from Adolphe Quetelet's desire to describe society with numbers to Sigmund Freud's quest for a deterministic physics of the brain. Along the way, though, the physics model on which the dream was based itself changed, morphing from the rigid determinism of Newton into the statistical descriptions of Maxwell-the same sorts of statistics used, by Quetelet and his followers, to quantify society. By the end of the 20th century, the quest for a Code of Nature was taken up by physicists who wanted to use those statistics to bring the sciences of society

Appendix

$$-3p + -5(1 - p) = -6p + -4(1 - p)$$

Applying some elementary algebra skills, that equation can be recast as:



out of 4.

Now, Alice will not want to change strategies when

$$3q + 6(1 - q) = 5q + 4(1 - q)$$

Which, solving for q, gives Bob's optimal probability for choosing Bus:

$$3q + 6 - 6q = 5q + 4 - 4q$$
$$6 = 4q + 4$$
$$2 = 4q$$
$$q = 1/2$$

So Bob should choose Bus half the time and Walk half the time.

Alice will not want to change strategies if

$$-2q + 2(1 - q) = 0q + 1(1 - q)$$
$$4q - 2 = q - 1$$
$$3q = 1$$
$$q = 1/3$$

So q, Bob's probability of playing hawk, is also 1/3. Consequent **5** ale the Nash equilibrium in this payoff structure is to play a whone-third of the time and dove two-thirds of the line.

Further Reading

There are dozens and dozens of books on game theory, of which solve the solution of the soluti

- Camerer, Colin. Behavious Came Theory. Princetor, N. Trinceton University Press, 2003.
- Gintis, Herbert. Game Theory Lyolving. Princeton, N.J.: Princeton University Press, 2000.
- Kuhn, Harold W. and Sylvia Nasar, eds. *The Essential John Nash*. Princeton, N.J.: Princeton University Press, 2002.
- Luce, R. Duncan and Howard Raiffa. *Games and Decisions*. New York: John Wiley & Sons, 1957.
- Williams, J.D. The Compleat Strategyst: Being a Primer on the Theory of Games of Strategy. New York: McGraw-Hill, 1954.
- Von Neumann, John and Oskar Morgenstern. *Theory of Games and Economic Behavior. Sixtieth-anniversary Edition.* Princeton, N.J.: Princeton University Press, 2004.

Two other readable books were very helpful:

- Davis, Morton D. *Game Theory: A Nontechnical Introduction*. Mineola, NY: Dover, 1997 (1983).
- Poundstone, William. *Prisoner's Dilemma*. New York: Anchor Books, 1992.

Notes

which was always influenced by others, so that such isolation is really not possible.

18. Ibid., excerpt. Available online at http://www.d.umn.edu/~revans/ PPHandouts/buckle.htm.

19. Ibid.

20. Quoted in P.M. Harman, The Natural Philosophy of James Clerk Maxwell, Cambridge University Press, Cambridge, 1998, p. 131.

21. James Clerk Maxwell, "Does the Progress of Physical Science Tend to Give Any Advantage to the Opinion of Necessity (or Determinism) over that of the Contingency of Events and the Freedom of the Will?" Reprinted in esale.c Lewis Campbell and William Garnett, The Life of James Clerk Maxwell, Macmillan and Co., London, 1882, p. 211.

22. Ignoring things like whether your opponent has a weak backbar

BACON'S SIKKOM

the d 1. www.imdb.com additional actors i who cannot be linked to P.c. n Pause they app an ther. e or with no other actors who had appeared in any other movie including actors connected to the mainstream acting community.

2. Similar network math was developed by Anatol Rapoport, who is better known, of course, as a game theorist.

3. Duncan Watts and Steven Strogatz, "Collective Dynamics of 'Small-World' Networks," Nature, 393 (June 4, 1998): 440-442.

4. Steven Strogatz, interview in Quincy, Mass., May 17, 2004.

5. These three examples were chosen because of the availability of full data on their connections; at that time, C. elegans was the only example of a nervecell network that had been completely mapped (with 302 nerve cells), the Internet Movie Data Base provided information for actor-movie links, and the power grid diagram was on public record.

6. Watts and Strogatz, "Collective Dynamics," p. 441.

7. In fact, here's a news bulletin: Oracle of Bacon hasn't updated its list yet, but as of this writing its database shows that Hopper has now surpassed Rod Steiger as the most connected actor, with an average of 2.711 steps to get to another actor versus Steiger's 2.712. Of course, these numbers continue to change as new movies are made.

8. Réka Albert and Albert-László Barabási, "Emergence of Scaling in Random Networks," Science, 286 (15 October 1999): 509.

9. Jennifer Chayes, interview in Redmond, Wash., January 7, 2003.

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