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Beyond Command and Control: Sense Making under Large World Uncertainty

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A Systems Engineering Approach To Conflict Resolution In Command and Control

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A Systems Engineering Approach To Conflict Resolution In Command and Control

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Abstract

The overall objectives of this article are to put the theory and practice of conflict resolution into proper perspective and to introduce the graph model for conflict resolution as a flexible methodology for systematically studying real-world conflicts which can arise in command and control problems within the military at both the strategic and tactical levels of decision making, international politics, engineering, business and other areas. Specific challenges that were addressed in the development of the graph model are described and it is explained how ideas from computational engineering and elsewhere were used to surmount them. For example, a difficult hurdle to overcome in the design of any decision model is how to obtain preference information. Accordingly, within the graph model paradigm for conflict resolution, a number of flexible procedures have been designed for conveniently eliciting ordinal preference information for each of the decision makers. Other algorithmic and computational difficulties that had to be surmounted included developing techniques for handling very large conflicts, modeling irreversible moves by decision makers and carefully defining stability definitions for mathematically describing a rich range of human behavior that can take place under conditions of conflict. The foregoing and other related developments have been incorporated into the decision support system GMCR II, which permits practitioners, students and researchers to carry out comprehensive strategic studies within a user-friendly windows operating environment.

The Cuban Missile Crisis of 1962 is employed for clearly demonstrating how GMCR II can be effectively used for modeling, analyzing and better understanding actual conflict in order to gain valuable strategic insights.

The Pervasiveness of Conflict

Conflict is a natural occurrence in every arena of human interaction (Wilmot and Hocker 1998). The types of conflict that can arise range from outright warfare among nations to a highly cooperative situation in which, for instance, labor and management work in harmony to assist their company in gaining a greater market share from their competitors in order to prosper and stave off bankruptcy in the face of stiff international competition. Differences of opinion can take place at a local level where a small group of soldiers must specifically decide on tactical ways to combat terrorists lodged in a village without harming local civilians, to debating strategy at a high level of decision making where military generals, in concert with their political leaders, deliberate over strategic approaches and policies for defeating an elusive enemy.

Many conflict problems are highly interconnected with other kinds of troubles, especially for the case of large-scale systems problems. For example, the debate over how to confront global warming and climate change is intertwined with arguments over how to tackle the food crisis, energy scarcity, the growing gap between the rich and poor, sagging industrial output in many regions, expanding populations, widespread pollution and lack of security. This great complexity and close interconnectedness of different kinds of systems, or system of systems, in combination with high risk and deep uncertainty, can lead to unexpected consequences, such as the unanticipated appearance of the ozone hole over Antarctica three decades ago. Fortunately, in this case, society had time to adapt and negotiate the 1987 Montreal Protocol to stop the production and release of CFCs and other associated chemicals that were creating the ozone hole. Luckily, the ozone hole was discovered before the point of no return had been crossed, in which plant and animal life on earth would have been destroyed as a result of large quantities of ultra-violet radiation reaching the earth's surface in the absence of the protective ozone layer (Flannery 2005). Likewise, politicians and military planners are deeply concerned over the effects of climate change (Gore 2006; IPCC 2007; Stern 2006), since more than about a two degrees Celsius increase in average temperature may cause massive reductions of crop production in many regions of the world, which in turn will create hundreds of millions of climate refugees who will stream into countries less affected by climate change. This, of course, constitutes a large-scale security and military problem having unforeseen emerging consequences and the potential for devastating 'climate wars' breaking out around the globe (Dyer 2008).

As a result of the foregoing and other reasons, a participatory, integrative and adaptive approach to governance is needed within an overall system of systems engineering perspective to tackle complex problems facing society now and in the future. Hipel and Fang (2005) argue that multiple participant-multiple objective decision making is a key characteristic of most types of systems, or system of systems, whether they be societal, environmental, intelligent or integrated systems, and that ethics should always be taken into account in the design, implementation and management of any system. Therefore, the development of formal methodologies and associated techniques for use in addressing complex decision problems in multi-agents systems presents a great challenge to the field of systems engineering (Sage 1992) and other related domains. As an expansion of earlier work by Maier (1998), Sage and Cuppan (2001), and others, Sage and Biemer (2007) describe seven characteristics that a system of systems may possess: operational independence of each individual system, managerial independence of an individual system, an often large geographical distribution of individual systems, emergent behavior, evolutionary development, self-organization, and adaptation. Additionally, a wide variety of interesting articles on system of systems engineering is provided by Jamshidi (2009). Descriptions of participatory, integrative and adaptive governance within a system of systems structure of governance are now available (for articles on this topic in which the importance of value systems and conflict resolution are stressed, see Hipel and Fang (2005), and Hipel et al. (2007, 2008a,b, 2009a,b, 2010a), as well as references contained therein). To meet the changing needs of the 21st century, Hipel et al. (2007) state that systems engineering methods must be refined and expanded: "from a system to a system of systems vision, from a disciplinary to a multidisciplinary outlook, from a mass production to a mass customization focus, from a steady state to a real-time perspective, and from an optimal to an adaptive approach." From a military command and control (C2) viewpoint, Alberts (2007) stresses that operations must be adaptive and agile in order to cope with increasingly complex operations, such as peacekeeping undertakings, humanitarian assistance, counterterrorism activities, information warfare, as well as responses to natural, technological, health-related and human-induced disasters. He also puts forward three core C2 concepts for complex operations: agility to allow organizations to tackle complexity and uncertainty; focus to furnish an overall decision context and define the goals and objectives of the military operation; and convergence to provide the goal-seeking process for directing strategies and results.

Conflict resolution is central to the paradigm of effective governance within a system of systems perspective, as well as the related idea of the C2 core concepts. Indeed, because controversies and differences of opinion are so pervasive within the realm of human decision making, there is a great need for having flexible decision technologies to assist in the modeling, analyzing, understanding and management of strategic conflict. Accordingly, the main objective of this article is to present an overview of a particularly flexible and realistic game theoretic methodology called the graph model for conflict resolution (Kilgour et al. 1987; Fang et al. 1993) as a comprehensive systems engineering approach for rigorously studying actual conflict. In the next section, formal techniques from the field of game theory are put into perspective by categorizing game theoretic methods according to qualitative and quantitative techniques. A decision support system, called GMCR II (Hipel et al. 1997, 2001, 2008a; Fang et al. 2003a,b), is then described for permitting researchers and practitioners to apply the graph model for conflict resolution to actual disputes. Subsequently, an intriguing international political confrontation – the Cuban Missile Crisis of 1962 – is employed as a real-world example for illustrating how the decision support system GMCR II permits the graph model methodology to be conveniently and expeditiously applied in practice. The strategic impact of Premier Khrushchev's underestimation of the determination of President Kennedy of the United States of America to stop the installation of Soviet missiles in Cuba is taken into account in a hypergame analysis. In fact, as a result of the decisive and wise leadership exercised by President John F. Kennedy during this very serious conflict, which had the potential to escalate into thermonuclear war between the two super powers, President Kennedy is worthy of being ranked as one of the truly great leaders of modern history. New advances in the graph model methodology are outlined for handling strength of preference and uncertain preferences as well as psychological factors such as emotions and attitudes.

Game Theory in Perspective

Because conflict exists in almost every domain of human endeavor, research on conflict resolution has been carried out in a wide variety of disciplines, including psychology, sociology, business, economics, operations research, and systems engineering. Articles on conflict resolution from a wide range of fields are contained in two volumes edited by Hipel (2009a,b) and a handbook edited by Kilgour and Eden (2010). Of particular interest are formal approaches to investigating conflict and its resolution, which have been largely developed in fields such as operations research, systems engineering and game theory. Based on an illustration originally presented by Hipel and Fang (2005), Figure 1 displays the genealogy of formal mathematical methods for modeling and analyzing conflict founded upon various underlying assumptions. As can be seen, the terminology of game theory is employed to stand for the set of formal techniques for investigating conflict in which the methods are classified according to non-quantitative and quantitative techniques. The methods listed in the left column are classified as being non-quantitative approaches since they only assume relative preference information in which a decision maker (DM) prefers one state or scenario in a dispute over another or equally prefers the two states—the DM does not have to know exactly by how much one state is preferred over another. Techniques falling under the right column generally assume cardinal preference information, such as cardinal utility values. Because real numbers are used for modeling preferences for a DM, these techniques are labeled as being quantitative. Nonetheless, it should be stressed that all the methods listed in both the columns in Figure 1 constitute formal mathematical models. In addition to being axiomatic, the techniques in the left column are also qualitative and, hence, these methods are especially suitable for formally investigating social conflicts because of their inherent non-quantitative nature.

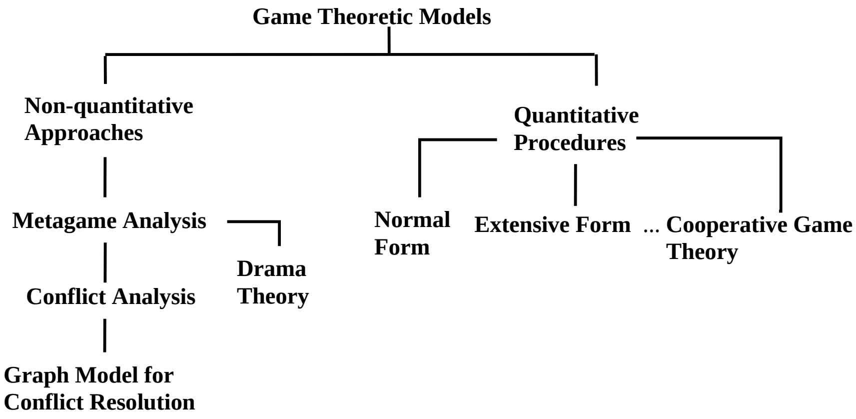

Figure 1. Genealogy of Game Theoretic Models

The quantitative methods listed in the right branch in Figure 1 were proposed by Von Neumann and Morgenstern in their seminal book entitled the "Theory of Games and Economic Behavior," which was published in 1944. Three popular model types are the normal and extensive forms, as well as cooperative game theory. A normal form model considers two or more players or DMs who interact only once – before the game starts, each DM has decided exactly how he or she will respond to every situation that could occur after the game begins. For the case of two DMs, a normal form game can be conveniently represented as a matrix, in which one DM controls his or her strategies given as rows, while the other DM is in charge of the column strategies. In extensive form, a tree-like structure is utilized to record the possible moves and counter-moves among the DMs. Extensive form models have been used for investigating compliance to environmental laws and regulations in environmental management (see, for instance, Hipel and Fang (1994) and Fang et al. [1997]) and adherence to treaties involving nonproliferation of nuclear weapons. Cooperative game theory models are employed to examine the interaction of individuals who must cooperatively decide on how to fairly divide a "pie" or some resource in an equitable manner. These models are often used to analyze coalition formation, voting systems and optimal resource allocation problems. For example, Wang et al. (2007a,b, 2008a,b) utilize ideas from cooperative game theory, economics and hydrology in an overall optimization model to fairly allocate water resources among competing users in a river basin. Similar models could be developed for fairly allocating resources and assignments within a military organization.

The left branch of Figure 1 contains non-quantitative conflict analysis techniques, in which only relative preference information is utilized. In 1971, Howard developed metagame analysis to make conflict models more realistic and intuitive by employing relative preferences in place of cardinal payoffs. To model human behavior for the purpose of determining stable states, Howard introduced the stability definitions called general metarational (GMR) and symmetric metarational (SMR) stability. Both GMR and SMR stabilities assume that opposing DMs may invoke countermoves to block an opponent's potential improvements without considering their own personal risk. For recording a conflict model, Howard devised a flexible notation called option form, which is utilized later in this article.

As shown in the left branch in Figure 1, metagame analysis was further developed in two directions. Howard himself developed drama theory, a methodology that structures conflicts as a three-act play, complete with a problem introduction (Act I), climax (Act II) and resolution (Act III) (Howard 1994a,b), in which dilemmas are successively resolved as the play evolves. Howard purposefully wrote his 1999 book, *Confrontation Analysis,* on drama theory for employment in military applications and elsewhere. Finally, Bryant (2003) furnishes a good description of drama theory, while Levy et al. (2009a,b) provide an explanation of recent advances in drama theory. As explained by Obeidi and Hipel (2005), drama theory and the graph model for conflict resolution provide complementary ways to investigate conflict, and the graph model can be employed to analyze a conflict at a particular phase in a drama.

The second line of methodologies springing from metagame analysis is conflict analysis (Fraser and Hipel 1979, 1984). Besides using the option form of the game for recording a conflict model, Fraser and Hipel (1979, 1984) introduced the tableau form for conveniently displaying a conflict model and calculating stability. Additionally, they introduced the new stability definitions of simultaneous and sequential stability (SEQ). Simultaneous stability examines the strategic impact of two or more DMs moving at the same time from a given starting state. In some cases, such a combination of moves can take the conflict to a new unexpected outcome. In sequential stability, all of the DMs are assumed to make "credible moves" and, hence, will not compromise their own interests when blocking another DM's improvements. Kilgour et al. (1987) and Fang et al. (1993) significantly expanded conflict analysis in their development of the graph model for conflict resolution, which combines elements of graph theory with a rich range of potential dynamic patterns of human behavior under conflict. Movement under the control of a given DM is naturally visualized as a graph, in which nodes represent states and arcs with arrows indicate unilateral movements. The many advantages of utilizing this comprehensive and flexible approach to systematically investigating conflict are illustrated later with the Cuban Missile Crisis application. However, to be able to conveniently and expeditiously apply the graph model methodology to an actual application, one requires a decision support system (Sage 1991; Hipel et al. 2008a).

Decision Support System for Conflict Resolution

The design of a decision support system for the graph model for conflict resolution, which is referred to as GMCR II, is displayed in Figure 2 (Hipel et al. 1997, 2001, 2008a; Fang et al. 2003a,b). Via the User Interface, an analyst can interact with the modeling subsystem, analysis engine and output interpretation subsystem when studying a given dispute. A conflict model is developed in terms of DMs and the options or courses of action controlled by each DM, within the modeling subsystem. By taking into account the combination of ways in which DMs can separately select their options, GMCR II can automatically determine the scenarios or states that could take place. States that cannot possibly occur in reality are removed from the conflict model in order to end up with the set of feasible states. Finally, a very important modeling step is to obtain the relative preferences of each DM with respect to the set of feasible states. With the application, an approach called option prioritization is employed to conveniently obtain preference information for a particular DM, expressed in terms of option selections by DMs. Ascertaining the relative preferences of DMs constitutes a crucial step in the calibration of a conflict model.

Subsequent to model calibration, a user can instruct the analysis engine to carry out a stability analysis and thereby ascertain the possible equilibria or compromise resolutions to the conflict, which will then appear as part of the output. A particular state is deemed to be stable for a specific DM if it is not advantageous for the DM to move to another state. For instance, a DM may be able to move on his or her own to a more preferred state by changing his or her option selections or strategy. Nonetheless, if the other DMs can invoke counter-moves that place the original DM in a less preferred situation, she is better off to remain at the initial state which is deemed to be stable. Since DMs may behave differently in conflict situations, a range of stability definitions have been formulated to define different patterns of moves and counter-moves under which these stabilities can occur. Some of these stability definitions were referred to in the previous section and are used later with the Cuban Missile Crisis application, where they are characterized and explained in Table 2.

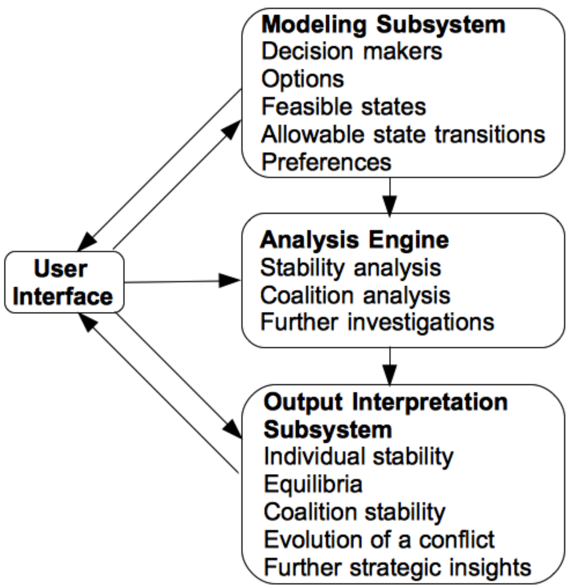

Figure 2. The Decision Support System GMCR II for Conflict Resolution

A sensible approach to follow when carrying out a conflict study is to first ascertain how well a given DM can perform on his or her own by acting independently. Subsequently, one can determine if the DM can do even better by cooperating with others by joining a coalition in which all members of the coalition benefit when joint actions are taken (Kilgour et al. 2001; Inohara and Hipel 2008a,b).

As written in the output interpretation subsystem box in Figure 2, one can also investigate the dynamic evolution of a conflict over time from a given starting state to an attractive equilibrium (Li et al. 2004b, 2005b). In some situations, it may not be possible to reach a desirable situation unless one cooperates with others via a coalition. In fact, one can employ a decision support system in an iterative fashion. By executing basic analyses and interpreting the results, one can gain a better understanding of the conflict and thereby make meaningful changes to the conflict model in the modeling subsystem and subsequently execute further analyses. Additional types of investigations that could be carried out are explained subsequent to the application under the section on future challenges.

The general graph model methodology depicted in Figure 2 can be used in the following three main types of situations:

- *Analysis and simulation tool for a DM in a conflict, or a DM's agent.* An analyst, for example, may advise the American government about strategic initiatives to implement in Afghanistan over time. GMCR II could be used as a decision aid to update results as the situation changes.

- *Communication and analysis tool in mediation.* GMCR II can be utilized by a mediator to assess the possible strategic consequences of DMs making small changes in their positions in order to attain a win/win resolution.

- *Analysis tool for a third-party analyst.* The American government may wish to determine the strategic effectiveness of Chinese policy in Tibet, even though the USA is not directly involved.

The graph model for conflict resolution constitutes a unique systems engineering approach for systematically studying a rich range of disputes arising in many different areas. Documented case studies are available in the published literature regarding the application of the graph model methodology to real-world conflicts occurring in a range of different fields, including aquaculture (Noakes et al. 2003, 2005), brownfields (polluted industrial or military land) (Hipel et al. 2010b; Yousefi et al. 2010a,b; Bernath Walker et al. 2010), bulk water exports (Obeidi et al. 2002; Hipel et al. 2008b), construction management (Kassab et al. 2010; Yousefi et al. 2010c), First Nations (Obeidi et al. 2006), international trade (Hipel et al. 2001), military and peace support (Kilgour et al. 1998), sustainable development (Ghanbarpour and Hipel 2009; Hipel and Bernath Walker 2011; Hipel and Obeidi 2005), and water resources management (Hipel 1992; Hipel et al. 1993; Hipel and McLeod 1994; Gopalakrishnan et al. 2005; Nandalal and Hipel 2007; Madani and Hipel 2011). This flexible methodology is now applied to the Cuban Missile Crisis in order to demonstrate how easy it is to apply this well-designed decision technology in practice and to point out the many benefits that can be garnered.

The Cuban Missile Crisis

Even though Cuba is located a mere 150 km off the American mainland, Premier Castro possessed the resilience and charisma to single-handedly rule his totalitarian communist state for more than five decades. From the cessation of the Spanish American War in 1898 until 1957, Cuba had been under the economic and political control of the United States. The corrupt government of Fulgencio Batista was subservient to US interests and many American companies possessed substantial investments in agriculture and tourism. In late 1956, a revolution to overthrow the Batista regime was initiated by Fidel Castro, an educated middle class socialist. The conquest of Cuba by Castro in 1959 resulted in the nationalization of all American property in Cuba and, hence, the Americans still have in place a trade embargo of Cuba. Following the revolution, Castro established close political, military and economic relationships with the Union of the Soviet Socialist Republics (USSR), America's mighty adversary during the infamous Cold War that emerged from the ashes of World War II and lasted until November 9, 1989, when the Berlin Wall was breached.

The United States was appalled by the confiscation of American property in Cuba and the perception of a communist military threat so close to home. This culminated in the ill-advised American-sponsored Bay of Pigs invasion in April 1961, in which Cuban exiles attempted to gain a foothold in Cuba. However, the invaders were quickly routed because of poor intelligence, the lack of proper military support after the landing and also the superior military tactics exercised by Castro's highly motivated troops. In fact, President Kennedy denied the invaders adequate military support after the initiation of the invasion because the Soviet Union had previously declared its willingness to aid Cuba in defending itself against the United States by furnishing military aid, including missiles. Nonetheless, after the Bay of Pigs fiasco, Kennedy publicly committed his administration never to tolerate offensive missiles in Cuba (Allison 1971).

On October 14, 1962, American aerial reconnaissance discovered irrefutable evidence of Soviet offensive missiles being installed at various sites in Cuba. In order to obtain sage advice on a plan of action from as many reliable and relevant sources as possible, President Kennedy wisely created the Executive Committee of the National Security Council. This committee included major cabinet and government agency officers with principal responsibilities for political and military decisions, representatives of major segments of the public, and some special advisors. The Executive Committee formulated a number of possible actions in response to the Soviet threat, including taking no aggressive action, executing surgical air strikes against the missile bases in Cuba, and imposing a naval blockade of Cuba by turning back all ships carrying military supplies to Cuba (Able 1969; Allison 1971).

Premier Nikita Khrushchev, the leader of USSR, had to decide whether or not to withdraw the Soviet missiles from Cuba. He could also escalate the conflict through coercive actions, such as putting pressure on West Berlin, attacking US naval vessels, bombing Southeastern American targets from Cuba or initiating an ICBM (Intercontinental Ballistic Missile) assault on the US.

The Cuban Missile Crisis was the closest the world has ever come to a nuclear apocalypse. There were several occurrences during the time of this crisis that could have easily triggered a nuclear exchange between the US and USSR, such as the downing of a U-2 spy plane over eastern Cuba and the US Navy's assault on a nuclear-armed Soviet submarine (Dobbs 2008). Moreover, Kennedy's military advisors vehemently urged him to take military action. General LeMay, for instance, argued that war with USSR was inevitable and there was therefore no other option than to carry out a military engagement in Cuba (Blight and Lang 2007). In 1992, a conference on the Cuban Missile Crisis was held in Cuba and was attended by American, Russian and Cuban officials who had participated in the crisis. American officials were utterly stunned by the admission of Russian officials that 162 nuclear warheads (including 90 tactical warheads) had been placed in Cuba and that Russian soldiers stationed there had been given authorization by Khrushchev to deploy these weapons in the event of an American invasion of the island (Rodriguez 2010).

Because of the wise restraint exercised by the heads of both superpowers, the Cuban Missile Crisis did not result in nuclear winter. Rather, the US adopted a strategy of blockading military shipments to Cuba, and the USSR withdrew the offensive missiles. To this day, the Americans have kept their promise not to carry out a military invasion of Cuba. In the next two sections, the Cuban Missile Crisis is modeled and analyzed for the first time using GMCR II in order to explain many of the key assumptions, concepts and algorithms underlying the graph model for conflict resolution, as well as to highlight the effectiveness of its design for realistically and systematically studying real-world conflict and procuring valuable strategic insights.

Modeling: Putting the Cuban Conflict into Perspective

The main components of a graph model are listed under the modeling subsystem in the top-right box in Figure 2. A graph model is now constructed for the Cuban Missile Crisis in the upcoming subsections.

Decision Makers and Options

The left hand side of Figure 3 lists each of the two main DMs in the Cuban Missile Crisis, as well as the options or specific powers under the control of each participant. Notice that the US controls the options of executing a surgical air strike (written as Air Strike in Figure 3), as well as implementing a naval blockade of Cuba to prevent further missiles from being shipped to Cuba by the USSR (Blockade). The USSR had the power to withdraw its missiles from Cuba (Withdraw) or escalate the conflict (Escalate). Cuba is not included as a DM in this model since it possessed no real power to exercise over the USSR or the US. The DMs and options shown in Figure 3 are the same as those put forward by Fraser and Hipel (1984, Ch.1) who analyzed this dispute using conflict analysis.

The three columns of Y's and N's given in Figure 3 represent three possible states, written in option form, that could occur in the Cuban Missile Crisis. A "Y" indicates "yes," the option opposite the Y is selected by the DM controlling it, while "N" means "no," the option is not taken. Consider for example, state number 7, which is shown on the far right in Figure 3 and represents the equilibrium or resolution to the Cuban controversy. At state 7, the US has followed the strategy of not performing an air strike and selecting the option of blockading Cuba. The USSR had chosen the strategy of withdrawing its missiles and not escalating the conflict. The strategy selections of both DMs combine to form the overall state numbered as 7. The reader should keep in mind that a number assigned to a particular state, such as state 7, is for reference purposes only – the state could have also been labeled using a letter or brief verbal description.

Reading from left to right, Figure 3 traces the evolution of the Cuban Missile Crisis from the status quo state through an intermediate state to the final equilibrium. The arrows indicate the option changes that take place to cause the game to progress from one state to another. Starting at state 1, in which both DMs have selected none of their options, the US can cause a unilateral movement from state 1 to 3 by implementing a naval blockade. Subsequently, the USSR controls the unilateral change from state 3 to 7 when it decides to withdraw its missiles from Cuba. Equilibrium state 7 is what occurred historically and the way in which the stability of this equilibrium is determined is outlined in the analysis section.

Decision Makers And Options	Status Quo State	Intermediate State	Equilibrium State
US			
1. Air strike	N	N	N
2. Blockade	N →	Y	Y
USSR			
3. Withdraw	N	N →	Y
4. Escalate	N	N	N
State Number	1	3	7

Figure 3. Decision Makers and Options in the Cuban Missile Crisis, as well as the Evolution of the Conflict from the Status Quo through an Intermediate State to the Final Resolution

Challenge # 1 – Recording Conflicts: The conflict model displayed in Figure 3 contains two DMs, each of whom has two options. Theoretically, this option form can record any finite number of DMs, each of whom can have any finite number of options. Additionally, a given DM may represent an individual person, a small group of people, a large organization or even a country, which is the case for both DMs in the Cuban conflict. Surprisingly, the decision technology described in the article appears to work equally well for any combination of different types of DMs. This is in sharp contrast to fields such as physics and hydrology where the kinds of models employed can vary radically according to the scale or size of the problem being studied. Moreover, although each option in a conflict model represents a binary choice, since it can be either taken or not, a sensible procedure can be adhered to when one desires to represent a continuum of values or levels for an action. For instance, the escalation of the Cuban Missile Crisis by the USSR could be given as a list of separate options reflecting a number of specific actions that the USSR could adopt. However, for the purpose of the study presented herein, any coercive action by the USSR would represent an escalation of the dispute and this can be most parsimoniously given as one overall option.

Feasible States

The decision support system GMCR II allows a user to conveniently enter into the computer the DMs and options, which are listed in the left column in Figure 3 for the case of the Cuban Missile Crisis. Because an option can either be selected or rejected, a conflict having k options contains a total of 2^k mathematically possible states. Hence, a dispute such as the Cuban conflict possess 2^4 or 16 possible states, while a conflict having a total of 20 options across all of the DMs has more than one million possible states! Clearly, one is heading directly into a "combinatorial brick wall," which, fortunately, can be cleverly scaled.

Challenge # 2 – Handling a Large Number of States: No matter how many states are included in a game model, the reader should keep in mind that they are all automatically generated by GMCR II. Because GMCR II possesses an effective design for its data structure and is programmed using C++, it is purposely built for handling small, medium and large conflicts. More particularly, a 32-bit DOUBLEWORD is utilized to represent the specific option selection defining a state wherein each digit or bit equals 1 or 0 to indicate whether or

> not the option it represents is taken or not, respectively. Since there are 32 bits, this design can accommodate up to 32 options, which is more than abundant for real-world applications. In addition, one can greatly reduce the number of feasible states to be considered by eliminating infeasible states which could not possibly occur and combining states which are essentially the same. Efficient algorithms for achieving the foregoing are encoded within the user interface program for GMCR II (Hipel et al. 1997, 2001; Fang et al. 2003a,b).

Figure 4 shows GMCR II's dialog box for specifying infeasible states using one or more of four specific procedures which are described in detail elsewhere (Hipel et al. 1997; Fang et al. 2003a,b). For the case of the Cuban conflict, the user has indicated in Figure 4 that he or she would like to remove states that are infeasible on account of mutually exclusive options. Because it is not realistic for the USSR to withdraw its missiles and escalate the conflict at the same time, the third and fourth options are checked as being mutually exclusive in the dialog box displayed in Figure 5. Finally, Figure 6 shows the twelve feasible states that remain in the Cuban conflict after GMCR II removes the four infeasible ones. In practice, it has been found that a fairly high percentage of infeasible states are eliminated, especially for larger games. For instance, after removing infeasible states from a twenty-option model describing an international trading conflict, about 185,000 feasible states were left from a possible million states (Hipel et al. 2008a).

Allowable State Transitions

For any feasible state, a particular DM may be able to unilaterally cause a transition from one state to another state by changing his or her option selection. For example, in Figure 3, the US controls the unilateral move from state 1 to 3, while the USSR causes the state transition from state 3 to 7. GMCR II automatically calculates all possible state transitions, if present, from each state for each DM.

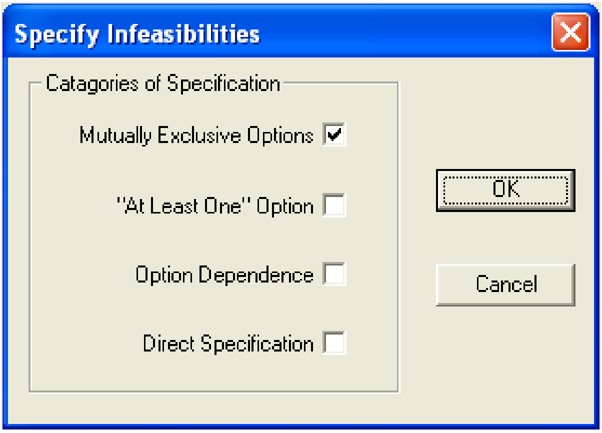

Figure 4. Selection of Procedure(s) for Specifying Infeasible States

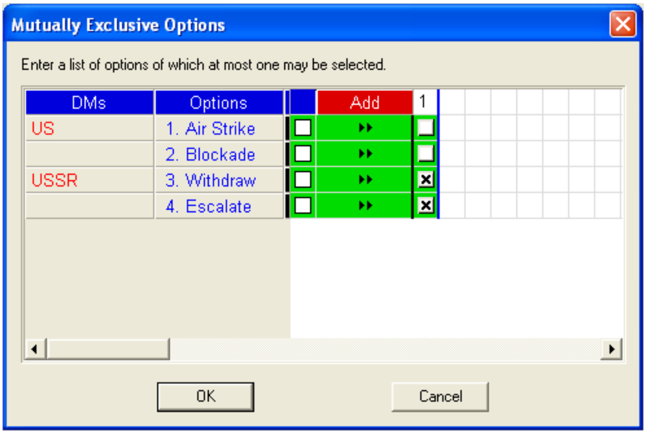

Figure 5. Mutually Exclusive Options in the Cuban Missile Crisis

DMs	Options	1	2	3	4	5	6	7	8	9	10	11	12
US	1. Air Strike	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y
	2. Blockade	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y
USSR	3. Withdraw	N	N	N	N	Y	Y	Y	Y	N	N	N	N
	4. Escalate	N	N	N	N	N	N	N	N	Y	Y	Y	Y

Figure 6. Feasible States in the Model of the Cuban Missile Crisis

Challenge # 3 – Keeping Track of Irreversible Moves: As can be seen in Figure 6, the US unilaterally controls the state transition from state 1 to 2 by executing a surgical air strike of the missile bases in Cuba. However, after the missile sites are bombed, the damage is inflicted and the Americans cannot move back to state 1 from state 2. Hence, the transition from state 1 to state 2 is irreversible and one would like to have a model that can take this into account. From a theoretical viewpoint, the graph model for conflict resolution contains a finite directed graph for each DM, in which the vertices represent the feasible states and the state transitions are the arcs on the graph connecting the vertices. Allowable state transitions in both directions between two states are indicated by two arrowheads pointing in opposite directions, whereas an irreversible move is marked using a single arrowhead. From an implementation perspective, GMCR II uses what is called a reachable list to keep track of the set of allowable state transitions for a given feasible state and DM. Unless it is not specified by the user, the program assumes that feasible unilateral movement can take place in both directions between two states for a given DM. Figure 7 explains how a user can specify irreversible moves brought about by the US executing an air strike.

Relative Preferences

Challenge # 4 – Preference Elicitation: Usually, the most difficult hurdle to overcome in calibrating a decision model is to obtain accurate preference information. A noteworthy advantage of GMCR II is that it requires only relative preference information among states for each DM. Additionally, a flexible set of tools is available for conveniently entering this preference information into the computerized system. Therefore, for a given DM, the analyst only needs to specify whether one state is more preferred than another, less preferred, or equally preferred and there is no requirement to estimate the "magnitude" of this preference. Hence, the problem of obtaining cardinal preference information, such as utility values, is avoided. Stated differently, the user of GMCR II has to somehow enter a ranking of states from most to least preferred for each DM, where some states may be equally preferred. The possibility of preference ties permits stability analyses even when the analyst lacks some preference information. In practice, this means that one can start with a "quick and dirty" analysis and subsequently refine preferences as more information becomes available. Although GMCR II assumes that the preferences for each DM are ordinal, and thus transitive, theoretically, the graph model for conflict resolution can handle a broader variety of preference types, including intransitivity (Fang et al. 1993, Ch. 8). Finally, the option prioritizing approach to obtaining relative preference information for each DM explained in this section accurately reflects the manner in which a person may contemplate his or her values or preferences in a specific conflict situation.

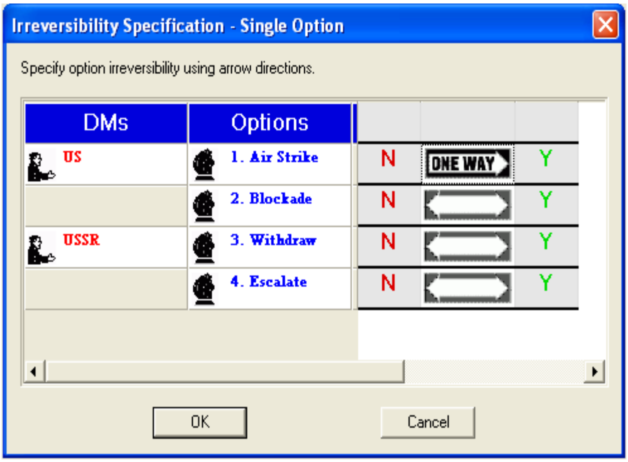

Figure 7. Specifying Irreversible Moves in the Cuban Missile Crisis

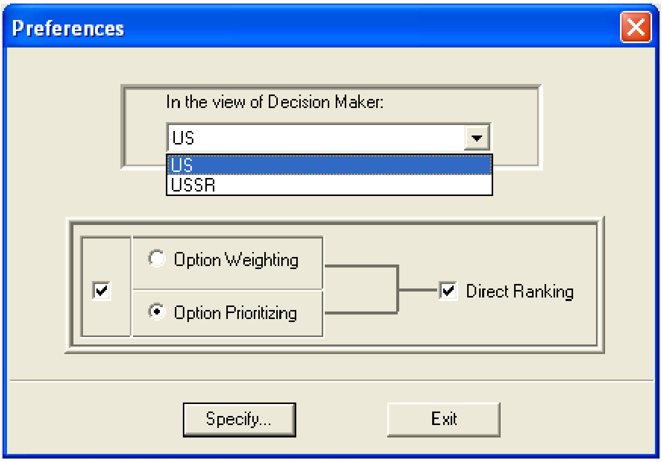

Figure 8. Obtaining Relative Preference Information for the US in the Cuban Missile Crisis

To avoid pairwise comparisons of states when obtaining relative preferences in moderate and large-size conflicts, GMCR II has two approaches to procuring at least an approximate ranking of states.

Subsequently, GMCR II enables the user to fine-tune the initial state ranking, if needed. Figure 8 summarizes the main steps to be followed as GMCR II obtains relative preference information for a particular DM. Because the US is highlighted, preferences will be entered for this DM. One can obtain a ranking of states using preference information expressed in terms of the options using either the Option Weighting or Option Prioritizing approach. Either of these procedures is ideal for entering preferences in larger models, but can in fact be employed with a dispute of any size. The Direct Ranking feature can be used to fine-tune, if required, a ranking initially obtained using Option Weighting or Option Prioritizing. Moreover, if desired, one can go directly to Direct Ranking and arrange the states in order on the screen. In Figure 8, the current status of the check box and radio boxes on the left indicates that the user has decided to use Option Prioritizing to first rank the states using preference information about options. The fact that the right check box is selected means that, if required, the user may fine-tune the initial ranking using Direct Ranking as the next step.

When employing Option Weighting, one simply assigns a numerical weight to each option for a particular DM. The greater the weight, the more preferred the option. Negative weights indicate options that the DM prefers not be selected. For a specified state, the weights are summed across the options and subsequently GMCR II ranks the states from most to least preferred, where ties are allowed. One should bear in mind that the magnitude of the weights is not meaningful and is used only to indicate relative preferences.

The Option Prioritizing approach in GMCR II constitutes a generalization of the “preference tree” method originally proposed by Fraser and Hipel (1988) and later expanded upon by Peng et al. (1997) and Fang et al. (2003a). Figure 9 demonstrates how Option Prioritizing is used in GMCR II, while Figure 10 shows how GMCR II ranks the states from most preferred on the left to least preferred on the right using only the preference information listed on the right in Figure 9. Essentially, this approach ranks states according to the truth or falsity of logical statements about option selections. In Figure 9, the importance of a preference statement is indicated by its position, with more important statements appearing higher in the list. The numbers in Figure 9 refer to specific options which are numbered on the left. A negative sign to the left of an option indicates that the option is not taken. The 3 entered at the top of the list of preference statements on the right side of Figure 9 means that the US most prefers that the USSR withdraws its missiles from Cuba by selecting option 3. Notice that the four states containing a Y opposite option 3 are listed on the far left in Figure 10, since they are more preferred than the eight states having an N beside option 3. Next, the Americans prefer that option 4 not be taken as indicated by the -4 typed below the 3 on the right in Figure 9. This preference statement causes states having an N opposite option 4 to be placed to the left of those with a Y beside option 4 in Figure 10, while still maintaining the hierarchical importance of the preference of option 3 given above -4 in Figure 9. The third level preference statement written as "-1 if 3" means that the US prefers that option 1 be rejected (-1) if option 3 is taken. This explains, for example, why states 5 and 7 are preferred to states 6 and 8 in Figure 10. In fact, the preference statements on the right in Figure 9 are based upon first order logic and each preference statement takes on a truth value of being either true or false. Even though the preference statements are written in terms of option numbers, they do in reality reflect the way one may verbally express preferences in an actual conflict situation. Consider, for example, the seventh preference statement from the top in Figure 9, which is written as 1|2 if -3 and -4. This simply means that the US prefers carrying out an air strike (1) or blockade (2) if the USSR does not withdraw its missiles (-3) and does not escalate (-4). The right side of Table 1 provides an explanation for the preference statements listed hierarchically on the right in Figure 9 and on the left in Table 1. By carefully examining the hierarchical list of preference statements in Figure 9 and Table 1, one can appreciate how the algorithm in GMCR II lexicographically ranks the states as shown in Figure 10. No additional fine-tuning is required to obtain this ordering of states, which contains no sets of equally preferred states, and hence, is strictly ordinal.

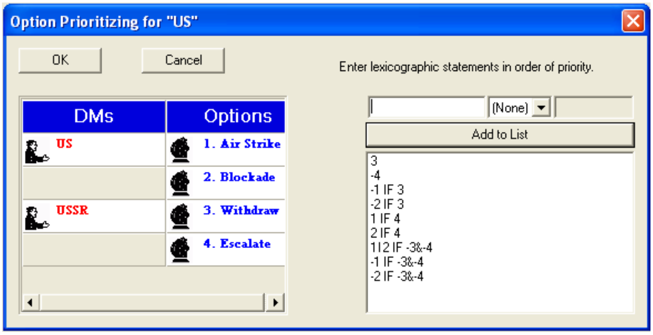

Figure 9. Option Prioritizing for the US in the Cuban Missile Crisis

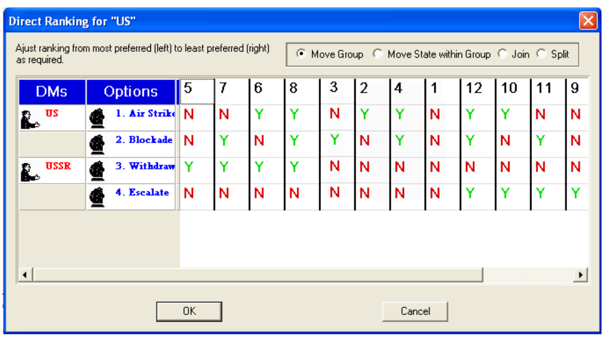

Figure 10. Ranking of States using Option Prioritizing for the US in the Cuban Missile Crisis

Table 1. Option Prioritizing for the US in the Cuban Missile Crisis

Preference Statements	Explanation
3	The US most prefers that the USSR withdraws its missiles from Cuba (takes option 3)
-4	The US next prefers that the USSR does not escalate (-4)
-1 if 3	The US then prefers not to have an air strike (-1) if the USSR withdraws its missiles (3)
-2 if 3	The US next prefers not to carry out a blockade (-2) if the USSR withdraws its missiles (3)
1 if 4	The US then prefers to have an air strike (1) if the USSR escalates (4)
2 if 4	The US next prefers to carry out a blockade (2) if the USSR escalates (4)
1|2 if -3&-4	The US then prefers carrying out an air strike (1) or blockade (2) if the USSR does not withdraw its missiles (-3) and does not escalate (-4)
-1 if -3&-4	The US next prefers not to have an air strike (-1) if the USSR does not withdraw its missiles (-3) and does not escalate (-4)
-2 if -3&-4	The US then prefers not to carry out a blockade (-2) if the USSR does not withdraw its missiles (-3) and does not escalate (-4)

The hierarchical list of preference statements written horizontally for the USSR is -4, 1 if 4, 2 if 4, -1 if -4, -2 if -4, 3 iff (if and only if) 1|2. The option prioritizing algorithm in GMCR II then ranks the states from most to least preferred using the state numbers as (1, 5, 7, 3, 6, 2, 8, 4, 12, 10, 11, 9).

Analysis and Results: Deciding What to Do

The analysis engine shown in the middle box on the right in Figure 2 is now utilized to carry out a stability analysis of the Cuban Missile Crisis. The output from an analysis can provide strategic insights and guidance.

Stability Analysis

> *Challenge # 5 – Realistically Describing Human Behavior in Conflict Situations:* Since people think and react to circumstances in rather qualitative and uniquely human ways, does it make sense to attempt to systematically describe the manner in which people make decisions through some type of formal mathematical modeling? The answer to this challenge is yes, as long as it is done non-quantitatively. In particular, within the paradigm of the graph model for conflict resolution, stability definitions, which mathematically define different ways in which humans may behave under conflict, are precisely defined using set theory, logic and graphs – the mathematics of relationships. As noted earlier, possible unilateral movements that a DM can make from states in one step are encapsulated theoretically within a directed graph or implemented practically using reachable lists within GMCR II. Accordingly, the graph model methodology is rigorously mathematical and axiomatic, yet completely non-quantitative. The most that is assumed about the preference structure for a DM is ordinality, and cardinal preferences are not required. Hence, there is no cardinal quantification whatsoever within this unique decision technology. Moreover, the graph model offers DMs and other interested parties valuable insights into what are possible compromise resolutions to a given dispute, how a given DM may wish to respond in an optimal way within the social constraints of the conflict, when it is advantageous to cooperate with others, and how the conflict could dynamically evolve to an eventual resolution.

Earlier, a conflict model was developed for the Cuban Missile Crisis in terms of DMs and options (Figure 3), feasible states (Figures 4 to 6), allowable state transitions (Figure 7), and relative preferences (Figures 8 to 10 and Table 1 for the US and within the text for the USSR). This calibrated conflict model developed within the modeling subsystem of GMCR II in Figure 2 is now entered into the main engine of GMCR II, where an exhaustive stability analysis is executed. In general, a particular state is stable for a DM if it is not advantageous for that DM to move away from the state unilaterally by changing the selection of options under his or her control. Additionally, a state is automatically stable for any DM who cannot move away from it. However, if a DM can move away from the state being examined, then what is required is a precise mathematical description of how the strategic consequences of such a departure are to be ascertained. A stability definition is such a description and is therefore a sociological model of behavior in a strategic conflict. When a given state is stable for all DMs according to a given stability definition, it is deemed to be an equilibrium or compromise resolution, since no DM has an incentive to move away from it with respect to that stability definition.

Table 2 lists and characterizes stability definitions that are encoded within the engine of GMCR II in Figure 2 for use with conflicts involving two or more DMs. The first column gives the names of the stability definitions and associated acronyms along with the original references, while the second column provides a description of how each stability definition works (kindly refer to Fang et al. (1993) for the graph model version of these stability definitions). The last four columns furnish characterizations of the stability definitions in a qualitative sense, according to the four criteria of foresight, disimprovements, knowledge of preferences and strategic risk. Foresight is a qualitative description of the number of moves and countermoves that a DM can envision when deciding upon the stability of a state. Disimprovement refers to the tendency of a DM to put itself in a less preferred situation to sanction unilateral improvements by a competitor. The characteristic called knowledge of preferences refers to the kind of preference information that is needed to execute a stability analysis. For instance, when calculating stability according to the top three stability definitions in Table 2, one only has to know the preferences of the given DM and not those of the sanctioning DMs. In these rather conservative approaches to stability, the threat of ending up in a worse situation as a result of unilateral moves by sanctioning DMs is enough to induce stability, even if it is not advantageous to the sanctioning DMs. Finally, strategic risk refers to the attitude of a DM to risk, which can range from ignoring risk under Nash stability to embracing risk under non-myopic behavior.

In their book, Fang et al. (1993) define (Chapter 3) and mathematically compare (Chapter 5) the stability definitions listed in Table 2. Additionally, they demonstrate how the graph model and an associated stability definition can be equivalently expressed using an extensive game, which is much more complicated, and thus, not as well suited for practical applications (Chapter 4). Hence, they illustrate the exact theoretical connections between the graph model for conflict resolution and classical game theory.

After a model has been established, a GMCR II analysis furnishes an assessment of the stability of every state from the point of view of every DM, under all of the stability definitions listed in Table 2. The three states that are stable according to sequential stability and limited move stability for various horizons h, are states 5, 6 and 7. This means that if the conflict were to arrive at one of these states, it would stay there, since it is an equilibrium. However, as shown in Figure 3, it is state 7 that can be reached from the status quo state 1 via state 3. Specifically, the US brings about a unilateral improvement from state 1 to 3 by imposing a naval blockade of Cuba. The USSR can then unilaterally take advantage of its unilateral improvement by withdrawing its missiles and causing the conflict to move to state 7, the resolution that took place historically.

Table 2. Stability Definitions and Human Behavior (Based upon Table 6 in Hipel et al. [1997])

Stability Definitions	Stability Description	Foresight	Disimprovement	Knowledge of Preferences	Strategic Risk
Nash stability (**R**) (Nash 1950, 1951)	DM cannot unilaterally move to a more preferred state.	Low	Never	Own	Ignores risk
General Metarational (**GMR**) (Howard 1971)	All focal DM's unilateral improvements are sanctioned by subsequent unilateral moves by others.	Medium	By opponents	Own	Avoids risk; conservative
Symmetric Metarational (**SMR**) (Howard 1971)	All focal DM's unilateral improvements are still sanctioned even after a possible response by the original DM.	Medium	By opponents	Own	Avoids risk; conservative
Sequential Stability (**SEQ**) (Fraser and Hipel 1979, 1984)	All focal DM's unilateral improvements are sanctioned by subsequent unilateral improvements by others.	Medium	Never	All	Takes some risks; satisfices
Limited-move Stability ($\mathbf{L_h}$) (Kilgour 1985; Fang et al. 1993)	All DMs are assumed to act rationally within a fixed number of state transitions (h).	Variable	Strategic	All	Accepts risk; strategizes
Non-myopic Stability (**NM**) (Brams and Whitman 1981; Kilgour 1984)	Limiting case of limited-move stability as the maximum number of state transitions increases to infinity.	High	Strategic	All	Accepts risk; strategizes

State 5 did not occur as the historical equilibrium because in order for it to be reached from the status quo state 1, the USSR would have to invoke a unilateral disimprovement from state 1 by withdrawing its missiles on its own without any coercive action by the US (see Figure 6 or 10 for a real-world interpretation of a given state using option form). In fact, when the Americans imposed a naval blockade, the USSR decided to withdraw its missiles and to thereby appear as a peacemaker to the rest of the world. It is interesting to point out that state 6, where the US performs surgical air strikes and the Russians remove their missiles, is an equilibrium because dropping bombs on the Soviet missile bases is considered to be irreversible in Figure 7. When this irreversibility restriction is dropped, state 6 does not remain as an equilibrium.

The results from an analysis can be employed for explaining why a state is stable or unstable for a given DM according to any of the stability definitions in Table 2. Consider, for example, why the equilibrium state 7 is stable according to the solution concept of sequential stability for the US in the Cuban Missile Crisis. As can be seen in Figure 10, the US can unilaterally improve from state 7 to 5 by removing the naval blockade. (Notice in Figure 10 that state 5 is more preferred by the US to state 7 and the Russian strategy of withdrawing its missiles is the same in both states. Hence, state 5 is a unilateral improvement for the US from state 7). However, the USSR has its own unilateral improvement from state 5 to state 1, when it decides not to withdraw its missiles. Because state 1 is less preferred to state 7 by the US (see Figure 10), the potential unilateral improvement from 7 to 5 for the US is credibly blocked by the USSR. As can be seen by examining Figure 10, the only unilateral improvement that the US has from state 7 is state 5. Therefore, all of the unilateral improvements from state 7 are credibly sanctioned and state 7 is stable according to sequential stability (SEQ) for the US. Figure 11 portrays the aforesaid reasoning for the stability of state 7 for the US.

From state 7, the USSR has no unilateral improvements that it can invoke. Hence, state 7 is stable according to rationality (R) for the USSR. Because state 7 is stable for both DMs, it forms a possible compromise solution or equilibrium in the Cuban Missile Crisis.

As noted earlier, each of the stability definitions in Table 2 is precisely defined mathematically for conflicts having two or more DMs. For instance, the mathematical definition for sequential stability for a conflict having two DMs i and j is as follows (Fraser and Hipel 1984; Fang et al. 1993, Ch. 3):

Definition of Sequential Stability: For a DM $i \in N$, a state $s \in S$ is sequentially stable (SEQ) for DM i iff for every $s_1 \in R_i^+(s)$, there exists $s_2 \in R_j^+(s_1)$ with $s_2 \leq_i s$, where N is the set of DMs, S is the set of states, $R_i^+(s)$ is the set of unilateral improvements (UIs) for DM i from state s, $R_j^+(s_1)$ is the set of unilateral improvements for DM j from state s_1, and $s_2 \leq_i s$ means that state s_2 is less preferred or equally preferred to state s by DM i. A rational state is actually a subset of the sequential stability definition for the special situation in which the set $R_i^+(s)$ is empty. As is the case for the theoretical definitions of all stability definitions in Table 2, special algorithms are programmed within the engine of GMCR II to calculate sequential stability for a particular state and given DM. For the case of state 7 in Figure 11, one can see that 7 satisfies the definition of sequential stability when the following substitutions are made: i = US, j = USSR, N = {US, USSR}, s = 7, S is the set of twelve states listed in Figures 6 and 10, $s_1 = 5$, $R_i^+(7) = \{5\}$, $s_2 = 1$, $R_j^+(5) = \{1\}$ and $1 <_i 7$.

	More preferred by US	**Particular State**	**Less preferred by US**
US			
1. Air strike	N	N	N
2. Blockade	N	Y	N
USSR			
3. Withdraw	Y	Y	N
4. Escalate	N	N	N
State Number	5	7	1

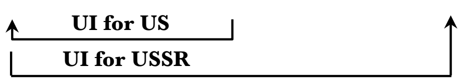

Figure 11. Stability of State 7 for the US According to the Sequential Stability Solution Concept

Preferences Envisioned by the US											
US Preferences											
5	7	6	8	3	2	4	1	12	10	11	9
USSR Preferences											
1	5	7	3	6	2	8	4	12	10	11	9
Preferences Envisioned by the USSR											
US Preferences											
5	1	7	3	6	2	8	4	12	10	11	9
USSR Preferences											
1	5	7	3	6	2	8	4	12	10	11	9

Figure 12. Preferences used in the Hypergame Analysis

Hypergame Analysis: Consideration of Misperceptions

A hypergame is a conflict in which one or more of the DMs has a misunderstanding about one or more aspects of the dispute (Bennett 1977, 1980; Fraser and Hipel 1984; Wang et al. 1988). Because the US had performed so poorly at the Bay of Pigs invasion, as well as for other reasons, Premier Khrushchev expected a weak response from the US to the placement of Soviet missiles in Cuba (Able 1969; Allison 1971). One possible manifestation of Khrushchev's faulty interpretation of the American preferences is the ranking of states for the US in the lower part of Figure 12. Notice that the top part of Figure 12 displays the correct preferences for both the US and USSR, while the lower portion shows how the USSR incorrectly interprets American intentions but, of course, correctly understands its own desires. For example, Khrushchev incorrectly believes that the status quo state 1 is more preferred by the US over states containing aggressive action by the US.

Before, GMCR II was used to analyze the conflict model shown in the upper part of Figure 12 and predicted state 7 as the most likely result, with the other equilibria being states 5 and 6. When the conflict model shown in the lower half of Figure 12 is entered into the engine of GMCR II, the only predicted equilibrium according to SEQ and L_h for various horizons h is state 1. In other words, Khrushchev incorrectly thinks that the status quo state is going to persist, and, hence he will be able to keep his missiles in Cuba with no American response. Accordingly, when the US imposes a naval blockade, Khrushchev is caught by surprise and his new knowledge of the situation causes the hypergame to disappear and results in the game shown in the top part of Figure 12. Premier Khrushchev then responds by withdrawing Soviet missiles from Cuba.

Sensitivity Analyses

> *Challenge # 6 – The Practical Effectiveness of GMCR II:* A question that often arises with almost any type of decision tool is whether or not it will perform well in practical situations and thereby be utilized by real-world DMs for actually providing decision support to help solve pressing problems. This author and his colleagues believe that this is the case for the graph model for conflict resolution and its associated decision support system GMCR II. Of practical import is the fact that GMCR II assists an interested party in better understanding the strategic consequences of a specific model of a given conflict. In fact, GMCR II is now being used for research purposes by 70 organizations in 25 countries. Although no one is ever completely certain of what will happen in the future, at least the potential results of a range of possible strategy choices can be much better envisioned

> using GMCR II. Recall that President Kennedy, for example, obtained crucial advice on various ways to respond to the Russian placement of missiles in Cuba from people with different backgrounds and knowledge who were members of the Executive Committee of the National Security Council. In a sense, President Kennedy was carrying out his own sensitivity analyses of what could potentially happen if he followed the advice of either his "hawks" or "doves", or adopted some policy that fell between the two extremes. Although GMCR II and many other formal models were not available in 1962, there is little doubt that President Kennedy was very rational and sensible in his thinking process. Additionally, as explained under future challenges, GMCR II can be significantly expanded to handle a rich range of new theoretical developments in areas such as preference uncertainty, formalizing emotional thinking, and coalition analysis. As explained earlier, GMCR II is a valuable tool for use in strategic analyses in conjunction with other societal and physical decision support systems within an overall system of systems framework for reflecting the key characteristics of a current systems engineering problem being formally investigated.

In a sensitivity analysis, one wishes to ascertain how meaningful changes in one or more model parameters affect the analytical findings with respect to potential conflict resolutions. Determining changes in equilibrium results due to different preference structures for one or more DMs constitutes one of the most common kinds of sensitivity analyses. For example, when one is not completely certain of the preferences of one of the DMs, one can analyze a reasonable range of preferences to ascertain how the equilibria are affected. If, for instance, the predicted equilibria do not change over a range of preference structures, then the equilibria are robust with regards to those preferences.

Especially when using GMCR II to help decide what to do in a current dispute, one would usually like to carry out sensitivity analyses by considering the strategic implications of a sensible range of different, but related models, of the conflict under study. Where misunderstandings may be present or one party wishes to deliberately misinform another, a hypergame analysis could be used in conjunction with GMCR II.

Currently, one can determine the best situation each DM can hope to achieve on his or her own using the output from GMCR II. The system can be expanded to allow coalitions and cooperation among DMs (Kilgour et al. 2001; Inohara and Hipel 2008a,b) to be considered to ascertain if a DM can do even better by joining forces with others. Further innovations that can be incorporated into a decision support system of conflict resolution are mentioned in the next section. Whatever advancement or further sensitivity analysis is thought to be worthwhile to pursue, a decision support system allows its strategic results to be immediately determined and interpreted.

Conclusions and Future Challenges

As demonstrated by the Cuban Missile Crisis case study, the Graph Model for Conflict Resolution methodology, in conjunction with the decision support system GMCR II, furnishes a valuable decision technology for systematically and rigorously investigating real-world conflict. By formally modeling this important international dispute in terms of decision makers, options and relative preferences, one can put the conflict into perspective and obtain a better understanding of its basic characteristics. Moreover, the analytical results provide strategic insights into how the conflict evolved from a status-quo situation to its final resolution. By taking into account Premier Khrushchev's misperception in underestimating the determination of President Kennedy to responsively rid Cuba of its nuclear missiles, a hypergame analysis clearly explains how this strategically affected the eventual outcome.

This author firmly believes that the demand for having a range of useful conflict resolution methodologies for addressing a spectrum of real-world conflict situations is going to continue to increase in the future. Although the Cold War came to an end two decades ago and the accompanying threat of a global nuclear war has thereby greatly decreased, a number of new types of conflicts are arising, while others are becoming more serious. For instance, the adoption of democracy and market-oriented economies by most of the nations of Eastern Europe since the fall of communism has meant that political differences now abound among political parties within a given country, and there is fierce business competition within and among countries. During the 1990s and on through the beginning of the 21st century, nationalism and cultural differences have created nasty civil wars to erupt in countries, such as the former Republic of Yugoslavia and Russia. The ongoing devastation of the earth's natural environment by the economic advancement of civilization and huge population increases has caused serious environmental problems, such as global warming or climatic change, and the pollution of water, land and air throughout the world. This in turn has brought about serious conflicts between proponents of development and environmentalists as they strive to reach a balance between economic progress and environmental stewardship, which is popularly referred to as sustainable development (Hipel and Obeidi 2005). At the international level, negotiations have taken place in an effort to reach agreement over important issues, such as reductions in the emission of greenhouse gases first within the Kyoto Protocol and later the December 2009 Copenhagen agreement. Unfortunately, both of these initiatives failed to reach arrangements in greenhouse gas reductions among nations that will avert massive, and perhaps irreversible, damage to the earth's climate and associated ecosystems. As noted earlier, this could result in the collapse of fragile states along with large-scale migrations of people, which poses serious security and military problems, in addition to other connected major crises such as water scarcity, crop failures, industrial stagnation, and spread of pandemics. In fact, Dyer (2008) believes that these large-scale system of systems disruptions will result in 'climate wars'. It is interesting to note that most of the scientific and engineering solutions required for cleaning up pollution in the environment are well known, but the political and economic means for realistically implementing them are not. Hence, the nations of the world are now in the midst of knowingly playing out a global "Tragedy of the Commons," in which they are all consciously contributing to the possible irreversible destruction of our current climate system wherein it jumps to a new and much hotter irreversible state. The foregoing and a host of other examples of differences in opinion dictate the need for developing a rich variety of decision tools for use in conflict resolution and there is little doubt that concepts in computational and system of systems engineering will play a key role in these developments.

One example of a major area in conflict resolution in which more formal models are greatly needed is the situation where negotiators attempt to benefit everyone taking part in the negotiations. Fisher et al. (1991), Raiffa (1982), Raiffa et al. (2002) and Radford (1988) suggest general procedures for encouraging DMs to work together in order to come up with creative solutions that are more preferred by all parties – the so-called win/win solutions. Within the graph model paradigm, the author and his colleagues are designing a new model structuring component that would allow the decision technology to be more easily used for brain-storming sessions in which groups cooperate to devise imaginative alternative solutions (Song et al. 2001). In a brainstorming session taking place at higher levels of decision making or near the start of a dispute, DMs tend to think about final desirable outcomes, rather than specific option choices to arrive at these outcomes. Hence, nodes standing for possible states could be drawn, along with arcs representing paths for reaching various states, for each of the DMs. Even the relative preferences for each DM can be entered using a directed graph. Because the graph model for conflict resolution assumes that states are the basic units among which strategic interactions occur, the current engine of GMCR II in Figure 2 could be used to produce the stability results for the graphical model input.

As noted under Challenge #4, a crucial step in calibrating a conflict model is obtaining reliable relative preference information for each DM involved in a dispute. Research is well underway for expanding the scope of the graph model for handling a richer variety of relative preference information that arises in practice. For example, the definitions of the top four stability definitions listed in Table 2 have been revised for taking into account strength of preference when a DM greatly prefers or greatly dislikes one state with respect to another (Hamouda et al. 2004, 2006; Xu et al. 2009b). For instance, the USA and other countries may greatly not prefer a situation or state in which North Korea substantially expands its nuclear arsenal and missile delivery systems relative to a state in which it does not. Hence, the threat of North Korea building many nuclear weapons can form a strong sanction against threatening actions by other countries. In certain conflicts, some of the relative preferences between states by one or more DMs may be unknown and this knowledge can be incorporated into the definitions of the first four stability definitions given in Table 2 for employment in stability calculations (Li et al. 2004a, 2005a). Ben-Haim and Hipel (2002) present an information gap (Ben-Haim 2006; Hipel and Ben-Haim 1999) approach for systematically addressing uncertainty in the preferences of a DM which can be used, for instance, for determining the robustness of equilibria under rigorous sensitivity analyses executed within a conflict study. Hipel et al. (2011) and Al-Mutaira et al. (2008) devise a method for having fuzzy preferences in conjunction with fuzzy stability definitions as another approach for taking into account uncertainty in the graph model for conflict resolution.

To design the graph model to be as realistic and useful as possible, a number of psychological factors are being incorporated into its structure. For instance, one would expect that when DMs in a dispute have positive attitudes towards one another, a better resolution for everyone could be reached. Inohara et al. (2007) have developed an approach for handling attitudes within the graph model paradigm whereby a DM can have positive, neutral and negative attitudes towards others and himself or herself, and the strategic impacts of any combination of attitudes can be ascertained. Bernath Walker et al. (2009) combine attitudes with the coalition algorithms of Kilgour et al. (2001) and Inohara and Hipel (2008a,b). Obeidi et al. (2005, 2009a,b) have created a unique procedure for formally bringing emotions into a conflict investigation. As demonstrated with the Cuban Missile Crisis, misperceptions can be considered in a graph model study using the construct of a hypergame (Bennett 1977, 1980; Fraser and Hipel 1984; Wang et al. 1988).

Research is well underway for ascertaining how a desirable equilibrium or other state can be reached from a status quo state through both independent and joint movement using a variety of algorithms collectively referred to as status quo analysis (Li et al. 2004b, 2005a, b). Figure 3, for example, displays how the Cuban Missile Crisis evolved from a status quo state via a transitory state to a final resolution. Existing and new advances in the graph model approach can be used to more realistically determine the best outcome that a given DM can hope to achieve, either individually or on his own, within the social and strategic constraints of a conflict. Zeng et al. (2005, 2006, 2007) explain how the graph model can be extended for utilization in policy analysis. Finally, the matrix approach for equivalently defining the graph model for conflict resolution provides an encompassing structure for formally incorporating all of the foregoing advancements into the graph model as well as associated algorithms for designing the next generation of a decision support system (Xu et al. 2009a,c). In addition, the case-based reasoning system put forward by Ross et al. (2002) could be incorporated into a decision support system for conflict resolution to utilize previous case studies to assist in the initial structuring and modeling of a new conflict that one would like to investigate.

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