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"C2 for Complex Endeavours"

Enhancing Cooperation in Complex Endeavours through Quantum Information Exchange

Track 1: C2 Concepts, Theory and Policy

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Abstract

The realities of complex endeavours necessitate the development of new approaches to command and control. While endeavours comprise entities seeking to cooperate towards overlapping goals, the level of cooperation actually achieved can be variable. Overcoming this limitation requires robust information sharing between participants as an important element of their engagement. Indeed, transformations introduced by the information age are providing such opportunities for organising endeavours. These are often framed around network-centric concepts based on the exchange of classically understood information. However, other information concepts may also be exploited. Novel new approaches, relying on the exchange of *quantum* information, are now being explored. Applied to bargaining situations represented by Games, the exchange of quantum information can allow for new types of cooperative behaviour to emerge. Directed to competitive domains, such as stock markets, the application of quantum information may introduce techniques for inducing cooperation and avoiding mutually disruptive behaviour. This paper will review the insights gained from the use of quantum information in bargaining situations and explore possible future applications to the command and control of complex endeavours.

Introduction

For complex endeavours, Command & Control (C2) is more than achieving goal alignment and establishing common intent. The rich interplay of military, political, economic and social forces necessarily renders such aspirations transient for all but the most ardent supporters of an endeavour. Rather, to be successful, complex endeavours require that some form of enduring cooperation be realised if individual and collective goals are to be achieved. What type of cooperation is needed and to what extent cooperation should be sought remain ambiguous questions.

The need to foster cooperation, or at least better coordination, has seen the introduction of new C2 concepts directed to enhancing engagement and building trust amongst the different actors. These include the Multinational Interagency Group (MNIG), Civil-Military Cooperation (CIMIC) and the use of Civil-Military Operations Centres (CMOC). Working at the operational or tactical level, these C2 structures aim to provide a forum for dynamic military, civilian and interagency interaction. However, it is recognised that engagement and interaction must extend to also include greater participation in strategic planning. To be mutually beneficial, some level of common agreement must be reached between the organisations involved in such collective planning activities. In the absence of prior interaction, for example through trials and exercises, such accord is unlikely to be built on trusted relationships, with little time provided during the planning process for trust to be

developed. Indeed, the inherent complexity of modern operations can often frustrate the development of trust at all levels of an endeavour.

An important element in overcoming the barriers to greater understanding and cooperation in complex endeavours is the use of widespread information sharing [Alberts & Hayes 2007, page 175]. But this should not simply be based on the distribution of yet greater volumes of information. Rather, more sophisticated approaches to information sharing and exchange are required if the challenges posed by complex endeavours are to be met. Exploiting the properties of quantum information may provide a novel new approach to achieving this goal.

This paper explores the possible application of quantum information to achieving greater cooperation between participants in complex endeavours. By exploiting the intrinsically quantum mechanical property of entanglement a form of team work can be introduced which can yield mutually better outcomes. The principal aim of the paper is to provide a brief exploratory look at how quantum information may enhance cooperation in bargaining. In this respect the paper seeks to explore a possible C2 application of quantum information in anticipation of future breakthrough technologies. It will be shown that quantum information can provide a significant advantage when exploited by a single bargaining participant but that, as shown by recent research, achieving cooperation through mutual quantum information exchange requires careful consideration of how the bargaining situation is structured. Through this review the reader will gain greater insight into the potential benefits and limitations of applying quantum information to complex endeavour C2, as well as the areas requiring further research.

The paper begins by discussing the nature of cooperation in complex endeavours and the role of information in their success. Consideration is then turned to the relevance of quantum technologies to C2, followed by an introduction to the use of quantum information in bargaining situations represented formally as Games. To illustrate the power of quantum information, application is made to a two player Game of relevance to complex endeavours where only one player has access to the new manipulations afforded by quantum information. Discussion is then directed to bargaining where all participants can exploit quantum manoeuvres. Options for structuring bargaining to best employ quantum information in complex endeavours are then explored, after which the paper is concluded with a brief discussion on areas of future work.

Cooperation and Complex Endeavours

An endeavour is defined as an undertaking involving *a large number of disparate entities whose activities are related to a broad range of effects, including not only (and very often not primarily) military, but also social, economic, political and informational factors* [Hayes, page 146]. The richness of the interactions between these participants, and the different interests being pursued, characterise such endeavours as complex, the cause and effect relationships often being obscure [Alberts & Hayes 2007, page 9] with the dynamics of interaction resisting reduction.

Within an endeavour *[n]o single actor or set of actors … is capable of achieving its relevant goals without appropriate activities and behaviours by other members* [Hayes, page 163-164]. To this extent an endeavour is seen to comprise entities who

have chosen to cooperate, at some level, in ways which prove mutually beneficial. However, some caution must be exercised. While it is known that endeavours extend to include entities only incidentally supporting the goals of the mission [Hayes, page 146], it may also be the case that involvement of some entities has value for reasons completely independent of the stated goals [Alberts & Hayes 2007, page 9, footnote]. Indeed, for some entities, participation itself may be the goal.

When considering the role of cooperation in complex endeavours the assumption of a type of participatory efficiency operating between entities may at times be made – that is, interactions between participants leading to recognisable, albeit dynamic, distributions of cooperating entities, friends of convenience, neutral parties and adversaries [Hayes, page 167]. Such an assumption may be unfounded. For instance, the requirement that endeavours be based on goal alignment [Hayes, page 165] makes little provision for some participants being more of a hindrance than a help, of stated mission goals differing from actual political objectives or of a simple lack of clarity in the mandate. Indeed, for many complex endeavours the underlying assumption of shared mission goals may not be present or easily defined, obscured by historical rivalries, institutional barriers, differing world views and inconsistent time horizons. As a consequence, the different actors in complex endeavours may not neatly map to any straight-forward characterisation or ontology.

The real question is: what is actually meant by *appropriate activities and behaviour by other members* [Hayes, page 163-164] and what type of cooperation is being sought? The ambiguity of this question necessitates a flexible approach which does not necessarily seek to pre-define the desired outcome or rely on established lines of trust. For situations characterised by differing capabilities, culture and motives, trust and common ground will need to emerge dynamically, and may do so in ways and in domains not anticipated by planners.

Information and Cooperation in Complex Endeavours

The sharing of information and shared awareness are seen to be important elements to the success of endeavours [Hayes, page 172]. Applying the tenets of Network Centric Warfare (NCW), widespread information sharing is to be achieved through the establishment of robust networks, leading to improved collaboration in sense-making and execution [Alberts & Hayes 2007, page 109]. While allowing for simultaneous action, a dominant effect of the improvements in information and communication technologies underpinning NCW is the increased flow of information through Command & Control systems [Ryan, page 11]. As a consequence, the aspiration of shared awareness may be overwhelmed by the active sharing of information, undermining synchronised behaviour and enterprise agility:

> *The technologies are information – and communication – based, and will have the predicted effect of increasing the volume of information and the amount of complexity with which decision makers must cope.* [Schmidtchen, page 76].

When considering how information should be applied to facilitate cooperation it is important to look beyond the claim that significant competitive advantage will necessarily be gained by those who have taken advantage of advances in information technologies [Alberts & Hayes, 2006, page 2], to also recognise that:

> *Taken as a whole, present-day military forces, for all the imposing array of electronic gadgetry at their disposal, give no evidence whatsoever of being one whit more capable of dealing with the information needed for the command process than were their predecessors a century or even a millennium ago.* [Van Crevald, page 265].

What is actually needed are robust socio-technical networks *supported* by information technology [Alberts & Hayes, 2006, page 3]. This recognises that a command system is made of both automated and manual processes, where sometimes the manual procedures are more appropriate [Ryan, page 9]. To effectively support these functions with information technology, while avoiding the limitations of unrestrained information exchange, consideration needs to be directed not only to the exchange of *better* information [Alberts & Hayes 2006, page 86], but to the very nature of the information being shared. As has been noted: *[t]he real issue is the nature of the sharing of information and the interactions that are necessary, not whether there should be more sharing of information and interactions* [Alberts and Hayes 2007, page 11].

Quantum Technologies and Command & Control

To find alternatives to the description and application of information appeal can be made to the different physical theories that describe nature itself. Fundamental amongst all such theories is quantum mechanics, an incredibly successful physical theory providing explanations for a range of observed phenomena. Quantum mechanics has led to the development of a host of new technologies, encompassing nuclear power to the design of lasers for CD players [Singh, page 325]. At its heart, quantum theory rests on the essential indeterminacy of the condition of unobserved microscopic entities. At the microscopic level, entities can exist as a mixture of different states whereas our normal intuition, that is our experience of dealing with macroscopic (that is classical) entities, is that physical objects exist in only one state at a time. Harnessing the ability of nature to exist as admixtures, or more formally superpositions, of microscopic states is the key to the new field of quantum computing. By placing the input and a computer into a superimposed quantum state many calculations can be run simultaneously, providing computing power of amazing proportions.

In reviewing the Air Force Research Laboratory's efforts in the domain of quantum information and quantum computing the question was asked [Drager & Walsh]: *"Is it possible for quantum technologies to be applied to command and control systems?"*. This was motivated by the potential for quantum computing to greatly improve the speed and ability of current processors, with possible application to C2 in areas such as information management and decision superiority. Looking more broadly, quantum computing has the potential to also provide benefits to supporting capabilities like signal processing and image reconstruction, as well as impacting on important scientific disciplines such as computational fluid dynamics. The relevance of future quantum technologies to C2 would thus seem assured.

Beyond computational applications, research into the exploitation of quantum information of potential relevance to C2 has largely focussed on the ability to introduce unbreakable codes for secure communication [Singh]. Such studies utilise

the uncertainties inherent in quantum information to allow a sender and receiver to devise an unbreakable message for which any tampering or intrusion can be easily detected. But communication is more than just passing secure messages; the actual content of the message is also important. Indeed, controlling and shaping the information communicated between different parties is an important C2 function, which for modern operations includes bargaining and negotiation in complex endeavours. Through the use of quantum communication technologies by each of the participants in a negotiation, a kind of teamwork may be introduced even in the absence of established trusted relationships.

Quantum Information and Negotiation

Information exchange across networks has traditionally been explored using classical notions of information. In the classical context, information is passed through the exchange of N-bit binary strings, N-bit binary sequences forming the basic computational representations of descriptive information [Ford]. An alternative, now under active research, is to communicate using quantum information. For quantum systems the analogous concept to the bit in classical information theory is the quantum bit or *qubit* [Nielsen & Chuang, page 13]. By exploiting the, often counterintuitive, properties of quantum objects new possibilities and efficiencies emerge which can be exploited to improve computational capabilities and promote alternative outcomes.

As with a classical bit, a qubit can exist in two possible states, represented as $|0\rangle$ and $|1\rangle$. However, unlike a classical bit, a qubit can also exist as a superposition of these states: $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$, where $\alpha, \beta \in \mathbf{C}$ and $|\alpha|^2 + |\beta|^2 = 1$. As a consequence, a qubit can realise a continuum of states. It is these quantum states that provide the novelty and power to quantum computation and information. For the quantum state $|\psi\rangle$ the values $|\alpha|^2$ and $|\beta|^2$ represent the probabilities that, when measured, the quantum state will be found in the state $|0\rangle$ or $|1\rangle$ respectively. That is, measurement of the qubit collapses the quantum state onto one of these two basis states. While only these, and not the superposition state, are realised physically, the state of the qubit $|\psi\rangle$ can be manipulated to vary the basis state probabilities $|\alpha|^2$ and $|\beta|^2$ [Nielsen & Chuang, page 13] and so influence the measured outcome.

For Command & Control systems based on the sharing of information, attention must be broadened to the interaction of multiple qubits. Consider the simple case of two individuals each exchanging qubits, where each individual is able to apply manipulations only on their own qubit. The quantum space of possibilities in such a case now allows for superpositions of these qubits which do not simply decompose into contributions from each individual's information set. For example, the quantum state $|\psi\rangle = \alpha|00\rangle + \beta|11\rangle$ cannot be decomposed into a product of qubits from each individual. Such states are described as entangled [Orlin Grabbe]. Entanglement is a uniquely quantum mechanical phenomenon central to many interesting applications of quantum computation and information [Nielsen & Chuang, page 11]. Within an entangled state any operation undertaken on one qubit will instantly affect the states of the qubits with which it is entangled [Orlin Grabbe]. As a consequence, while only

formally manipulating their own information, individuals exchanging qubits which have become entangled can alter the informational states of their interlocutors – leading to new and counterintuitive results.

Recently, quantum information exchange has been applied to bargaining situations represented by Games (see [Orlin Grabbe] for an introduction). For complex endeavours characterised by ongoing, dynamic, bargaining between participants with differing agendas and interests, Game Theory provides a natural framework to investigate alternative approaches to achieving mutually beneficial outcomes. Applied in this context, the role of Game Theory is not to provide specific predictions on how particular engagements will play-out. Rather, Game Theory provides a formal means to structure analysis, and make explicit the underlying assumptions of that analysis [Gates & Humes], from which lessons may be drawn for application in the, obviously more complex, situations found in actual operations.

Choice of strategies in Games can be represented as an exchange of information between bargaining participants. By generalising to the exchange of quantum information application can be made of quantum effects, such as entanglement, to aid the development of cooperative outcomes. Extending to real-world operations, insights may be drawn on how the additional degrees of freedom introduced through the use of quantum information can be used to overcome some of the uncertainties inherent in how cooperation will emerge in complex endeavours.

While quantum information exchange holds much promise, it must be acknowledged that the field of quantum computation and quantum information is in its infancy. Efforts to build quantum information processing systems have had limited success to date, with large scale quantum information processing not yet a reality [Nielsen & Chuang, page 4]. Nevertheless, quantum information is being successfully applied to cryptography and may provide a solution to the classical computational limits represented by Moore's law [Nielsen & Chuang, pages 4-5]. Furthermore, it has been shown that the problem of finding the prime factors of an integer can be solved efficiently on a quantum computer [Nielsen & Chuang, pages 6-7], it also being recently demonstrated that networked quantum computers can require exponentially less communication to solve certain problems than if application were made of classical computing networks [Nielsen & Chuang, page 9]. Fundamentally, the promise of a quantum approach to information sharing is to harness technology to improve decision outcomes by enhancing our application of the actual concept of information rather than simply adding greater capacity and more network complexity.

Quantum versus Classical Information Exchange in Bargaining: An Illustrative Example

To illustrate the power introduced into bargaining through the use of quantum information consider first the example of a situation involving two participants where one player has access to the full set of manipulations on quantum information, with the other restricted to the classical domain. Recognising that in complex endeavours some participants may be less than cooperative, application will be made of the 2x2 Game known as the Inspection Game. Investigation of this Game is interesting as, unlike many other examples of quantum players challenging classical players in

Games [Flitney & Abbott], the Inspection Game is not symmetrical and so can yield different outcomes.

In the Inspection Game an Agent works for a Principal. Utilising one advocated approach to the description of endeavours [Hayes, pages 165-166], the Principal may be described as an entity at the "Centre" of the endeavour with goals aligned with that of the operation. On the other hand the Agent may be described as one of the "Cooperating Actors" who share the basic goals but also have other interests.

The following description of the Inspection Game is taken from [Fundenberg & Tirole pages 17-18]. In this Game the Agent can choose to either Shirk or Work, while the Principal can either Inspect or Not Inspect. Working costs the Agent g while Inspection costs the Principal h, although Inspection does provide evidence on whether the Agent is working. Work by the Agent produces output v for the Principal, with the Principal providing a return of value w to the Agent, unless there is evidence that the Agent has Shirked. If caught Shirking the Agent receives 0. For the Game in question it is assumed that $v > w > g > h > 0$. This description of the interaction between the Principal and the Agent is consistent with the characterisation of an endeavour by [Hayes, page 166] where *the Centre* [Principal] *must constantly monitor the Cooperating Actors* [Agent] …, although it may be expected to also apply more broadly to less well defined participants where one actor simply lacks incentive to support the interest of the other. For the simple Game situation employed here the two players choose their strategies simultaneously and play only once.

The Inspection Game is shown in strategic form in Figure 1,

		Principal	
		Not Inspect	Inspect
Agent	Work	***w-g, v-w***	***w-g, v-w-h***
	Shirk	***w , -w***	***0, -h***

Figure 1: Two Player Inspection Game

where the first entry in each element of the matrix corresponds to the payoff for the Agent. As defined, the Inspection Game has no classical pure strategy equilibrium, but does have a Nash equilibrium in mixed strategies. This mixed strategy equilibrium is achieved when the Principal Inspects with probability g/w and the Agent Shirks with probability h/w. Such a strategy may arise when the Principal must interact with numerous Agents so that the mixed strategies are learnt by the participants.

The two possible choices of strategy for the Principal and Agent can be couched in information terms as the communication of a single bit: the transmission of either 0 or 1 by each player corresponding to Not Inspect (0) or Inspect (1) for the Principal, and

Work (0) or Shirk (1) for the Agent. To generate a quantum game classical information carriers, bits, must be generalised to qubits and subsequently mutually entangled [Benjamin & Hayden]. This is achieved by describing the initial state of the system in qubits as $|\psi_{initial}\rangle = |00\rangle$ and then employing an entangling operator $\hat{J}$. Manipulations by the players are then applied, $\hat{P} \otimes \hat{A}$, after which the qubits are disentangled and measurement of the realised state made. The final quantum state can thus be represented as: $|\psi_{final}\rangle = \hat{J}^{+}(\hat{P} \otimes \hat{A})\hat{J}|\psi_{initial}\rangle$. The payoff for the Principal and Agent are then given by the expectation value [Flitney & Abbott]:

$$\langle Payoff \rangle = U_{00}\left|\langle \psi_{final} | 00\rangle\right|^2 + U_{01}\left|\langle \psi_{final} | 01\rangle\right|^2 + U_{10}\left|\langle \psi_{final} | 10\rangle\right|^2 + U_{11}\left|\langle \psi_{final} | 11\rangle\right|^2 \quad (1)$$

where U_{ij} is the payoff for each player associated with the corresponding game outcome, e.g. $U_{00} = w - g$ for the Agent, while $U_{00} = v - w$ for the Principal.

For a 2x2 Game the entangling operator may be written as [Benjamin & Hayden]:

$$\hat{J}(\gamma) = \hat{I}^{\otimes 2}\cos\frac{\gamma}{2} + i\sigma_x^{\otimes 2}\sin\frac{\gamma}{2} \qquad \gamma \in \left[0, \pi/2\right] \quad (2)$$

where $\otimes 2$ means the tensor product of the operator two times, $\hat{I}$ is the identity operator and $i\sigma_x = \begin{pmatrix} 0 & i \\ i & 0 \end{pmatrix}$ is the bit flip operator. That is, representing $|0\rangle$ as $\begin{pmatrix} 1 \\ 0 \end{pmatrix}$ and $|1\rangle$ as $\begin{pmatrix} 0 \\ 1 \end{pmatrix}$ application of the bit flip operator yields: $i\sigma_x|0\rangle = i|1\rangle$ and $i\sigma_x|1\rangle = i|0\rangle$. It follows that:

$$\hat{J}(\gamma)|\psi_{initial}\rangle = \hat{J}(\gamma)|00\rangle = \cos\frac{\gamma}{2}|00\rangle + i\sin\frac{\gamma}{2}|11\rangle \quad (3)$$

Recalling the continuum of states that can be represented by a quantum superposition, $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$, a pure strategy quantum operator acting on the qubits for both the Principal and Agent may be written as [Flitney & Abbott]:

$$\hat{U}(\theta, \phi, \rho) = \begin{pmatrix} e^{i\phi}\cos\frac{\theta}{2} & ie^{i\rho}\sin\frac{\theta}{2} \\ ie^{-i\rho}\sin\frac{\theta}{2} & e^{-i\phi}\cos\frac{\theta}{2} \end{pmatrix} \quad (4)$$

where $\theta \in [0, \pi]$ and $\phi, \rho \in [-\pi, \pi]$. A classical mixed strategy is represented in this formalism by an operator which does not manipulate the phase of the qubit $\tilde{U}(\theta) = \hat{U}(\theta, 0, 0)$.

In the case that both the Principal and the Agent have access to all the available quantum moves, an interesting result from quantum games is that, on the maximally entangled state, any move undertaken by the Agent, $\hat{A} = \hat{U}(\theta, \phi, \rho)$, can be exactly

undone by the Principal by choosing $\widehat{P} = \widehat{U}(\theta, -\phi, \pi/2 - \rho)$. As a consequence, should the Principal know the Agent's move, the Principal can produce any desired final state, and conversely.

To restrict to a classical-quantum Game allow the Principal to retain access to quantum manipulations and restrict the Agent to classical moves. The interest is in determining what advantage the Principal can gain from this access to quantum moves which will assist in dealing with, potentially recalcitrant, Agents.

As has been noted, a quantum playing Principal can exactly undo any manoeuvre by a classical Agent, i.e. the Principal can employ $\widehat{P} = \widehat{U}(\theta, 0, \pi/2)$ against any $\widetilde{A} = \widetilde{U}(\theta)$. This assumes knowledge on the part of the Principal as to what move the Agent will make. Introducing instead some level of ignorance about the Agent's move, the best plan for the Principal is to assume that the Agent will play the average move $\widetilde{A} = \widetilde{U}(\pi/2)$, undoing this move through application of $\widehat{P} = \widehat{U}(\pi/2, 0, \pi/2)$ and then preparing the final desired state. Should the final desired state be $|00\rangle$ no additional operations other than $\widehat{P} = \widehat{U}(\pi/2, 0, \pi/2)$ are required. However, if the final desired state is $|01\rangle$, $|10\rangle$ or $|11\rangle$ additional discrete operations will need to be performed by the Principal on its qubit. Because the qubits of the Agent and Principal are entangled, such manipulations by the Principal also alter the state of the Agent's information [Flitney & Abbott].

For the Inspection Game of Figure 1, the desired final state for the Principal occurs when the Agent Works and No Inspection is required, that is the state $|00\rangle$. As there is only one, mixed, classical Nash equilibrium the specific question becomes: does the Principal playing $\widehat{P} = \widehat{U}(\pi/2, 0, \pi/2)$ at some level of entanglement $\gamma \in \left[0, \pi/2\right]$ improve on its classical outcome when the Agent, playing classically, plays this classical Nash equilibrium strategy? Recalling that in the classical equilibrium the Agent Shirks with probability h/w it follows that in the quantum formalism the Agent will play $\widetilde{A} = \widetilde{U}(2 \arctan \sqrt{h/w - h})$.

To simplify the analysis we introduce specific values for the parameters defining the Inspection Game and set $v = 5$, $w = 3$, $g = 2$ and $h = 1$. The strategic form of the Inspection Game (Figure 1) then becomes (Figure 2):

		Principal	
		Not Inspect	Inspect
Agent	Work	***1, 2***	***1, 1***
	Shirk	***3, -3***	***0, -1***

Figure 2: Two Player Inspection Game with defined payoffs

Applying the quantum formalism of entangling the initial qubit state, performing the classical and quantum manipulations of the Agent and Principal and then disentangling the qubits yields, after some manipulation, the following expected payoffs for the Principal and Agent:

$$\langle Principal \rangle^{Q}_{Payoff} = \frac{5\sqrt{2}}{3}\sin\gamma - \frac{5}{6}\sin^2\gamma + \frac{1}{3} \tag{5}$$

and

$$\langle Agent \rangle^{Q}_{Payoff} = -\frac{2\sqrt{2}}{3}\sin\gamma + \frac{5}{6}\sin^2\gamma + \frac{7}{6} \tag{6}$$

The expected payoffs for the Principal and Agent when both are playing the classical Nash equilibrium strategies are: $\langle Principal \rangle^{C}_{Payoff} = 1/3$ and $\langle Agent \rangle^{C}_{Payoff} = 1$. These results for different levels of entanglement are shown in Figure 3.

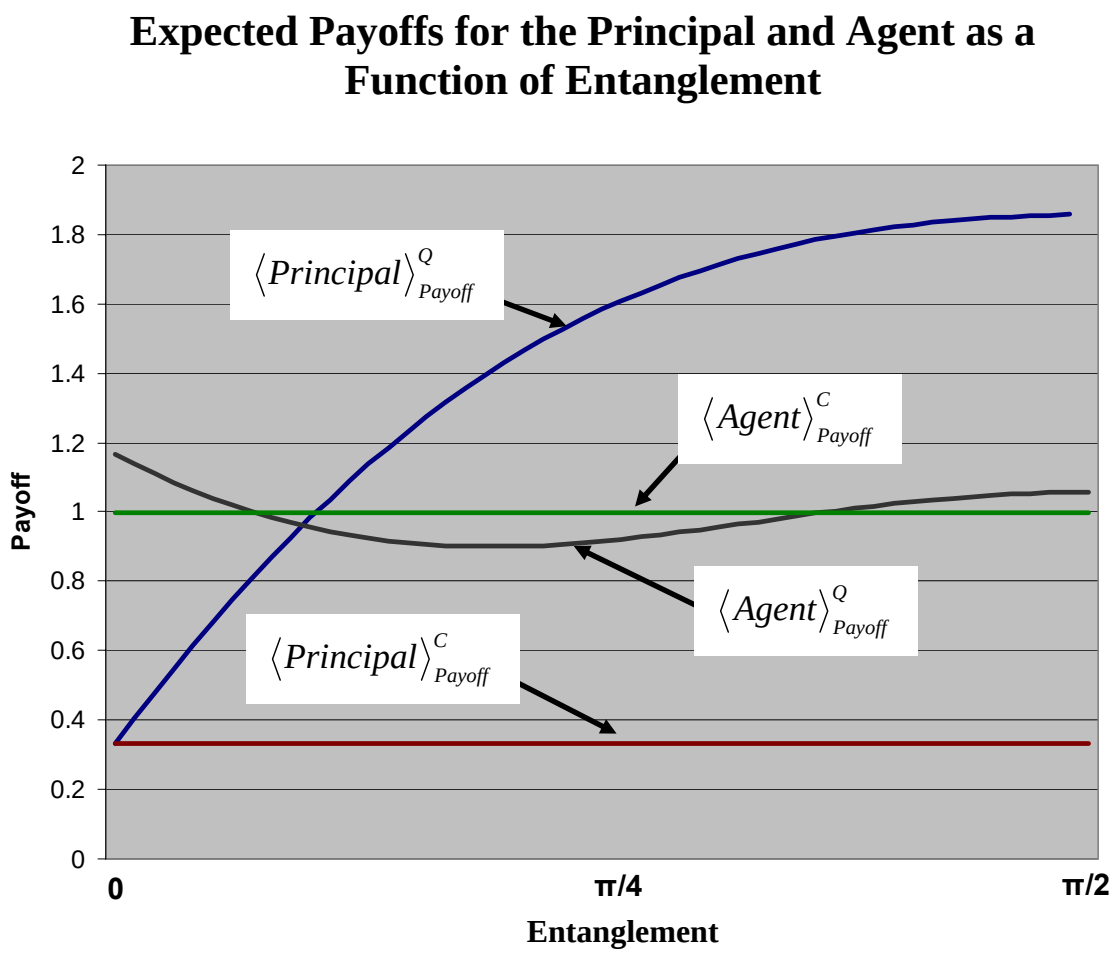

Figure 3: Expected payoffs for the Principal and Agent as a function of entanglement

As can be seen from Figure 3, the expected payoff for the Principal improves with increasing entanglement and is always better than its classical outcome when $\gamma > 0$. The outcome for the Principal approaches, but does not match or better, the mutual cooperation outcome of Work-Not Inspect, however this is to be anticipated as the contributions to this expected result from other states of the Game do not provide sufficient weighting to yield such a payoff. This means that, should the Agent choose always to Work, the Principal should also play classically and choose to Not Inspect – although this is not a classical equilibrium. The outcome for the Agent when playing a quantum player is worse than what would be expected in the classical Game for a range of entanglements but is marginally better for maximal entanglement.

Cooperation and Mutual Quantum Information Exchange

For the Inspection Game the Agent is marginally better off when the Principal uses quantum manoeuvres under maximal entanglement. In this case the Agent would have no incentive to deviate from its classical strategy. However, this precludes the possibility that the Agent could substantially improve its position if it also had access to quantum manoeuvres. More generally, for classical-quantum Games there is likely to be little incentive for the classical player to abide by the outcomes of the bargaining process when the structure of the negotiation is so clearly biased. To be successful a negotiation needs to be underpinned by a notion of fairness, and in bargaining this entails some sense of even-handedness in how participants are engaged. Such an approach is fundamental to engendering trust, an important ingredient if responsibility for planning and execution is to be distributed effectively amongst the participants of a complex endeavour. In considering the application of quantum information to bargaining we must thus turn attention to the case where all players have access to the quantum regime.

For two-player Games it turns out that the ability of a quantum player to undo the move of their opponent undermines the negotiation process. When there are just two qubits *neither player can anticipate what the other will do and there can be no cooperation* [Cho, page 15]. However, if a larger number of players are involved superior equilibria can emerge. This has been investigated for the simple case of static Games by [Benjamin & Hayden], who found that the existence of new cooperative outcomes is strongly dependent on what Game is being played, the number of players involved and whether there exists a high performing dominant strategy in the classical Game. For example, applying the quantum approach to a 3-player version of the Prisoner's Dilemma allows *radically superior equilibria to emerge* [Benjamin & Hayden], whereas applied to a 3-player version of a different Game, the Minority Game, the new equilibria produce outcomes of limited interest.

Where useful new equilibria emerge the outcomes necessarily reflect a new type of cooperation between the players introduced by entanglement. The role of entanglement in quantum games is to *enforce a kind of unavoidable teamwork* [Cho, page 14]. This teamwork does not entail all players choosing the same cooperating strategy, such as all players choosing to not inform on their colleagues in a Prisoner's Dilemma scenario, but instead results in coherent actions which allow escape from dilemmas by providing better options for the players involved. *In this respect quantum entanglement fulfils the role of a contract* [Benjamin & Hayden].

To apply multi-player quantum bargaining to complex endeavours it will be necessary to understand the nature of the negotiation (e.g. is there a classically dominant strategy that players will pursue which makes void any attempt to improve matters using quantum information) and to structure the bargaining process to allow the power of quantum information to yield superior cooperative outcomes. Given that the number of players involved is a determinant of the success of this approach, the structured bargaining process will need to control the number of players interacting at any one time. Such structured bargaining has, in fact, been previously discussed in the context of complex endeavour Command & Control [Hanlon]. There it was shown that classical players arranged on a particular network which limits the number of player interactions can promote cooperative outcomes, particularly if the information structure amongst the players is altered. This was demonstrated, however, in the case of evolutionary rather than static games. Applying to quantum games, players could be similarly arranged onto networks where the order of each node is limited, as shown in an illustrative example limiting interaction to at most two neighbours in Figure 4:

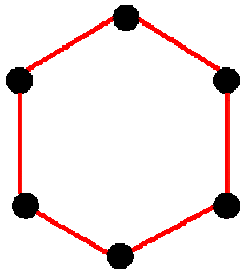

Figure 4: An illustrative arrangement of players (black circles) arranged on a network which limits interactions to at most two neighbours.

If extendable to quantum games, such structured bargaining would be particularly useful in planned negotiations which seek to establish the initial conditions for an endeavour amongst a large number of participants – an important application as *[t]he nature and extent of the collaborations that will take place will be, to a great degree, determined by the initial conditions.* [Alberts & Hayes 2006, page 40]. For ongoing interactions in the field, the constraint on the number of players who can usefully be engaged in a quantum negotiation may provide helpful, objectively based, guidance on how such negotiations should be pursued. The utility of such approaches requires further investigation, but are certainly no more radical than other applications, such as the proposal that stock market traders encode decisions in qubits and utilise entanglement to promote cooperation and avoid crashes [Cho, page 15].

Discussion

The application of quantum information holds the potential to provide radically new approaches to achieving teamwork and cooperation in complex endeavours. While the underpinning technology is still in its early stages of development, early exploration of the possibilities will preposition Command & Control approaches to exploit these new capabilities. Three areas of further research naturally arise from the considerations in this paper:

Evolutionary Quantum Games on Networks

As previously discussed, by exploring the application of quantum games on networks, and generalising to the consideration of evolutionary rather than just static quantum games [Iqbal & Cheon], greater insight will be gained on how quantum information can be exploited. The extension to evolutionary games is important as negotiations proceed as an ongoing dynamic process. Further, it is known that cooperation can arise in evolutionary classical games, an effect which is enhanced on networks which limit player interaction [Ohtsuki, Hauert, Lieberman & Nowak], [Lieberman, Hauert & Nowak]. Extending to quantum games it would be of interest to determine if even greater amplification of cooperation could be achieved.

Complex Games and Alternative Information Structures

The static Inspection Game considered in this paper is a very simple example of a game drawn from a much larger Game Theory literature. Indeed, even the games considered in the evolutionary case are, generally, only simple games. There is considerable scope to investigate the application of quantum theory to more sophisticated games, including games with nontrivial information structures – for example different players having different levels of knowledge about the game situation. This would open the way for more detailed investigations into the possible strategic application of information in negotiation, and in conflict situations more broadly.

Multi-Stage Quantum-Classical Games

Quantum games presume that the players engaged in the game will actually undertake the actions which the game outcomes dictate. However, not being intuitive, there is no guarantee that the equilibrium outcome of the quantum game will survive contact with the actual classical level actions undertaken by the players. A natural extension, therefore, is to consider a multi-stage game where players partake in the quantum game and then, armed with the knowledge of the quantum game outcome, play a classical game which actually dictates their actions. Such an approach is consistent with the idea that if greater realism is to be attributed to Game Theory outcomes then effort must be expended in expanding the description of the Game being analysed.

Arguably, the idea of multi-stage quantum-classical games could be extended further to also include the initial negotiation on whether players wish to engage in quantum based negotiation at all. This could open the door to situations where a quantum player does indeed negotiate with classical players. In such a situation analysis would need to be made of a three stage game: (i) a classical game to determine which players will employ quantum manipulations; (ii) a second quantum game to introduce a quantum level of teamwork and mutually useful outcomes; and (iii) a third classical game where the players choose their actually action.

Further research in these domains will help to clarify the potential role of quantum information in future Command & Control capabilities, as well as point to other possible applications involving information exploitation and strategy development.

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