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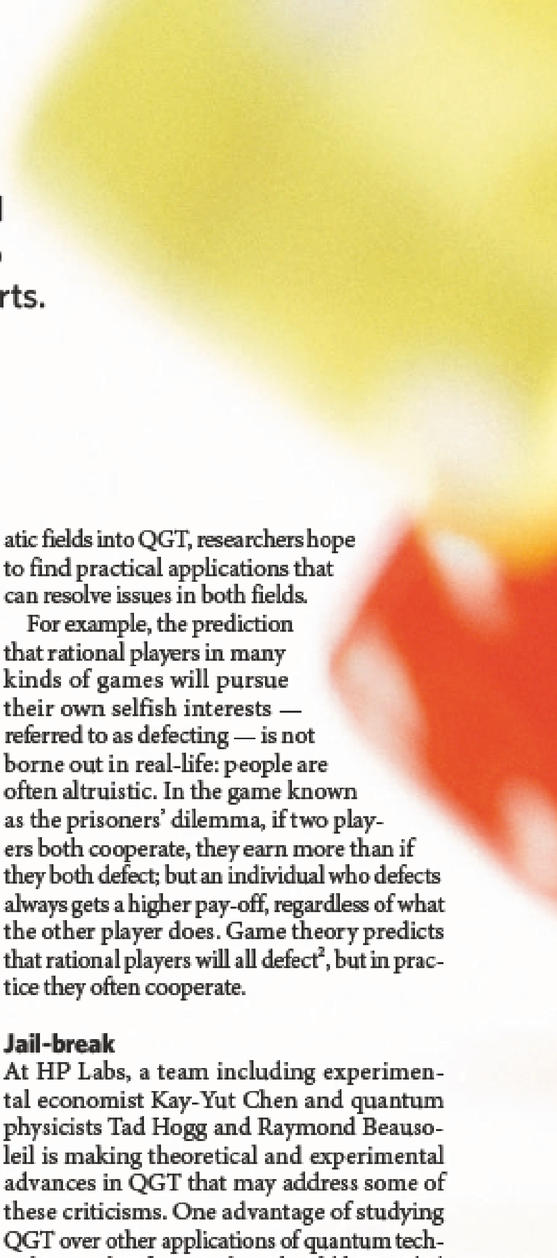

Life is full of events that are basically games, from paying for a meal to bidding in an auction. Can incorporating a quantum strategy into the rule book increase your chances of winning? **Navroz Patel** reports.

States of play

The year is 2015. Representatives from the world's leading defence firms are gathered in a high-security room at the Pentagon. Each is seated facing a screened-off console. Together, they are bidding in an auction that will allocate the various contracts for a $100-billion project to develop a new breed of fighter aircraft. But this is no ordinary auction — it is designed to ensure that the companies bidding will collectively offer the US government the lowest price for the whole project.

In an ordinary auction, one firm might be prepared to offer a low price for a particular contract if it could be sure that another company, with which it has collaborated, will win the contract for another component. If this situation could be encouraged, then the government could shave billions off the cost of the project. But such conditional bids are unlikely as none of the firms wants to reveal its bidding strategy to the others, or even to the auctioneer.

"We can safely assume that 99% of the population could not accurately be described as quantum physicists."
— Kay-Yut Chen

Which is where the new strategy comes in — the contracts for this project will be decided by a 'quantum auction'. The participants use their consoles to manipulate qubits (the bits inside their quantum computers) to produce quantum states that correspond to each of their desired bids. Because the bids are encoded in fragile quantum states, no one, not even the auctioneer, can read the information in the qubits without destroying them.

The success of the auction depends on repeated exchange of information between the bidders, through a quantum algorithm that operates on the qubits, until an optimal outcome is reached. In the process of reading this outcome, the individual bids are destroyed. This guarantees that losing bids will never be revealed and so dramatically increases trust between the participants. The ability to express conditional bids in a secure way is what leads to the more ideal outcome.

Think this all sounds too futuristic to take seriously? Think again. A group of researchers at HP Labs, the research arm of Hewlett-Packard in Palo Alto, California, is working to create the quantum protocols that could allow such an auction to take place within a decade. And their work is helping to bridge the gap between theory and practice in both game theory and quantum information processing.

The field of quantum game theory (QGT) is still in its infancy: just tens of economists and quantum physicists have so far published a total of 200 or so papers on the topic. Its roots stretch back to a paper published in 1999 by mathematician David Meyer of the University of California, San Diego[1]. In it, Meyer showed how a quantum approach always beats a classical strategy in a simple game where two players flip a coin. This is because the laws of quantum mechanics allow the coin to exist in a state that is a combination of heads-up and tails-up at the same time, so the person playing by classical rules will always be outmanoeuvred.

That's all fine in theory, but subsequent work on QGT has struggled to be taken seriously. "Much of the claimed superiority of quantum games to their classical counterparts has been the result of incorrect comparison," Meyer acknowledges. Some of the scepticism arises because both game theory and quantum information processing have unresolved issues. Like QGT itself, the field of quantum information processing is mostly theoretical and, because computers that can handle hundreds of qubits are several decades away, critics argue that much of the research is simply impractical. Game theory — which is used to analyse strategic situations and the behaviour of participants seeking to maximize their success in such games — also has problems, not least of which is the fact that some of its predictions contradict what happens in the real world. But by linking these two problematic fields into QGT, researchers hope to find practical applications that can resolve issues in both fields.

For example, the prediction that rational players in many kinds of games will pursue their own selfish interests — referred to as defecting — is not borne out in real-life: people are often altruistic. In the game known as the prisoners' dilemma, if two players both cooperate, they earn more than if they both defect; but an individual who defects always gets a higher pay-off, regardless of what the other player does. Game theory predicts that rational players will all defect[2], but in practice they often cooperate.

Jail-break

At HP Labs, a team including experimental economist Kay-Yut Chen and quantum physicists Tad Hogg and Raymond Beausoleil is making theoretical and experimental advances in QGT that may address some of these criticisms. One advantage of studying QGT over other applications of quantum technology is that fewer qubits should be needed to play quantum games, so it might be possible to implement them fairly soon. HP Labs hopes that Chen and Hogg's work on quantum auctions will ultimately lead to a new business model for selling digital content on the Internet that might help to discourage illegal downloading.

In terms of game theory, how digital content is sold and distributed on the Internet can be seen as a 'public-goods game'. Much as in the prisoners' dilemma, which is a two-player version of this type of game, selfless choices by members of a group reap greater benefits for the group as a whole, although selfish behaviour produces the greatest personal gain. So how do content providers prevent illegal downloading of software, music and videos, when others have already paid for the privilege of exclusive access?

The problem is similar to that faced by a table of diners in a steakhouse when it comes to settling the bill. Experience shows that when people agree to split the cost of a meal between

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them, if the group is small — just a few people — the diners tend to order more modestly priced items from the menu, and may even offer to pay more than their share of the bill. But as the size of the group increases, people feel a greater sense of anonymity and may conclude that their individual decisions will have a smaller impact on the overall bill. The end result is defection: some people will order the most expensive steak rather than a cheap cheeseburger and, to add insult to injury, might not even stump up their share of the bill. Game theorists refer to this kind of player behaviour, which is detrimental to the wider good, as free-riding.

Game on

In their quantum approach to the public-goods problem[3], Hogg and his colleagues focused on multiple games of prisoners' dilemma played between pairs of people within a larger group. In a three-player group, for example, each player would play two games, one with each of the other two. Unlike classical game theory, the quantum version of the prisoners' dilemma predicts that players will cooperate in 50% of the games played. And, unlike in real-life classical situations, Hogg and Chen predicted that the greater the number of players involved, the less of a problem free-riding should be.

In a classical prisoners' dilemma, defecting is always the best strategy for rational players. In the quantum version of the game, which intrinsically links the two players' decisions through quantum mechanics, the outcome is often probabilistic in that the players can't be sure their pay-off will be the same each time, even when all players make the same choices. This uncertainty alters the structure of the game to one in which no single choice is best. "The quantum version of the game is more like scissors, paper, stone," says Hogg. In such games, there is no single move that will win each time, so a mixed strategy — choosing moves randomly or based on guesswork — is the best option for rational players.

This analysis worried the researchers as people don't usually play mixed-strategy games very well. As with all game-theory research, one question loomed large: will the outcomes predicted by Hogg and Chen occur in reality? "We can safely assume that 99% of the population could not accurately be described as quantum physicists," says Chen. "So we needed to understand how players would behave in this kind of game."

In 2004, Chen and Hogg set out to show that it is possible for people to play primitive quantum public-goods games[4], using a dozen or so students from Stanford University. The experiments, which mimicked both classical and quantum versions of the games, did not involve actual quantum computers or qubits, instead the students interacted with computers that simulated the players' operations on quantum states. Indeed, the students were completely unaware that any feature of the game aped the laws of quantum mechanics.

Place your bets

In both the classical and quantum games, the students were each given $100 and randomly grouped into pairs to play a version of the prisoners' dilemma in which the choice was either to keep the $100 or to contribute it to a common fund. The pair were better off if they both cooperated and contributed to the fund, but individuals got higher pay-offs by defecting and not contributing no matter what the other player decided.

In the quantum version of the game, the decision of whether or not to contribute was determined by a more complex process intended to simulate quantum entanglement between qubits assigned to each player. Entanglement means that the quantum states of two or more disparate objects are intrinsically linked in some way — so changing the state of one object automatically affects the state of the others. Players were asked to pick three numbers that controlled the probabilities of the various outcomes of the entanglement; before and during the game, they were given software tools to help them to understand the consequences of their choices and those of their opponents. But because their opponents' choices remained unknown, and because the probability of an outcome was rarely 100%, each player could only guess at the best numbers to choose.

Overall, the students cooperated roughly 50% of the time in the quantum games, as opposed to just 33% of the time in the classical version. "We were surprised. Our lab experiments

showed that players without any training in quantum mechanics exhibited behaviour indistinguishable from that predicted by our theory," Hogg says. This optimal behaviour seemed to emerge because players tried to second-guess what their opponent's strategy was, resulting in a mixed strategy even though that was not what they intended.

Joint effort

Although these experiments involved two-player games, and so simulated two-way entanglement between players' qubits, Hogg and Chen also studied larger groups of three of four players, in which each permutation of pairs played a game of prisoners' dilemma. The results suggested that free-riding decreases as game size increases to three or four players. If confirmed with larger groups, this effect would be highly desirable in the context of Internet piracy, where the number of players, that is downloaders, can run into tens of millions. "There are many complexities in this context, but it falls within the scope of what quantum public-goods games research can address," Hogg says.

Hogg and Chen believe that their experiments can mimic more complex entanglement within larger groups of players, using relatively few qubits. "The way we are creating these protocols — with the small number of qubits required and pair-wise entanglement — is, we believe, physically doable within five to ten years," says Chen. Such experiments might allow them to study economic problems in which the arguments for players using a quantum approach are compelling. Chen says they hope that their work on quantum auctions will soon produce a protocol that will enable collaborative auctions without needing to rely on trusted third parties (the auctioneer) or prior agreements to reach a preferred outcome.

Knowing what your competitors will bid is a major uncertainty at every auction, but knowing what a potential collaborator will bid and factoring that into your strategy is a more subtle uncertainty, referred to by economists as 'allocative externality'. In the fighter-jet example, this might translate to a company that is bidding to build the undercarriage wanting to bid less if another specific firm wins the contract for the landing gear. "Allocative externality is a prevalent problem in the awarding of large government contracts, and is something that all non-quantum auctions fail to address," says Chen.

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How we split a restaurant bill mirrors a game whose outcome could be improved by quantum mechanics.

Last summer, Chen and Hogg began to investigate how people behave in a quantum auction — although they first chose to study a simpler highest-bid-wins auction without collaborative bids. In this, the bidders decided how much they wanted to bid, and then deployed a quantum protocol similar to that used in the public-goods game to encode their bid and keep it private.

> "Much of the claimed superiority of quantum games to their classical counterparts has been the result of incorrect comparison."
> — David Meyer

To process the multiple bids, the researchers simulated the action of a quantum algorithm designed to find the maximum value of a quantum state — in this case, the maximum revenue received by the auctioneer. In an actual implementation, this search would be performed during the repeated exchange of qubits between the auctioneer and participants until an optimal answer was converged upon. At that point the auctioneer would perform a measurement of the qubits to decide the outcome of the auction, and all the losing bids would be destroyed.

Initial three-player auctions revealed flaws in the quantum search algorithm. "Deficiencies in the algorithm enabled players to potentially misrepresent bids so that ultimately they could win with a lower bid," says Hogg. He adds that the team is currently redesigning the algorithm to avoid such problems before tackling more complex collaborative auctions.

Chen and Hogg hope to introduce allocative externality into their quantum auctions in the next year or so. Although it will be some years before they begin to experiment with actual qubits, Meyer is encouraged by the team's experiments: "I'm fairly optimistic about the kind of research they are doing." Given the obvious security advantages of quantum auctions, Meyer believes that there is now a greater chance that QGT will prove to be genuinely useful.

Hogg and Chen's studies have also been welcomed by physicist Paul Ellsmore, co-author of a recent UK report on the commercial prospects for quantum information processing[5] and chief executive of semiconductor firm Nanion in Oxford. Conceptually, quantum games have some attractive features, Ellsmore says, but the creation of robust algorithms to encode quantum information has been lacking. "Commercialization had been considered a dirty word in this field," he says. "It's encouraging that researchers are now developing algorithms that could be implemented with technology that will be viable in the near future." ■

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