

Quantum Games

Taking advantage of quantum effects to attain a winning edge

By IVARS PETERSON

Over a chessboard or in a diplomatic conference room, players strive for even the slightest advantage that would tilt a game's outcome in their favor. Reasoning, bullying, bluffing, and cheating can all come into play in the search for a winning strategy.

Game theory offers mathematical tools for analyzing simple games. Originally formulated in the 1940s, it provides a framework for deciding who wins under various circumstances and suggests optimal strategies for achieving certain ends.

Because researchers can interpret many human activities in terms of games, they've applied game theory to important issues in fields such as economics (SN: 3/28/98, p. 205), international relations (SN: 5/4/96, p. 284), and computer science and artificial intelligence (SN: 7/18/98, p. 40).

Until recently, however, the realm of games appeared far removed from the domain of physics and quantum mechanics, which governs the interactions of atoms and electrons. Now, theorists are poised to exploit peculiarities of quantum behavior to work out novel strategies for winning games.

It's like having a quantum penny, says mathematician David A. Meyer of the University of California, San Diego. An ordinary penny comes up either heads or tails. A quantum penny has the additional property that it can be put into a state that mixes both heads and tails.

The extra possibility of a mixed state permits quantum-game strategies that can theoretically be more successful than conventional ones in various games, Meyer contends.

In the light of quantum theory, coin tossing, chess, and perhaps even international negotiations take on a startling, new dimension. In some cases, using a hypothetical quantum computer in place of a conventional one should speed up

searches to identify a winning strategy. In other instances, quantum logic changes the game itself.

Computers play a mean, brute-force style of chess. When chess computer Deep Blue triumphed over world champion Garry Kasparov in 1997, it relied heavily on extensive searches (SN: 5/17/97, p. 300). For a given arrangement of chess pieces, the computer simply looked ahead a fixed number of moves, evaluated the strength of each move, and selected the best one.

In principle, a chess computer can foresee a game's end by checking each possible path to its outcome. It can then choose an appropriate sequence of moves to ensure a win, maintain a draw, or delay a loss. In a game of 40 moves, however, the number of different board positions that can develop exceeds 10^{120} . There's no way even the fastest conventional computer can check every possibility to play a perfect game.

That's where quantum computers would help.

Ordinary computers rely on vast arrays of tiny transistors, arranged in logic units called gates, to perform their calculations. They typically use the presence or absence of certain amounts of electric charge to represent the 0s and 1s of a computer's binary code.

The hypothetical quantum computer replaces the 0s and 1s with entities called quantum bits, or qubits. Each qubit is encoded as a quantum state—a particular energy level of an atom, for instance. One energy level would correspond to the 0 state and another, to the 1 state. Unlike an ordinary bit, however, a qubit can also exist as a combination, or superposition, of those two states.

Computer scientists can, in principle, take advantage of superposition and the wavelike nature of quantum particles. They would set up calculations so that computational paths yielding unde-

sirable results cancel each other out, while computational paths leading to the answer reinforce each other (SN: 1/14/95, p. 30). In effect, quantum interference allows them to zero in quickly on the relevant result.

In 1996, Lov K. Grover of Lucent Technologies' Bell Labs in Murray Hill, N.J., invented a quantum-based procedure that would significantly speed up searches of an unsorted list to find a desired item (SN: 8/31/96, p. 143).

Grover's search algorithm can itself be thought of as a kind of game, Meyer remarks. As in the game of 20 questions, which calls for "yes" or "no" answers to specific requests for information, Grover's procedure queries a database to learn whether one is on the right track to the answer.

David Deutsch and Artur Ekert of the University of Oxford in England have considered how a chess-playing quantum computer would use Grover's procedure. It could investigate a trillion possible continuations from a given position in the same number of steps as a conventional computer would need to check out a million. Quantum superposition allows the computer to cancel out a lot of unpromising possibilities that a conventional computer must look into one by one.

Several researchers, including Grover and Scott Aaronson of Cornell University, have investigated such potential improvements in performance. They discovered that the search speed-up in a game in which two players take turns looks

especially promising if there is, at most, just one winning choice per move. Since then, Grover has generalized his quantum-search method to cover situations where there may be multiple solutions.

So, if Deep Blue comes



out of retirement someday, it might face a newfangled quantum computer and quite possibly a crushing defeat.

The results would be even more dramatically one-sided if a player were to stack the quantum deck. Such a surreptitious act could change a game of chance into one he or she can't lose.

Say the Starship Enterprise faces a dire emergency, and Captain Picard is preparing for the worst. Suddenly, Q appears on the scene. This all-powerful but malevolent being offers to help, provided that Picard can beat him at a childishly simple game involving a penny.

The adversaries start with a closed box containing a penny, heads up. Neither can see into the box at any time. Hiding his action from Picard, Q either flips over the box (and the penny) or leaves it as it is. Picard then takes a turn, after which Q gets a final chance. Q wins if the penny is heads up when the adversaries together open the box.

Q's penny-flip challenge is an example of a two-person, zero-sum game: What one player gains, the other loses.

Applying standard game theory, Picard figures that his chances of winning the game are 50:50. He agrees to play—but loses to Q, not just once but again and again.

Meyer invented this *Star Trek* scenario for his article in the Feb. 1 *PHYSICAL REVIEW LETTERS*. It illustrates what would happen if one player takes advantage of a quantum strategy and the other doesn't.

Picard doesn't know that the penny in question is a quantum coin—an object that can be both heads and tails at the same time. Q does, so he performs a quantum flip on the penny. Instead of swapping tails for heads, this particular move leaves the coin in a superposition of the two states, half heads and half tails.

On his turn, Picard responds with a standard flip or does nothing. Neither choice, however, alters the penny's mixed state. Q then does another quantum move that unscrambles the superposition, bringing the coin back to heads to win the game.

The key to Q's success is that he has access to quantum moves unavailable to Picard, Meyer says. A quantum computer should have a similar advantage over a conventional computer.

Researchers are now looking closely at the sorts of problems that stump standard mathematical methods but can be solved efficiently by algorithms that take full advantage of quantum effects. So far, they've identified only a handful of such algorithms, including a method for factoring whole numbers (SN: 5/14/94, p. 308) and Grover's quantum-search technique.

A game-theory perspective may suggest new possibilities for efficient quantum algorithms, Meyer says. Meanwhile, he's looking for other games in which quantum strategies potentially offer an advantage.

It's also possible to imagine a quantum game with quantum players, in which everyone wins.

Consider the game called the Prisoners' Dilemma, which has been the subject of thousands of experiments and theoretical investigations in social science, psychology, and economics since it was invented in the early 1950s.

Two prisoners charged with a serious crime are held in separate cells. Their captors offer each of them the same deal.

If one testifies against the other and the other says nothing, the squealer goes free and his associate gets a heavy sentence. If both remain silent, each one gets a light sentence. If both snitch, each gets a medium sentence.

Unable to confer and lacking faith in the other's trustworthiness, each prisoner inevitably concludes that the best strategy is to spill the beans. Both end up serving a medium sentence, which is far worse than the light sentence they would have received if they had trusted each other and said nothing.

The same thing can happen when two competing stores cut prices to lure customers or when two countries are in an arms race. Even though each party makes the best possible choice from its own viewpoint, both end up worse off than if they had cooperated.

The dilemma inherent in this situation, however, can disappear in a quantum version of the game, says physicist Jens Eisert of the University of Potsdam in Germany. "The players escape the dilemma if they both resort to quantum strategies," he remarks.

Eisert, Potsdam colleague Martin Wilkens, and Maciej Lewenstein of the University of Hannover in Germany describe their approach in the Oct. 11 *PHYSICAL REVIEW LETTERS*.

In the standard version of the Prisoners' Dilemma, one can either squeal or stay silent. The quantum edition allows a third option: a superposition of squealing and staying silent. Moreover, the choices of the two prisoners can be entangled, so that one influences the other.

Quantum particles show just that sort of behavior. If two particles are in an entangled state, then even if the particles are physically separated by miles, they behave in some respects as a single entity rather than two separate entities (SN: 8/5/89, p. 88).

So, when a physical process creates an entangled pair of photons of light, detecting the state of one of them automati-

cally fixes the corresponding state of the other, even when the two photons are far apart. Quantum cryptography takes advantage of this effect (SN: 2/10/96, p. 90).

Eisert and his collaborators describe a physical model of the Prisoners' Dilemma in which both prisoners have secret access to such particles and can manipulate their states. In effect, the prisoners become quantum players.

The researchers demonstrate that the best strategy for both prisoners is initially not to squeal or stay silent. Instead, they can feel each other out using weird quantum combinations and, in the end, make the choice that rewards them.

"Very much as in quantum cryptography and computation, we have found superior performance of the quantum strategies if entanglement is present," Eisert and his coworkers assert.

At this early stage, no one knows where quantum game theory may eventually lead. Eisert, Meyer, Grover, and others have taken just the first steps into a strange, unexplored realm.

Many questions remain. Meyer, for instance, is now pondering what might happen in games that involve three or more people, when coalitions, betrayals, and shifting allegiances come into play.

At the same time, researchers keep in mind that quantum computation is, as yet, a theoretical playground. The late Rolf W. Landauer often urged his colleagues to include the following disclaimer with their papers: "This scheme, like all other schemes for quantum computation, relies on speculative technology, does not in its current form take into account all possible sources of noise, unreliability, and manufacturing error, and probably will not work."

Nonetheless, researchers find themselves irresistibly drawn to the subject. Insights from the nascent field of quantum game theory could shed light on quantum communication issues (SN: 4/3/99, p. 220), for instance, or play a role in schemes to ensure fairness in Internet gambling.

Even more intriguing is the possibility of a link to the behavior of biological systems. "We may speculate that games of survival are being played already on the molecular level, where quantum mechanics dictates the rules," Eisert and his colleagues note.

"It will be some time before quantum games in any form become practical," Grover cautions. "Nevertheless, the concept is very exciting and has already stimulated a number of new ideas." □

