

Quantum Game Theory

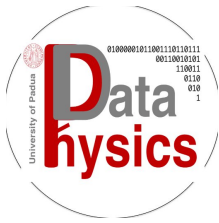
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Game Theory

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Abstract

In this report will be summarized the recent developments in quantum information that pushed scientists to apply the rules of quantum mechanics also to game theoretical problems. It will be provided the step-by-step reformulation of such games in a quantum world, together with the redefinition of other game theory's concepts. In the end, a canonical example, the Prisoners' Dilemma, will be analyzed and simulated in order to prove the advantages brought by the quantum moves and the new interesting kind of equilibria of such games.

1. From Classical to Quantum Game Theory

Game theory is the study of mathematical models of strategic interaction among rational decision-makers. Such decision-makers are players that have to follow fixed rules and have interests in all the possible outcomes, which do not depend only on the choices they individually make but also from the decisions took by the other contenders. At the very beginning, this discipline was mainly focused on the contest of economic theory, until its first formalization provided by Von Neumann and Morgenstern. Subsequently much work was done in this field, transforming it in a mature discipline, that is now used in several areas such as social sciences, political sciences, biology and engineering.

However, in the middle of 90's, physicists started applying the rules of quantum mechanics to classical information theory, giving way to birth of a new discipline that nowadays is known as quantum information theory. Some of them, moreover, started thinking also about a possible recast of classical game theory using quantum probability amplitudes, and hence studying the effect of quantum superposition, interference and entanglement on the agents' optimal strategies. There are several reasons for which quantizing games may be interesting:

- classical game theory is a well defined discipline in applied mathematics with applications in economy, psychology, biology,... and is based on probability to a large extend, and so there is a fundamental interest in generalizing it to the domain of quantum probabilities;
- a lot of games require a "nature choice" or even a "nature player", but under this new perspective, such nature is ruled by quantum mechanics;
- if the "selfish gene" theory proposed by Dawkins to justify the selfishness behavior of individuals, even when they live in groups, is reality, than someone can speculate about it bringing adversarial games back to a molecular level in which quantum mechanics dictates the rules [8];

- there is an intimate connection between game theory and quantum communication: whenever a player passes his decision to another one, he is basically transferring information, and so in a quantum world it is legitimate to start thinking about quantum information transferred.

Moreover, it will be shown that in most of the cases, a quantum description of a system provides advantages over the classical situation.

The paper starts analyzing zero-sum games, considering just two adversarial players, and will proceed reformulating several "canonical" problems under this new perspective, showing also that the extension of game theory to the quantum world will be quite "natural" and not even so complex.

2. Spin-Flip Game

In this section it will be provided an example of a game in which a "quantum player" can, in some situations, achieve better results than a classical one [9].

Let's start considering a modern version of a classic game theory problem, the penny-flip game, in which, instead of a coin, players use spin-1/2 particles (e.g. electrons) and distinguish between two possible outcomes depending on the spin state of such system, that can be either up or down. The game starts taking the particle initially set in a spin-up state, $|\uparrow\rangle$, then the players, Alice (A) and Bob (B), alternatively (A first, then B, then again A), can decide to flip the spin or do nothing.

Always remember that this is no more a classical but a quantum system, and so its actual state at any time will not be just "only spin-up" or "only spin-down", but a quantum superposition of the two. This means that, in the end, if the particle is in a generic state $a|\uparrow\rangle + b|\downarrow\rangle$, with $|a|^2 + |b|^2 = 1$, $a, b \in \mathbb{C}$, so a (quantum projective) measure on it will return just "spin-up" or "spin-down" with probabilities $|a|^2$ and $|b|^2$ respectively.

A wins if, at the end, the resulting spin is up, while B wins if it is down. This is a two-players zero sum static game of incomplete information, meaning that none of the contenders will know which strategy his opponent will choose, and the

final payoffs will be equal and opposite. The problem can be analyzed using a proper bi-matrix of payoffs, in which the columns represent B's strategy, that is just a single action selected from the available set $\{F, N\}$ where F stands for "flip" and N for "no flip", while the rows represent A's strategies, that are instead pairs of actions (because A has two turns).

		Player B	
		N	F
Player A	NN	$1, -1$	$-1, 1$
	NF	$-1, 1$	$1, -1$
	FN	$-1, 1$	$1, -1$
	FF	$1, -1$	$-1, 1$

The entries of the matrix are, as the name suggests, the payoffs for players A and B respectively, at the end of the game.

For a better understanding of the problem, it can be useful to construct a manageable mathematical framework: a quantum system made up only by one spin-1/2 particle is defined in an Hilbert space \mathcal{H} of dimension 2, and the most natural basis that we can construct for such space is made just by the two spin's eigenstates $\{|\uparrow\rangle, |\downarrow\rangle\}$. Using the \mathbb{C}^2 representation:

$$|\uparrow\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \quad |\downarrow\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

Pure strategies, instead, has to be defined as unitary operators over \mathcal{H} , i.e. 2x2 matrices in $SU(2)$, acting by left multiplication on the vectors representing the state of the spin. In particular, the strategies F and N described before, can be represented as:

$$\hat{F} = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \quad \hat{N} = \mathbb{1} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

A generic *mixed strategy*, so a linear combination of F and N with probabilities p and $1-p$ respectively, can be constructed consequently:

$$\hat{m} = \begin{pmatrix} 1-p & p \\ p & 1-p \end{pmatrix}$$

As last clarification, it may be useful to introduce the representation of quantum states via density matrices: in this case the initial state of the problem considered can be written as

$$|\psi_0\rangle = |\uparrow\rangle \longrightarrow \rho_0 = |\uparrow\rangle\langle\uparrow| = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$$

In order to exploit this representation, pure strategies U have now to be applied as contractions over density matrices, while mixed strategies are, as always, just convex combination of them:

$$\rho_{\text{pure}} = U\rho_0U^\dagger \quad \rho_{\text{mixed}} = pU_1\rho_0U_1^\dagger + (1-p)U_2\rho_0U_2^\dagger$$

Back to the original problem, suppose that only Alice has studied quantum mechanics and can apply these new quantum strategies, while Bob didn't and so is limited to classical

mixtures. First move is of player A, that decides to apply the following operator to the spin in the initial state

$$U_1 \equiv U(a, b) = \begin{pmatrix} a & b \\ \bar{b} & -\bar{a} \end{pmatrix} \quad \rho_1 = U_1\rho_0U_1^\dagger = \begin{pmatrix} a\bar{a} & ab \\ \bar{a}\bar{b} & b\bar{b} \end{pmatrix}$$

Next is player B's turn, that selects a generic mixed strategy:

$$\begin{aligned} \rho_2 &= p\hat{F}\rho_1\hat{F}^\dagger + (1-p)\hat{N}\rho_1\hat{N}^\dagger = \\ &= \begin{pmatrix} p\bar{b}\bar{b} + (1-p)a\bar{a} & p\bar{a}\bar{b} + (1-p)ab \\ pab + (1-p)\bar{a}\bar{b} & pa\bar{a} + (1-p)b\bar{b} \end{pmatrix} \end{aligned}$$

Given the density matrix of the final state, the expected payoffs of that configuration can be computed considering the probability that the outcome of a projective measure in such state returns $|\uparrow\rangle$ or $|\downarrow\rangle$. Since A has bet on "spin-up" and B on "spin-down" the final utility values will be:

$$\text{payoff}_A = p_\uparrow \cdot (+1) + p_\downarrow \cdot (-1) = -\text{payoff}_B$$

where p_\uparrow and p_\downarrow are given by the diagonal entries of ρ (formally they can be computed as expectation values: $p_\uparrow = \langle\uparrow|\rho|\uparrow\rangle$, $p_\downarrow = \langle\downarrow|\rho|\downarrow\rangle$).

Considering just this restricted two-moves game, its Nash equilibrium can be computed by reasoning on the quantities in the last density matrix ρ_2 :

- setting $p = 1/2$, both diagonal terms of ρ_2 will be equal to 1/2, meaning that Bob's strategy would lead him an expected payoff of 0, independently of Alice's actions;
- if A were to employ any strategy for which $a\bar{a} \neq b\bar{b}$, B could instead obtain an expected payoff of $|a\bar{a} - b\bar{b}| > 0$ just by setting $p = 0, 1$ to whether $b\bar{b} > a\bar{a}$, or the reverse;
- similarly, if Bob were to choose a mixed strategy with $p \neq 1/2$, Alice could maximize her payoff up to $|2p - 1|$ by setting $a = 1$ when $p < 1/2$ or $b = 1$ in the other case.

Thus, the mixed/quantum equilibria for this restricted game are pairs

$$NE = \left\{ U(a, b), \left(\frac{1}{2}\hat{F} + \frac{1}{2}\hat{N} \right) \right\} \quad \text{with } a\bar{a} = \frac{1}{2} = b\bar{b}$$

and the outcome is the same as if both players utilize optimal mixed strategies (1/2, 1/2).

But Alice has another move at her disposal (U_3), which again transforms the state of the electron by conjugation as $\rho_3 = U_3\rho_2U_3^\dagger$. If a particular operation is considered (in quantum information this is the *Hadamard Gate*)

$$U_1 = U\left(\frac{1}{\sqrt{2}}, \frac{1}{\sqrt{2}}\right) = U_3 = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$$

the first application puts the electron in a quantum superposition of both up and down states, $|\psi_1\rangle = 1/\sqrt{2}(|\uparrow\rangle + |\downarrow\rangle)$, which is therefore invariant under any mixed strategy selected by Bob during his turn; the fact is that Alice's last move inverts her first action projecting the system into the state $\rho_3 = |\uparrow\rangle\langle\uparrow|$, and so a measure over the electron will return, with probability 1, "spin-up" at the end of the game.

Since A can do no better than winning with probability 1, this is an optimal quantum strategy for her, and all the pairs

$$\left\{ p\hat{F} + (1-p)\hat{N}, U\left(\frac{1}{\sqrt{2}}, \frac{1}{\sqrt{2}}\right), U\left(\frac{1}{\sqrt{2}}, \frac{1}{\sqrt{2}}\right) \right\}$$

are mixed/quantum equilibria of the game, with final pay-offs of $(1, -1)$ for the two players.

The main purpose for this game being illustrated, is to teach that quantum mechanics can, in some scenarios, offer profitable strategies over the classical ones.

3. Formalization of a Quantum Game

Basically, any quantum system that can be manipulated by at least one party and where the utility of the moves can be reasonably defined, quantified and ordered, may be conceived as a quantum game.

The simpler way to fully specify a game in classical game theory is using its *normal form* Γ , i.e. listing players, strategies and payoffs. For a quantum game, a couple of additional terms have to be given, then the extension is straightforward:

$$\Gamma = \{\mathcal{H}, \rho, (M_i)_{i=1,\dots,N}, (S_i)_{i \in M}, (u_i)_{i \in M}\}$$

where \mathcal{H} is the Hilbert space of the physical system, $\rho \in \mathcal{S}(\mathcal{H})$ is the initial state ($\mathcal{S}(\mathcal{H})$ is the associated state space), M_i is the set of N players while S_i and u_i are the available quantum strategies and payoffs associated to each of that players.

A generic *quantum strategy* $s_A \in S_A$ is a collection of admissible quantum operations, that are maps from $\mathcal{S}(\mathcal{H})$ onto itself and usually are supposed to be positive-defined and trace preserving operators. In many two-person problems, like the previous example $\mathcal{S}(\mathcal{H}) = SU(2)$.

As anticipated in the first section, the extension of game theory to the quantum world is quite "natural", since the only thing to do is to re-adapt some definitions. In particular, the concepts of *dominant strategy*, *Nash equilibrium* and *Pareto optimality* are formally identical but extended to include also quantum strategies.

A full description of all the results found in these last 20 years in the field of quantum game theory would be very huge, and would be quite off topic respect to the initial purposes of this paper. For this reason, a deeper analysis will be reserved to a particular, and simple, class of games, that involve two players, each of them with a finite set of strategies, playing a static game of complete information. These are basically the foundations of classical game theory, since problems like these can be generalized and applied to much more complex tasks.

Stick to the example seen before, there is another result coming from classical game theory, that is worth to recall: according to Von Neumann, not every two-person zero-sum finite game has an equilibrium in the set of pure strategies, but there is always an equilibrium at which each player follows a mixed strategy. By definition any other strategy deviating from the equilibrium would lead to a smaller expected

payoff, and so it should never be chosen by a rational player. But this is not what shown instead in the quantum spin-flip game. The answer to this problem was found by A. Meyer, one of the initiators of quantum game theory, that was able to derive three interesting theorems (the proof can be found in the original article [7]).

Theorem 1. *There is always a mixed/quantum equilibrium for a two-person zero-sum game, at which the expected payoff for the player utilizing a quantum strategy is at least as great as his expected payoff with an optimal mixed strategy*

Of course, the more interesting question is for which games there is a quantum strategy which improves upon the optimal mixed strategy, and another one is what happens if both players utilize quantum strategies.

Theorem 2. *A two-person zero-sum game need not have a quantum/quantum equilibrium.*

Here it is possible to recognize the equivalent classical result, in which several games (like odd/even or rock/paper/scissor for example) lack of pure strategy Nash equilibria. But, at the same time, this result suggests to look for the analogue of Von Neumann's theorem about mixed strategies.

Theorem 3. *A two-person zero-sum game always has a mixed quantum/mixed quantum equilibrium.*

3.1. Quantum 2 x 2 Games

In traditional 2x2 games, usually there are two contenders that can choose a single move in a given finite set of available strategies. In order to construct a physical quantum model for these kind of problems, it is not enough to construct *superpositions* of actions just as linear combinations of them (like for mixed strategies), but a further step is needed: it is necessary to produce an *entanglement* between various moves. Entanglement is a peculiar quantum mechanics' concept without classical equivalent: if the game that is being studied shows this phenomenon, then the two states composing the system (one for each player) cannot be anymore defined independently one of the other, and any action/modification/measure on the first will inevitably have repercussions also on the second.

Always keep in mind that a classical game has to be a subset of its quantum version, and so anyone should be able to re-derive it as a particular case.

The quantum formulation proceeds by assigning the possible outcomes of the classical strategies D and C (usually *defect* and *cooperate*) represented by two basis vectors $|D\rangle$ and $|C\rangle$ in the Hilbert space of the two-state system (i.e. qubits). At each instance, the state of the game is described by a vector in the tensor product space $\mathcal{H} \otimes \mathcal{H}$, which is spanned by the classical game basis $|CC\rangle, |CD\rangle, |DC\rangle, |DD\rangle$, where the first and second entry refer to Alice's and Bob's qubit, respectively. A generic game can be represented by a simple quantum circuit (1, [1]):

- In the first part of the system, the game is built taking two classical strategies (represented as separated

qubits) to which a gate \hat{J} is applied: this operator generates the entanglement between the two qubits, introducing non-classical effects in the game (without using it, the problem would be equivalent to the classical one, when solved using mixed strategies); the game's initial state vector is now $|\psi_0\rangle = \hat{J}|CC\rangle$ (the initial choice of $|C\rangle$ or $|D\rangle$ is meaningless, as long as the other operations are "tuned" correctly).

- \hat{U}_A and \hat{U}_B are the quantum strategies effectively selected by Alice and Bob: as anticipated in the spin-flip example, these have to be represented by unitary trace-preserving operators, most of the time in $\mathcal{H} = SU(2)$. In a more general treatment, each player should be allowed to use any local operation that quantum mechanics provide, that is applicable to the problem; the fact is that an eventual analysis of all the possible cases would probably fill up an entire book and would not be even necessary, since the solutions found in $SU(2)$ are usually better (and simpler) than all the others.
- The last part of the circuit consists in a disentangling gate \hat{J} , that finally separates the players' states, allowing a measurement (projective measure in the original basis $\{|C\rangle, |D\rangle\}$). Then it's just about consulting the payoff's table.
- Just a couple of remarks about \hat{J} and \tilde{J} :
 - \hat{J} is a unitary operator, symmetric with respect to the interchange of the two players, and known by both of them and so it is common knowledge;
 - since the classical game was required to be a subset of the quantum one, necessarily \hat{J} commutes with the direct product of any pair of classical moves:

$$[\hat{J}, \hat{C} \otimes \hat{C}] = [\hat{J}, \hat{D} \otimes \hat{D}] = [\hat{J}, \hat{C} \otimes \hat{D}] = 0$$

Moreover: $\tilde{J} = \hat{J}^\dagger$.

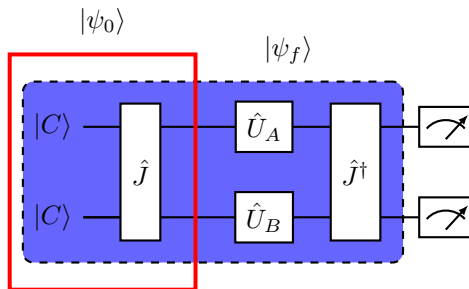


Figure 1: Quantum Circuit of a generic 2x2 game

The final part of the system consists, as said, by a couple of two-channels detectors, each of them labeled by $\sigma = C, D$, representing the outcome of the measure. The final state of the game prior to detection is given by

$$|\psi_f\rangle = \hat{J}^\dagger (\hat{U}_A \otimes \hat{U}_B) \hat{J} |CC\rangle$$

Then, given a certain joint strategy selected by Alice and Bob, the final expected payoff of each of them can be computed with

$$\langle i_s \rangle = \sum_{\sigma\sigma'} P_{\sigma\sigma'} |\langle \psi_f | \sigma\sigma' \rangle|^2$$

where $\sigma\sigma'$ represents the possible outcomes of the detector (CC, CD, DC and DD), and $P_{\sigma\sigma'}$ is the corresponding entry of player i in the payoff matrix.

If the actions' space is restricted to $SU(2)$, then each quantum strategy can be written as function of 2 parameters:

$$\hat{U}(\theta, \phi) = \begin{pmatrix} e^{i\phi} \cos \theta/2 & \sin \theta/2 \\ -\sin \theta/2 & e^{-i\phi} \cos \theta/2 \end{pmatrix} \quad \theta \in [0, \pi], \phi \in [0, \frac{\pi}{2}]$$

The readers with an higher knowledge about group theory may have notice that $SU(2)$ in reality has 3 generators, and so a matrix belonging to it should depend on at least 3 independent parameters. The reason of the usage of just θ and ϕ is that if player are allowed to exploit any possible strategy in $SU(2)$, then there would be virtually no Nash Equilibria, [3]. Consequently, from now on, quantum strategy will be defined as matrices in a subset of $SU(2)$, with the restriction shown above.

And also classical strategies have this kind of representation in which

$$\hat{C} = \mathbb{1} = \hat{U}(0, 0), \quad \hat{D} = \hat{\sigma}_x = \hat{U}(\pi, 0)$$

while $\hat{U}(\theta, 0)$ is the set including all classical mixtures.

To conclude this section, exploiting quantum information together with abelian group theory, an explicit form of the entangling operator \hat{J} is provided, and the nice thing is that this form is a function of a parameter γ that can be seen a sort of "measure of entanglement":

$$\hat{J} = \exp(-i\gamma \hat{D} \otimes \hat{D}/2) \quad \gamma \in [0, \frac{\pi}{2}]$$

For a separable game $\gamma = 0$, and the joint probabilities $P_{\sigma\sigma'}$ factorize for all possible pairs of strategies. A different situation holds for $\gamma = \pi/2$, that corresponds to states that are maximally entangled, and so the game played is as far as possible from its classical counterpart.

4. Quantum Prisoners' Dilemma

In this section will be analyzed and simulated a canonical non-zero sum game usually known as the prisoners' dilemma. In these kind of games, in contrast to zero-sum games, the two players no longer appear in strict opposition to each other, but may rather benefit from mutual cooperation.

Note. All the plots shown in this section have been realized in Python: the original code is contained in a Jupyter Notebook that can be found on Github [10]. It may be useful to give a look there if interested in a computational implementation of this problem and/or a deeper overview of it.

There are two players, Alice and Bob, that are thieves caught by the police, which are being questioned, and can choose among two strategies, Mum (collaborating, C) or Fink (defecting, D). The payoffs are distributed according table 1 and, as usually, the objective of each player is to maximize his or her individual utility.

		Player B		(1)
		C	D	
Player A	C	3, 3	0, 5	
	D	5, 0	1, 1	

Analyzing the problem using classical game theory, one can conclude that the best strategy to be played is found at the Nash Equilibrium, i.e. playing $\{DD\}$. The "dilemma" in the name of the game stands exactly for this: $\{DD\}$ is a strategy that is Pareto dominated by $\{CC\}$, so both players have, at least from a theoretical point of view, the possibility of obtaining an higher payoff simply unilaterally changing their own strategies, but the common rationality instead force them to play D .

But when the problem is instead reformulated in the quantum context [4], it can be proven that :

- there exists a particular pair of quantum strategies which always gives high reward and is a Nash equilibrium;
- there exists a particular quantum strategy which always gives a positive reward if played against any classical strategy.

According to the formalism presented in the previous section, assuming that each player is able to use quantum strategies, than the available actions at the beginning of the game are represented by operators in $SU(2)$ (unitary and trace-preserving 2x2 matrices). Moreover, in order to properly construct a quantum game, also a dose of entanglement, adjusted by the parameter γ , is needed.

From the numerical simulation of the problem it is possible to assert that all the Nash equilibrium strategies are of the type $\{\hat{U}(\pi, \phi_A), \hat{U}(\pi, \phi_B)\}$ and the corresponding utility values are $[1, 1]$. But remember that $\hat{U}(\pi, \phi)$ is nothing but the old pure strategy of defection \hat{D} . A further confirmation of this comes from figure 2, that shows the expected payoffs for player A as function of θ_A and θ_B (since the values of ϕ are not influent, and the equivalent heatmap for B is identical but reflected): as expected, if one player goes for $\theta \rightarrow 0$ and the other for $\theta \rightarrow \pi$ the game falls in a classical situation like $\{CD\}$ or $\{DC\}$, in which the utility is high for someone and low for the other, but this is not a NE. From the right plot, it is obvious that if A selects \hat{D} his utility is maximized regardless of the opponent's strategy, and the same holds for B. This means that $\{\hat{D}, \hat{D}\} \equiv \hat{D} \otimes \hat{D}$ is an equilibrium in dominant strategies. Indeed separable games ($\gamma = 0$), manifest the same behavior as their classical counterpart, bringing also to the same results.

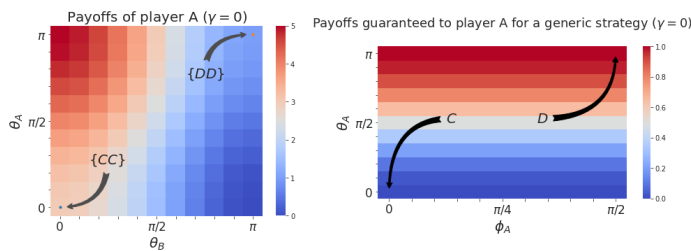


Figure 2: Utilities of the contender A in a game with $\gamma = 0$, as function of the strategies chosen (left). Minimum payoff guaranteed to A for a generic strategy of B (right).

The situation is entirely different for a maximally entan-

gled game, with $\gamma = \pi/2$: this time, any pair of strategies chosen will have no counterpart in the classical domain, providing new and interesting solutions. To be precise, one can always re-derive the original prisoners' dilemma if both players choose actions of the type $\hat{U}(\pi/2, 0)$. From the numerical analysis of the problem [10], one can clearly observe that there are no dominant strategies this time, and this means that $\{\hat{D}\hat{D}\}$ is no longer an equilibrium in dominant strategies. Furthermore, such NE is replaced by a new joint strategy of best replies (from which no rational player would deviate), i.e. $\{\hat{Q}\hat{Q}\}$.

$$\hat{Q} \equiv \hat{U}(0, \frac{\pi}{2}) = \begin{pmatrix} i & 0 \\ 0 & -i \end{pmatrix}$$

This is the new unique equilibrium of the game, and guarantees a final payoff of 3 for both players; in fact

$$\text{payoff}_A(\hat{Q}, \hat{U}_B) = \cos^2\left(\frac{\theta}{2}\right) (3 \sin^2 \phi + \cos^2 \phi) \leq 3 \quad \forall \theta, \phi$$

and the same holds for Bob.

Using the same representation as before, according to the payoff plot 3 of player B, notice that, assuming that the first player chooses this new optimal strategy \hat{Q} , then there is no choice for the second that would improve his payoff rather than \hat{Q} as well.

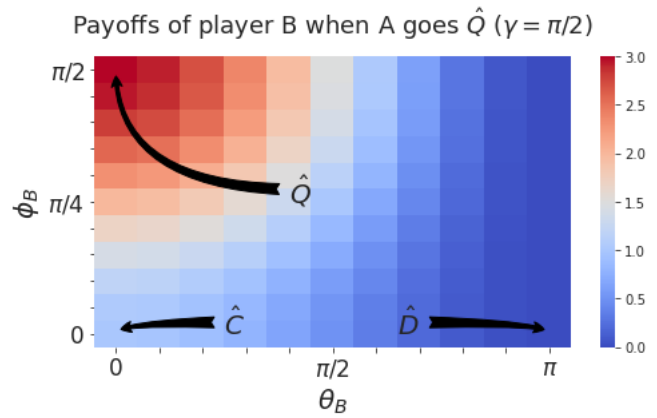


Figure 3: Utilities of player B when A selects the optimal strategy \hat{Q} .

Moreover, $\hat{Q} \otimes \hat{Q}$ is not just a Nash equilibrium but has also the property of being *Pareto Optimal*, meaning that deviating from this pair of strategies it is not possible to increase the payoff of one player without reducing the utility of the other. The solution of the classical game was not Pareto optimal: the only strategy with this property was the mutual cooperation, but such choice was not holdable by rational players without considering a multistage game (with carrot and stick or grim trigger approaches). And this is the first advantage provided by the quantum transposition of the game since, in a certain sense, the dilemma has just been solved.

4.1. Quantum player vs Classical opponent

What if the game was instead unfair like the spin-flip example presented in the second section, in the sense that quantum strategies are accessible only to one player?

Suppose that Alice has studied quantum mechanics, so her state space is still $SU(2)$, while Bob is limited to select actions characterized by $\phi = 0$: in this case A is well advised to play the so called *miracle move* (according to Eisert et al. [4])

$$\hat{M} \equiv \hat{U}(\pi/2, \pi/2) = \frac{1}{\sqrt{2}} \begin{pmatrix} i & -1 \\ 1 & -i \end{pmatrix}$$

that guarantees the following payoffs

$$payoff_A(\hat{M}, \hat{U}(\theta, 0)) \geq 3 \quad payoff_B(\hat{M}, \hat{U}(\theta, 0)) \leq \frac{1}{2}$$

The comparison among the possible combinations of actions is shown in figure 4.

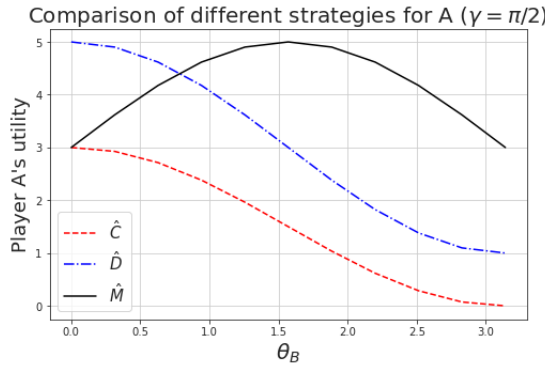


Figure 4: Final payoffs for different strategies selected by Alice, as function of the parameter θ_B .

So player A (rationally) will play "always \hat{M} ", since this strategy will give her a utility of at least 3, regardless of the strategy chosen by B, which is inevitably in a position of disadvantage. This approach certainly outperforms "tit-for-tat", at least in these kind of asymmetric problems.

Finally, it may be interesting to study also the effective payoff of the quantum player as a function of the degrees of entanglement of the game, i.e. the parameter γ . The minimal expected payoff accessible by Alice is given by

$$m = \max_{\hat{U}_A \in SU(2)} \min_{\hat{U}_B \in \{\hat{C}, \hat{D}\}} payoff_A(\hat{U}_A, \hat{U}_B)$$

and the plot realized is shown in figure 5.

It is immediately possible to notice that under a certain threshold, in term of entanglement degrees, that is found to be around $\gamma_{th} = \arcsin(1/\sqrt{5}) \simeq 0.464$, the forced choice is playing \hat{F} ; after such threshold, near to the maximum entanglement among the states, then the best reply is always the miracle move. An interesting fact, not shown by the graph because of the limited precision, is that the "strategy swap", from \hat{F} to \hat{Q} is much more discontinuous than how it appears: this is a clue that a phenomenon known as *quantum phase transition* has occurs around γ_{th} .

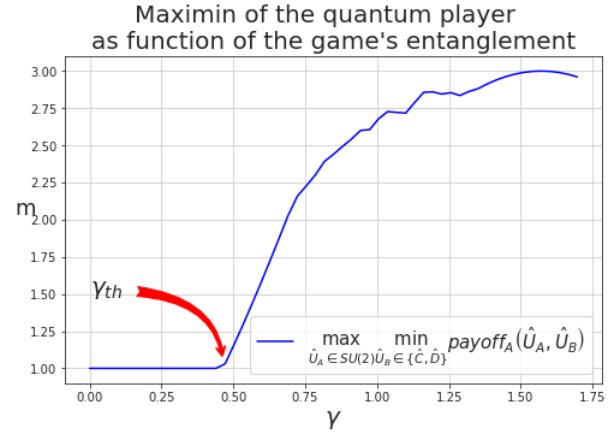


Figure 5: Payoffs guaranteed to player A as function of the entanglement measure γ .

5. Multi-Player Quantum Games

From the previous analysis done, it became clear that moving from a classical to a quantum game corresponds to a huge increment of the set of available strategies: just considering 2-players games as above, the number of possibilities accessible to both players moved from 2 to basically infinite. And the same consequence could hold also for the number of equilibria of the match, making the computational analysis very challenging.

For this reason, the extension of the previous formulation to games with more than two players will be very difficult but, at the same time, will provide new and surprising results. One of the first and most complete attempts is traceable to Benjamin and Hayden [2] in 2001 that, via the formulation and successive analysis of famous multi-player games like the Prisoners' Dilemma and the Minority Game, have shown that, differently from classical problems, several quantum players are able to cooperate to perfectly exploit their environment and guarantee the highest payoff to anyone. And the key ingredient that gives rise to this possibility is the entanglement among the different players' states.

The formulation suggested by Benjamin and Hayden, reported in figure 6 is a generalization of the elegant scheme proposed also by Eisert [4] in which:

- each player is associated to a qubit, and all the qubits together represent a state of the system;
- such qubits can be entangled;
- the pure strategies available to the players are single-qubit operators represented by maps that are unitary, trace-preserving and positive defined;
- it should be possible to re-derive the classical game as a particular case.

Regarding the third point of the list, someone could argue about the fact that in classical games, the only restrictions over the action space were those imposed by classical physics: well, formally one could build a quantum game leaving players to choose among all the possibilities offered by the entire quantum mechanics, but he would end up with a problem nearly impossible to analyze, simulate or imple-

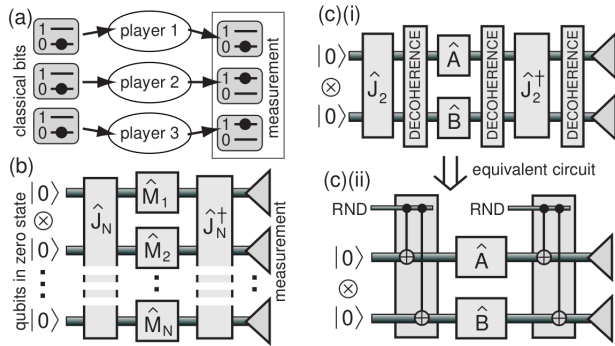


Figure 6: (a) classical game in which each player has two actions available (flip or not) and the state of the system is a set of bits. (b) an N-player quantized game. (c) a more "realistic" version of the quantized game in which also the decoherence (progressive loss of quantum correlations) is taken into account.

ment, and probably without any practical application.

To avoid making this paper too much long, the analysis of the 3-Prisoners' Dilemma and the N-player Minority Game will not be reported: the only thing that is worth to recall is that, as anticipated, entanglement acts as a sort of "contract" among the different contenders, that allows them to play "cooperatively" knowing that no one can successfully "defect" against the others.

Apparently, in the last years, you cannot find any other work like the one of Benjamin and Hayden, or at least of the same relevance, focused on the theoretical formulation of Multi-Player Quantum Games. The reason is probably mainly the difficulty of the analysis: redefining the problem in a quantum world means basically moving from a discrete to a continuous set of possibilities, with a consequent infinite number of different situations. Also simulating an N-player problem on a classical computer is almost impossible, as long as you want to obtain results with a reasonable accuracy.

6. Conclusion

In this report a brief overview over the formulation of quantum games has been provided, together with the simulation in Python of a canonical problem like the Prisoners' Dilemma. It has been shown that quantum games can provide new and unexpected Nash equilibria, can make some classical results to disappear and can improve a lot the degrees of freedom of the players. Moreover, it has been shown that a quantum player, most of the times, has an advantage over the classical player, with new and surprising "always-win" strategies.

An interesting observation about this branch of game theory is that most of the articles, papers, projects, that you can find on the internet have been written around 1999 and 2001, that are also the years in which the discipline of quantum information has been, for the first time, formalized, arising the curiosity of many scientists also belonging to different research areas. The fact is that such wave of first interest vanished as it was born, and no other "revolutionary" discov-

eries or studies, have been realized in the following 20 years. As repeated several times, in fact, the formulation of a quantum game is not so challenging once you have some knowledge about group theory and quantum mechanics, but the successive analysis in order to find solutions and equilibria is very complex in a continuous space. One possible frontier is the numerical simulation, as for the problems analyzed here, but using just a classical computer the amount of resources required is enormous. And this is the reason for which apparently in 2020 the interest of scientific community seems to start rising again: the new innovations (especially engineering) provided by big companies in the development of quantum computers allowed scientists to exploit the power of physical qubits to perform simulations with a decent level of accuracy for the results. And here the situation changes completely, making the analysis much faster and precise. Actually, however, there is no quantum computer that has reached the "perfection" yet, and the main problem is always the noise produced by atoms' fluctuation (one can think to something similar to bits corruption), as shown also in a recent paper [5], in which the 3-player Dilemma is simulated over a quantum computer, and the results are presented as function of the channels' noise.

So to conclude, there are still a lot of directions to expand quantum game theory that have been unexplored yet, mainly because of the lack of practical implementation, but the recent improvements in quantum technology, especially in term of accessibility, will probably soon open a large number of new possibilities that will bring back this forgotten branch of game theory under the sights of the scientific community.

A. Some concepts from Quantum Information Theory [6]

A.1. Qubits

The actual calculus model implemented in classical computers is based on the implementation of functions from n bits to m bits, formally $f : \{0, 1\}^n \rightarrow \{0, 1\}^m$, where 0 and 1 are **distinguishable states** of our system.

The quantum mechanical analogue of a classic bit is called **qubit**, that is a 2-dimensional, normalized, complex vector in an Hilbert space with basis $\{|0\rangle, |1\rangle\}$, a set of two distinguishable (quantum) states: a *fundamental* and an *excited* one. From the **Superposition Principle** of QM it is immediately possible to write the form of a generic qubit (in the traditional *Dirac's* or *bra-ket's* notation):

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle \quad \alpha, \beta \in \mathbb{C}, |\alpha|^2 + |\beta|^2 = 1$$

In quantum information, qubits are usually expressed in the \mathbb{C}^2 representation, in term of a so called **Computational Basis**:

$$|0\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \quad |1\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

One could ask if the "amount of information" stored in a qubit or in a bit is the same, but the answer is not so trivial: each quantum state is fully encoded by two complex numbers, and so one could potentially store an infinite information in their (infinite) amount of digits. The fact is that in the end, once the qubit is being measured, because of the projective nature of quantum measurements, the results can be only either 0 (w.p. $|\alpha|^2$) or 1 (w.p. $|\beta|^2$), losing almost entirely the other information stored. However those complex numbers are still "alive" during the process and the transformations applied to the state, and can influence its evolution.

Other advantages provided by the usage of qubits is the possibility of exploiting non-local effects, peculiar of quantum mechanics, like the entanglement, in order to implement circuits and algorithms with many more degrees of freedom than their classical counterparts.

A.2. Many-Body Systems

Given a quantum system made of N independent components, the state of such system can be written as the **tensor product** of the states of the components:

$$|\psi\rangle = |\psi_1\rangle \otimes |\psi_2\rangle \otimes \dots \otimes |\psi_N\rangle$$

and the result will be defined in an Hilbert space that is a tensor product as well $\mathcal{H} = \mathcal{H}_1 \otimes \dots \mathcal{H}_N$.

In quantum information, for example for $N = 2$, you need to extend the computational basis:

$$|00\rangle = \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix} \quad |01\rangle = \begin{pmatrix} 0 \\ 1 \\ 0 \\ 0 \end{pmatrix} \quad |10\rangle = \begin{pmatrix} 0 \\ 0 \\ 1 \\ 0 \end{pmatrix} \quad |11\rangle = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix}$$

Many-Body quantum systems are actually one of the areas of major interest in quantum information, especially because for a system of N components, a complete description of its state in classical physics requires only N bits, whereas in quantum physics it requires 2^N complex numbers. So this kind of problems usually scales exponentially with the number of atoms/bodies/parts, and scientists are always looking for models (e.g. the *Ising Model*) and techniques in order to find complete but efficient solutions.

A.3. Entanglement

Not all the systems' states can be "splitted" as tensor products, since this is possible only when the parts are independent. But there are some situations in which many qubits show some kind of quantum correlation and they cannot be anymore be described one independently of the other. This phenomenon is known as **entanglement** and is one of the most interesting and mind blowing effects of quantum mechanics, because it has not a classical counterpart and is a non-local feature. If two qubits are entangled it is not possible to write them as $|\psi_1\rangle \otimes |\psi_2\rangle$, and any kind of measure or transformation on one of them will inevitably influence also the second, regardless of their actual position in the spacetime.

A.4. Density Matrices

A **density matrix** is a matrix that describes the statistical state, whether pure or mixed, of a system in quantum mechanics. If it is known that a certain system is in state $|\psi_i\rangle$ with probability p_i (given a set of pure states with the relative probabilities), then the density matrix associated can be calculated with:

$$\rho = \sum_i |\psi_i\rangle \langle \psi_i|$$

The probability for any outcome of any well-defined measurement upon a system can be calculated from the density matrix simply tracing over it: given an observable \hat{A} , then its expectation value in a state described by ρ is

$$\langle \hat{A} \rangle = \text{Tr}(\rho \hat{A})$$

A.5. Measurements

The process of extracting numerical information from a set of qubits is called measurement. There are several types of measurements in quantum mechanics, but the one mainly used in quantum information is the **Von Neumann projection**. Given a system in the state $|\psi\rangle$ and a generic observable of interest \hat{A} , that can be decomposed along its eigenstates as

$$\hat{A} = \sum_i \lambda_i |\phi_i\rangle \langle \phi_i|$$

then, the result of a measure will be one of the eigenvalues λ_i , with probability $|\langle \phi_i | \psi \rangle|^2$. Moreover, the state of the system immediately after the measurement will be exactly the eigenstate $|\phi_i\rangle$, with the same probability.

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