

## The science of strategy

### Game theory is making its mark, from economics to quantum physics

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*First of two parts*

Millions of people have seen the movie, and thousands have read the book, but few fully grasp the math invented by John Nash's beautiful mind.

Nash, the troubled mathematician played on film by Russell Crowe, won the 1994 Nobel Prize in economics for pioneering research in the 1950s on an arcane branch of math called game theory.

For decades, few researchers outside economics paid much attention to game theory. But in the 1980s, some biologists began having fun with it, and now scientists from other disciplines are learning how to play as well.

Offshoots from Nash's work have sprouted in several scientific fields, entangling economics with biology and psychology, sociology, neuroscience and even quantum physics. Nowadays game theory turns up in everything from fighting terrorists to designing smarter robots. And game-theory-based studies of the brain have challenged basic tenets of economic science, revealing surprising nuances in human behavior.

"I think in 10 years, economics will be completely changed because of this work," says Paul Zak, an economist at the Claremont Graduate University in California. "Literally, the textbooks will be rewritten."

At the time of Nash's early work, game theory was briefly popular among Cold War analysts as well as economists studying how people make profit-maximizing choices.

"But it didn't take off," says Sam Bowles, an economist at the University of Massachusetts Amherst. "Like a lot of good ideas in economics, it just fell by the wayside."

By the early 1990s, though, game theory had recaptured economists' attention, as recognized with the Nobel award to Nash and two other pioneers in the field, John Harsanyi and Reinhard Selten. Even before then, though, biologists had begun to exploit game theory's insights, applying them to the competition for survival among animals and plants. More recently psychologists have used game theory to probe the inner workings

of the human mind. And with the turn of the new century, neuroscientists have joined in the fun, peering inside the brains of game-playing people to discover how their strategies reflect different motives and emotions.

"We're quantifying human experience in the same way we quantify air flow over the wings of a Boeing 777," says neuroscientist Read Montague of Baylor College of Medicine in Houston.

Game theory's roots go back centuries, but the first explicit presentation of the math came in a 1928 paper from the Hungarian mathematician John von Neumann. Building on that work, von Neumann collaborated with the economist Oskar Morgenstern to produce the bible of the field, *Theory of Games and Economic Behavior*, in 1944.

"We hope to establish," they wrote, "that the typical problems of economic behavior become strictly identical with the mathematical notions of suitable games of strategy."

But game theory's original formulation was limited, focusing mostly on two-party "zero-sum" games in which one player wins only what the other player loses. Nash expanded the scope of game theory to more realistic economic situations.

In one paper, he analyzed the problems faced by two negotiators attempting to reach an agreement – or make a bargain – that maximizes the payoffs for both parties. In other work, he treated non-zero-sum games, where one player's winnings do not have to equal another's losses. Nash established that for many types of such games, with multiple non-cooperating players, some best-case scenario for all concerned can be computed using game theory. In other words, all interests can be balanced in what is now called a "Nash equilibrium."

"The concept of the Nash equilibrium is probably the single most fundamental concept in game theory," says Dr. Bowles, who is also affiliated with the Santa Fe Institute in New Mexico.

Nash's results hinged on assumptions central to economic theory, especially the notion that people behave rationally and act in their own self-interest. Put another way, the No. 1 rule is that everybody is out for No. 1. Game theory provided a way to quantify that notion in terms of "utility," the value a rational agent assigns to goods or actions when making economic decisions.

### **Optimum strategy**

Given the additional assumption that you have enough information to know what's best for you, game theory provides straightforward math for choosing the optimum economic strategy. In principle, such math could guide negotiations between labor unions and management, help nations reach trade agreements or improve the prospects of winning in Vegas. (Von Neumann's work relied heavily on analyzing common card games like poker and bridge.)

In practice, though, people don't always choose the strategies that standard economic theory predicts. Part of the problem, says Dr. Bowles, is the old textbook view that people in an economy interact only with prices. It's known as the Robinson Crusoe model – living on an island, he interacted only with nature.

But in a real economy, nobody's an island; people interact with other people, making choices not only in response to prices but also by anticipating what the other guy will do next, an element missing from the Robinson Crusoe approach.

"Game theory adopts a different framework," Dr. Bowles said in a telephone interview. "My well-being depends on what somebody else does, and your well-being depends on what I do. Therefore we are going to think strategically."

Choosing sound strategies in such interactions is what game theory is all about. It provides a method of testing how people's actual strategies compare with what standard economic theory predicts.

### **Clarifying the question**

"Game theory has really provided a way of posing the question . . . in a very clear way," Dr. Bowles said. "Game theory is also then part of how you solve the problem."

Disenchanted economists began challenging standard theory in the 1980s by devising laboratory experiments to gather data on how people really do reason and choose. (George Mason University economist Vernon L. Smith shared the 2002 Nobel in economics for early work in that field.) Data from such experiments fueled the development of a field known as behavioral economics.

"Behavioral economics is a school of thought that says let's go back and question some of the basic mathematical foundations of economics," says Colin Camerer, a professor of business economics at the California Institute of Technology in Pasadena.

Dr. Camerer specializes in the branch of behavioral economics called behavioral game theory, using games to test how psychological realities drive economic behavior that departs from standard assumptions.

After all, he notes, there is nothing sacred about those assumptions. Many of them originally arose mainly for computational convenience.

Most economists have known all along, for example, that people are not always rational and seldom have complete information. But early efforts to make economics rigorous had to ignore such complications. There are many ways, for instance, in which people can behave irrationally. Assuming rational behavior was the only way to be mathematically precise, many economists maintained.

"They've often used that as an excuse," Dr. Camerer said in an interview. "But our view is completely different, which is to say let's ask scientists who have been thinking about how brains actually work ... for some help."

There may well be many ways to be irrational from an economist's point of view, he said. But psychologists may be able to discover in which ways people actually are irrational.

"Economists have been kind of conservative about this, saying if you give up rationality, we'll never be able to have anything precise," said Dr. Camerer. "But we will, and it's emerging pretty rapidly by using the evidence."

An important new source of such evidence is the newborn discipline of neuroeconomics, where researchers can spy on people's brains during economic game-playing.

### **Neuroscience no-brainer**

Mixing economics with neuroscience is the ultimate no-brainer. After all, says Dr. Zak, economics is about making decisions and choosing behaviors, actions governed by the activity of nerve cells in the brain.

"There's such affinity between these two groups, it's absolutely natural to combine them," he said in an interview.

Game theory on its own can't answer questions about why people make certain choices, he points out. But experiments combining games with brain scans can reveal the players' underlying mental activity responsible for the behavior.

"If you ask subjects, why did you make this decision, they can't tell you," Dr. Zak said. "Using neuroscientific techniques allows us to get around that problem. I can just measure directly what's happening."

Neuroeconomics is far from the only realm where game theory has gained in popularity. In battling terrorism, for example, it has emerged as an important way to evaluate standard approaches to analyzing intelligence data and formulating policy.

Todd Sandler, a political economist at the University of Southern California, has pursued game theory's implications for terrorism since the 1980s. Papers before then had discussed various aspects of anti-terrorism policy, but none with game theory's mathematical rigor.

"There was no theoretical framework to looking at how government decisions may interact with terrorist decisions," Dr. Sandler said in an interview at USC. "And that's what game theory does, it looks at the interactions between the two players. ... It often gives results that are not intuitively obvious at first."

Another possible application of game theory to terrorism comes from studies of smallpox vaccination strategies. Chris Bauch and David Earn, of McMaster University in Canada, and Alison Galvani, of the University of California, Berkeley, have combined game theory with the math describing epidemics to assess the policy of voluntary smallpox vaccinations. Individual decisions guided by self-interest are likely to produce a less-than-optimum level of vaccination for the whole population, the researchers reported last month in the *Proceedings of the National Academy of Sciences*.

Game theory's ramifications extend even to the physical sciences and technology. For example, game theory has guided experiments for teaching robots how to communicate. Robots programmed to play language games can teach themselves new words to describe objects in their environment. Sounds correctly linked with meanings earn the robots higher scores in the games, as described by Luc Steels of the University of Brussels and the Sony Computer Science Laboratory in Paris in a recent issue of *Trends in Cognitive Sciences*.

### **Quantum game theory**

Among physicists, interest is growing in quantum versions of game theory, in which the weird math of the subatomic world offers new twists to standard game strategies. In quantum physics, many possibilities can exist simultaneously. Adapting quantum math to decision-making in games provides a richer repertoire of choices than mere yes-or-no responses.

David Meyer, a mathematician at the University of California, San Diego, introduced a simple quantum game in a 1999 paper published in *Physical Review Letters*. Progress in devising more elaborate quantum games has so far been mixed, he said in an interview. But communication among game players using quantum signals is technologically possible, he points out. Combined with other new online communications techniques, quantum information could give birth to new species of games.

"The Internet and modern telecommunications are likely to change the way we think about game theory," he said.

Even without quantum leaps, though, game theory is likely to assume a more prominent role in economic policy, especially in the wake of advances in behavioral game theory and neuroeconomics.

"We're not quite ready to make too many policy prescriptions," said Dr. Camerer, "but people have a few ideas."

Ultimately, he believes, policy-makers will recognize that the game-behavior approach to economics is just a way of making it more realistic, unconstrained by the old ideas about people being perfectly rational.

"Behavioral economics," says Dr. Camerer, "is kind of a step back to something which is more sensible."

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## **GAME THEORY BASICS**

In game theory, a "game" is any situation in which participants (agents or players) make choices (strategies) in an attempt to achieve a desirable outcome (preference). Each player chooses actions from among a set of possible strategies. The outcome of the game depends on the combined effects of each player's set of choices.

Game theorists analyze the math describing the various combinations of choices, attempting to show which strategies will produce the most desirable outcomes for the players.

Below are several examples of games used in this kind of analysis ...

### **Prisoner's Dilemma**

One of the most famous of game theory games, Prisoner's Dilemma illustrates the conflict between individual and group interest. In this game, Alice and Bob are a crime team. Both are captured and interrogated separately. If neither rats out the other, both will get one year in prison. If Bob rats out Alice, he goes free, and Alice gets 10 years – unless both of them rat out each other, in which case both get five years.

The best choice for the team is for both to stay silent. But neither can be sure the other won't act in total self-interest and agree to testify. So usually both players will defect, giving the team as a whole the worst possible outcome.

In real life, various situations correspond to Prisoner's Dilemma games, including arms races and missile defense strategies.

### **Zero-Sum Games**

Zero-sum games are games of conflict – one player's gain comes at the expense of another.

A simple zero-sum game is Matching Pennies. Alice places a penny on the table, hidden from Bob. Bob then places his penny on the table. Alice reveals her choice – if the pennies match (both heads or both tails) then Bob gives Alice a dollar. If the pennies don't match, Alice gives Bob a dollar. Somebody wins, somebody loses.

### **Investment Game**

In this game, Alice and Bob do not know each other. Alice is given a sum of money and told she may keep it all or "invest" some of it by giving it to Bob. The amount invested is multiplied by some factor (tripled, perhaps) and Bob then gets to decide how much of the invested money to keep and how much to return to Alice.

Since Bob can choose to keep all the money, Alice's best strategy is to invest nothing, keeping all the initial money for herself. But if she trusts Bob, she can boost her and his payoff (not a zero-sum game). While the optimum game-theory strategy is for Alice to take the money and run, in real life many players are trusting enough to invest some of the money, and many of the recipients are trustworthy enough to return some.

### **Battle of the Sexes**

In this game, Alice and Bob are married. It is a coordination game, but not without conflict. Alice and Bob want to go out somewhere together, but Alice prefers movies and Bob prefers basketball games. So the ideal outcome for Bob is to go to the game with Alice; the ideal outcome for Alice is to go to the movies with Bob.

If Bob makes the first move, he can opt for basketball, and Alice can then choose going with Bob or going to the movies by herself. Strategies in this game depend on whether Alice knows Bob's choice before making hers.

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