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Game theory and climate diplomacy

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ABSTRACT

Starting with the "New Periodic Table" (NPT) of 2×2 order games introduced by Robinson and Goforth (2005), we provide an exhaustive treatment of the possible game-theoretic characterizations of climate negotiations between two players (e.g., Great Powers or coalitions of states). Of the 144 distinct 2×2 games in which the players have strict ordinally ranked utilities, 25 are potentially relevant to climate problem. The negotiations may be characterized as a No-Conflict Game, Prisoner's Dilemma, Coordination Game, Chicken, Type Game, or Cycle, depending on the payoff matrix. Which game corresponds to the actual state of the world depends both on the severity of risks associated with climate change and the perceptions of the governments engaged in the negotiations. Nash equilibrium or Maxi-min equilibrium (or neither) may be the outcome. Achieving universal abatement of greenhouse gas emissions may require side payments or enforcement mechanisms outside the game framework, but we show how the negotiations themselves may offer opportunities to select between Nash equilibria or alter the payoff rankings and strategic choices of the players. In particular, scientific information pointing to the severity of the risks of climate change suggests characterization of the negotiations as a Coordination Game rather than a Prisoner's Dilemma.

1. Background

Game-theoretic models provide an elegant formalization of the strategic interactions that underlie the international climate negotiations. Needless to say, there is a long and lively tradition of applying game theory to problems of international relations, including global environmental protection. We will not attempt to give a comprehensive survey of this literature.[1] Instead, we will comprehensively examine all of the 2×2 order games[2] that might be relevant to the climate negotiations, and that show how the payoff structure depends on interpretation of the scientific evidence. We will argue that assessment of the magnitude of the global climate risk is the key determinant of the kind of "game"[3] being played. This in turn affects the feasibility of reaching an agreement, and the possible role of equity considerations in facilitating an agreement.

Game theory incorporates key elements of both the realist and liberal views of international politics (Stein, 1990). It is consistent with realism because the players are assumed to have a unitary will, that is, each government acts as a single agent rather than as some kind of complex organization whose decisions result from domestic political interactions.[4] At the same time, it shows how self-interested behavior can lead to order and welfare-improving outcomes (though it need not necessarily do so), just as the market economy can. The game-theoretic approach does require that governments are able to

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[1] A wide-ranging application of game theory to global environmental protection (which also gives a wealth of historical and institutional background for several examples, including the climate negotiations) is Barrett (2003). Stein (1990) offers numerous applications to a range of situations in international relations, and is a fine example of the richness of the 2×2 game framework as a source of insight into the strategic interactions that can arise.

[2] Order games are games in which the outcomes stemming from governments' policy choices are ranked ordinally (without indifference).

[3] The terminology "game theory" is an historical accident. As Shubik (1983, p.7) put it, "[p]erhaps the word 'game' was an unfortunate choice for a technical term. Although many rich and interesting analogies can be made to Bridge, Poker, and other parlor games, the usual sense of the word has connotations of fun and amusement, and of removal from the mainstream and the major problems of life. These connotations should not be allowed to obscure the more serious role of game theory in providing a mathematical basis for the study of human interaction, from the viewpoint of the strategic potentialities of individuals and groups." There is no way to go back in history and persuade von Neumann and Morgenstern, the intellectual giants whose book (1944) and prior work (von Neumann, 1928) launched the field, to adopt more descriptive titles.

[4] Realist thinking in international relations encompasses more than this principle alone. For example, some Realist theorists emphasize the importance of *relative* power as a priority of governments. For a critical review of Realism see Donnelly (2000).

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rank-order outcomes in a manner that is consistent with agent rationality (i.e., a ranking can be assigned to each outcome and the rankings are transitive). Note that the perceived interests of the governments can allow for some weight being given to the well-being of other nations; all that is required is that the outcomes be ranked. In general, the payoffs of a game can be either ordinal (only a rank ordering is possible) or cardinal (different outcomes can be compared on an absolute scale, such as in monetary units). We will focus most of our attention on ordinal rankings. Conclusions based only on ordinal rankings are more general; cardinal evaluations of outcomes require much stronger assumptions about the utilities of the agents. Ordinal ranking of outcomes allows us to bypass the comparisons of utility across countries with very different levels of income that plague conventional cost–benefit analysis.[5] Because ordinal rankings are preserved under any positive monotonic transformation, any conclusions based only on the ordinal ranking of outcomes carry over if the game payoffs are expressed in monetary or utility units.

Consider first the simplest possible games. There are only two players, who will be identified as “Row” and “Column.” We will consider games with more players below, but we concur with Barrett that the essence of many international relations situations can be captured by the simple 2×2 framework.[6] We use this nondescript “Row” and “Column” terminology for the players because the games will be interpreted as representing different kinds of international relations — sometimes Great Power rivalry (as between the United States and China, for example) and sometimes other strategic interactions (as between the relatively rich OECD countries and the relatively poor developing nations). Each player chooses one of two strategies, “Abate” or “Pollute.”

The payoffs of the games are given in a simple matrix, each cell of which has two elements, the payoff for Row followed by the payoff for Column. The generic payoff matrix is shown in Fig. 1. Thus, a in the upper left cell of the matrix is the payoff for Row if Row chooses the strategy Abate, and Column chooses the strategy Abate. Similarly, u is Column's payoff from this pair of strategy choices. The payoffs to each player are measured in ordinal terms, so $\{a, b, c, d\}$ and $\{u, v, w, x\}$ can take on values {4, 3, 2, 1}, with 4 corresponding to the best outcome, 3 and second-best outcome, 2 the next-to-worst outcome, and 1 the worst outcome for each player.

There are 144 distinct games of this simplest type. The number of distinct 2×2 order games has been known since the 1960s, but recent work by Robinson and Goforth (2005) shows that these games can be organized in a unified topological framework based on a natural measure of the “distance” between payoff structures.[7] Robinson and Goforth's book synthesizes what has been known about the classification of 2×2 games to date, and their “New Periodic Table” (NPT) of the 2×2 games efficiently organizes the information and leads to new insights about the nature of the games. We will use the Robinson and Goforth NPT to provide an *exhaustive and theoretically unified treatment of all 2×2 games that might be relevant to the climate negotiations*. We will be able to cover every possible case of preferences and strategic interactions, and drawing on the NPT topology we will show how different subsets of the climate-relevant games fall into categories with specific characteristics. Determining just which situation is most descriptive of the actual state of play in the negotiations then depends on how the preference rank-orderings of the players are assessed.

Column's Strategy

		Abate	Pollute
Row's Strategy	Abate	a, u	b, v
	Pollute	c, w	d, x

Fig. 1. Generic 2-player game.

First we must establish which of the 2×2 games are potentially applicable to the climate problem. We narrow down the number of games by requiring that the payoff structures satisfy two “climate relevant” restrictions: (1) The outcome (Abate, Abate) is preferred by both players to the outcome (Pollute, Pollute), and (2) Each player's pollution imposes a negative externality on the other. The first of these two restrictions amounts to assuming that there is no economic or geopolitical advantage to be gained by either party if both pollute instead of both abating, and that the climate problem is real. It does not require that climate is either party's top priority. The second restriction amounts to the presumption that neither party's pollution benefits the other party. In the generic payoff matrix of Fig. 1, the first restriction says that $a>d$ and $u>x$. The second restriction requires $a>b$, $c>d$, $u>w$, and $v>x$. These two restrictions reduce the number of climate-relevant 2×2 games to 25.[8]

It should be noted that our two climate-relevance conditions apply to countries' greenhouse gas emissions. A small country rich in oil or gas reserves may derive much of its national income from the export of its fossil fuel resources. From a short-term perspective, the government of such a country might prefer that the rest of the world adopt the Pollute strategy, violating our “negative externality” condition (2). This situation might apply to a few countries, but not to the major powers.[9]

In addition, we do not consider the thinly-supported claims that some countries or regions would benefit from global warming (see the critique of these claims in Ackerman et al. (2009a)). The world is already committed to some amount of warming because of cumulative emissions to date, and the pending policy question is how much more warming can be allowed if we are to avoid “dangerous anthropogenic interference with the climate,” even if there may be some relatively minor increases in agricultural productivity in a few regions stemming from the warming, changes in precipitation patterns, and CO_2 fertilization.

[5] For example, global welfare-maximizing integrated assessment models have to employ a scheme such as Negishi weighting to construct the social welfare function to be maximized. If Negishi weights are used, the social welfare function embodies and largely freezes the current distribution of income (Stanton, 2010).

[6] Barrett (2003) cites Stein that “[m]ost basically, nations choose between cooperation and conflict, and such situations underlie the entire range of international relations from alliances to war” (1990, pp. 3–4).

[7] There are (4!)×(4!)=576 ways to arrange four pairs of utility rankings in an array such as Fig. 1. Robinson and Goforth show that only 576/4=144 of these games are distinct (2005, Chapter 2, pp. 15–19). Rapoport and Guyer (1966) and Brams (1977) count only 78 distinct games because they define “‘distinct’ in the sense that no interchange of the column strategies, row strategies, players, or any combination of these can turn one game into another — that is, these games are structurally different with respect to these transformations” (Brams, 1983, p. 173), and they eliminate “reflections” as defined by Rapoport and Guyer. However, “[t]here are strong arguments against eliminating reflections” (Robinson and Goforth, 2005, p. 19) if the players are not indistinguishable. Thus, for our purpose (determining the games that might be applicable to climate negotiations) the Robinson and Goforth count of 144 is appropriate.

[8] Of the games having essentially different structures, some are analyzed so frequently as to be given distinctive names, such as the Prisoner's Dilemma, Chicken, Battle of the Sexes, and Stag Hunt. We will use the names given by Robinson and Goforth if they seem apposite. Some of the games are named after Cold War or Vietnam-era events or situations that have nothing to do with climate, and in these cases we identify the games by their NPT numbers only.

[9] An international climate agreement that reduced the risk of climate change would correct a market failure (allowing free disposal of greenhouse gases into the atmosphere) but would create a pecuniary externality by causing a loss of fossil fuel wealth and revenues to OPEC members. Pecuniary externalities are typically considered to be part of the dynamic market process and are in fact necessary for allocational efficiency. The political process, however, makes no distinction between pecuniary externalities and “real” externalities (Holcombe and Sobel, 2001).

		Column's Strategy	
		Abate	Pollute
Row's Strategy	Abate	4, 4 *,+	3, 2
	Pollute	2, 3	1, 1

* Nash Equilibrium
\+ Maxi-min Equilibrium

Fig. 2. Harmony: 366.

A recent paper by Perlo-Freeman (2006) defines a class of "Co-operate–Defect" (C–D) games "which are characterized by each player having a dominant preference for a particular strategy by the *other* player" (p. 1). This class of games corresponds to the games satisfying our second climate-relevance criterion. There are exactly 36 C–D games. Eleven of these fail to satisfy our first climate-relevance criterion. Perlo-Freeman's paper shows how the C–D games are applicable to arms race games and collective action problems, and that they form an interesting subset of the NPT with topological properties related to those of the NPT. The players of the C–D games can be described by one of six distinct preference-ordering types, and Perlo-Freeman demonstrates how slight changes in the preference ordering of one of the players can result in sharp changes in the Nash equilibrium of the game.[10]

2. The "No-Conflict" Games

There is no reason to assume from the outset that the climate problem is inherently one of international conflict. There are a number of games satisfying the two climate relevance restrictions in which reaching an international agreement should be relatively easy. These no-conflict games have a payoff of (4, 4) for the (Abate, Abate) strategy choices, although they are not the only interesting games with this pattern (see below). Consider the game named "Harmony" and numbered 366 in the Robinson and Goforth NPT (Fig. 2).

Rational players will settle on the (Abate, Abate) strategy pair whether they are following Nash or Maxi-Min strategies. The *Nash equilibrium* is named for the famous mathematician who proposed the concept in (1950, 1951).[11] A Nash equilibrium is defined as an outcome such that neither Row nor Column can improve its payoff by deviating unilaterally from the outcome if the other continues to play the equilibrium strategy. Clearly, if both are playing Abate in this game, neither has any incentive to "defect" and begin polluting. Indeed, Abate is the *dominant strategy* for both players. This means that Row's payoff for playing Abate is greater than its payoff for playing Pollute, no matter what strategy Column chooses. The same is true for Column; its payoff to playing Abate is greater than its payoff from playing Pollute no matter what Row does.

The Nash equilibrium is the most familiar equilibrium concept, but it is not the only possible one.[12] The Maxi-min strategy is "[a] strategy

Harmony: 366		
	Abate	Pollute
Abate	4, 4 *,+	3, 2
Pollute	2, 3	1, 1
Row's DS = Abate Column's DS = Abate		

No Conflict: 311		
	Abate	Pollute
Abate	4, 4 *,+	2, 3
Pollute	3, 2	1, 1
Row's DS = Abate Column's DS = Abate		

Pure Common Interest: 316		
	Abate	Pollute
Abate	4, 4 *,+	2, 2
Pollute	3, 3	1, 1
Row's DS = Abate Column's DS = Abate		

Pure Common Interest: 361		
	Abate	Pollute
Abate	4, 4 *,+	3, 3
Pollute	2, 2	1, 1
Row's DS = Abate Column's DS = Abate		

326		
	Abate	Pollute
Abate	4, 4 *	1, 2
Pollute	3, 3 +	2, 1
Column's DS = Abate		

362		
	Abate	Pollute
Abate	4, 4 *	3, 3 +
Pollute	2, 1	1, 2
Row's DS = Abate		

321		
	Abate	Pollute
Abate	4, 4 *	1, 3
Pollute	3, 2 +	2, 1
Column's DS = Abate		

312		
	Abate	Pollute
Abate	4, 4 *	2, 3 +
Pollute	3, 1	1, 2
Row's DS = Abate		

* Nash Equilibrium
\+ Maxi-min Equilibrium
DS = Dominant Strategy

Fig. 3. The eight No-conflict Climate-relevant games.

for which the worst possible payoff is at least as good as the worst payoff from any other strategy. The Maxi-min payoff is the highest payoff that a player can guarantee herself" (Robinson and Goforth, 2005, p. 163). In Harmony, Row's worst payoff from playing Abate is 3, which is greater than 1, the worst payoff if Row plays Pollute. Similarly, Column's worst payoff from playing Abate is 3, better than the worst payoff Column could get from playing Pollute. In the case of the Harmony game, the Nash equilibrium and the Maxi-min equilibrium are the same, but this is not the case for all the 2×2 games.

In playing a Maxi-min strategy, Row will not pick the row with the lowest payoff and Column likewise will not pick the column with the lowest payoff. In other words, the Maxi-min strategy guarantees for a player the best outcome that can be had regardless of the strategy of the other player. No assumption needs to be made about the other player's rationality, strategic behavior, or motivations. A player using Maxi-min is truly "on his own." Extremely risk-averse players might well choose Maxi-min, and as we shall see, this could be the route by which climate stability is reached.[13]

There are a total of eight climate-relevant no-conflict games, shown in Fig. 3. The figure is arranged so that the adjacent games are symmetric with respect to the identities of Row and Column. The Robinson and Goforth NPT number and their nomenclature (if given) are included. In all eight of these games, the Nash equilibrium is for both players to Abate, and this is also the Maxi-min equilibrium for 4 of the games: 366, 311, 361, and 316. These are also games for which the dominant strategy for both players is to Abate. However, for four of the games only one player has a dominant strategy, and in those cases the Maxi-min equilibrium is sub-optimal in the sense that each player could achieve its best outcome if both play Abate. Thus, even in this case of "no-conflict" games, there might be a need for international cooperation to get the parties to understand that (Abate, Abate) is Pareto-superior to any other outcome. Negotiations could serve to build trust among the parties whose tendency might otherwise be to "go it alone."

[10] We are grateful to David Goforth for bringing the Perlo-Freeman paper to our attention.

[11] It is an interesting historical oddity that the solution concept named after Nash was put forward in only slightly different form by Cournot in 1838. The Cournot strategy for an oligopolistic firm, in which the firm produces the output that maximizes its profit given the outputs the other rival firms are producing, amounts to the Nash equilibrium when all firms follow this strategy. Ingrao and Israel's history of the concept of economic equilibrium (1990) gives Cournot appropriate credit for the first definition of this type of equilibrium.

[12] Technically, we will be considering only pure strategies, in which the players pick one or the other strategy. A *mixed* strategy is defined as one in which the player chooses each of the two possibilities with some probability. While mixed strategies are potentially important in some games (e.g., Poker), it is difficult to imagine how a realist nation-state could play a mixed strategy on a matter of vital national interest. Hence, we will confine our discussion to pure strategies only.

[13] It should be noted that the concept of "equilibrium" is ill-defined if one or both of the players acts irrationally or according to no pattern at all.

Even so, if the preferences of the negotiating partners correspond to any of these eight "no-conflict" games, the prospects for an international agreement are bright. Indeed, it may be that the success of the Montreal Protocol can be explained by its belonging to this category. The damage from stratospheric ozone depletion may have been seen as so serious to major countries like the United States that abatement of the ozone depleting substances was a dominant strategy, and the Nash equilibrium was universal abatement. This possibility has been discussed by Sunstein (2007), and Barrett (2003 pp. 229–230), argues that accession to the Montreal Protocol was a dominant strategy for most industrialized countries.

In another sense, however, the ease of arriving at the Pareto-superior Nash equilibrium in these games may be seen as evidence that these games do not capture the payoff structure of international climate diplomacy. If reaching the optimal outcome were so easy, why does the climate problem seem so difficult? Despite 20 years of negotiations, beginning with the run-up to the Framework Convention on Climate Change in Rio de Janeiro in 1992, very little progress has been made. There is no global agreement committing all the major powers to specific emissions reductions. The United States has not made any legally binding commitment to reduce its own greenhouse gas emissions[14] through an alternating succession of two Republican and two Democratic presidencies and two changes in the control of Congress (not counting situations with the House and Senate controlled by different parties). The lack of agreement on climate is like Sherlock Holmes' dog that did not bark; it suggests that the climate problem is not one of the "no conflict" games.

3. The Prisoner's Dilemma and Related Games

Probably the most frequently discussed game structure is the Prisoner's Dilemma (PD). Sometimes it is considered to be the quintessential characterization of non-zero sum conflict, although we know that the PD and similar games are only a small subset of the 144 distinct 2×2 order games. Nevertheless, the PD is an important case. The name arises from the hypothetical situation in which two suspects are arrested and placed in separate interrogation rooms. Each is offered a deal: Confess to the crime and testify against the other suspect, and you will receive a light sentence. If you maintain your innocence and the other suspect confesses, you will be convicted on the other suspect's testimony and will receive a very heavy sentence. However, the suspects realize that there is a good possibility that if both refuse to confess, the police will not have enough evidence to convict either of them, so there is a good chance (but not a certainty) that they will receive no sentence at all. What is the best strategy for a suspect?

One possible structure of payoffs in the global environmental protection game is like that of the Prisoner's Dilemma. Imagine that the game is being played between two Great Powers, and that the highest priority of each is to avoid a decline in its economic and military strength relative to the other. Both powers would benefit from jointly reducing emissions by playing Abate, but because abatement of emissions is costly, the worst outcome for either power (at least in the short run) is to play Abate while the other continues business as usual (i.e., polluting). The payoff matrix to this game is as shown in Fig. 4.

In the PD, the unique Nash equilibrium is that both play Pollute and the payoff is (2, 2). If, for example, Row were to deviate and try playing Abate while Column continues to play Pollute, the payoff to Row would be 1, less than what Row receives when both play Pollute.

[14] That is, no commitment other than its reductions of ozone-depleting substances (ODSs) under the Montreal Protocol. Many of the ODSs are powerful greenhouse gases, and the reductions under the Montreal Protocol have been the equivalent of approximately five times the reductions called for under the Kyoto Protocol (Velders et al., 2007).

		Column's Strategy	
		Abate	Pollute
Row's Strategy	Abate	3, 3	1, 4
	Pollute	4, 1	2, 2 *,+

* Nash Equilibrium
\+ Maxi-min Equilibrium

Fig. 4. Climate policy as the Prisoner's Dilemma: 111.

Similarly, if Column were to deviate and play Abate while Row plays Pollute, Column's payoff would drop from 2 to 1. Both countries would be better off if they could somehow negotiate an *enforceable* international agreement to Abate, but this would be quite difficult because for both countries the highest priority is to prevail in geopolitical competition and each would always have an incentive to defect. For example, if both were playing Abate, Column could improve its payoff from 3 to 4 if it began to play Pollute while Row continued to Abate. Each country is a sovereign entity, so the problems of compliance, verification, and free-riding are salient. In contrast to the outcome of (Abate, Abate), the Nash equilibrium (Pollute, Pollute) is self-enforcing in the sense that neither country has an incentive to deviate from it.

It is clear that the outcome in which both Row and Column play Abate is Pareto-superior to the outcome when both play Pollute. Both players would prefer a payoff of (3, 3) to the Nash equilibrium of (2, 2). If it were somehow possible to achieve the outcome in which both play Abate, what would be required to maintain it given that both parties have an incentive to defect? One possibility is that side payments to discourage defection might be arranged, drawn from the surplus generated by the difference between the (3, 3) and (2, 2) outcomes. The specific form such side payments might take would require more information than just the ordinal ranking of the outcomes. If the payoff numbers were cardinal values (measured perhaps in dollars), the side payment agreement might be that any player announcing an intention to defect would receive a side-payment of 1 unit. If the side payment came from the non-defector's payoff in the (3, 3) outcome, the non-defector would be no worse off than in the Nash equilibrium, and the potential defector would be just as well off as if it had defected (because it would receive a total of 4 units of utility). Unfortunately, the transferrable surplus might not be large enough to deter defection — the payoff rankings are given only in ordinal terms in Fig. 4, so it is possible that the (3, 3) and (2, 2) outcomes on the diagonal correspond to cardinal measures of utility, but that the (4, 1) and (1, 4) payoffs are really (10, 1) and (1, 10) in cardinal terms.

The side payment approach has a more basic flaw, however. If it were known that side payments were possible, each party would have an immediate incentive to announce its intention to defect. Even more fundamentally, if the Great Powers are concerned primarily with their relative power, then a country might reject any treaty that provided greater gains for its rival than for itself, even if both gained. Economists are too quick to apply the Pareto principle to absolute levels of wealth or income, while not paying attention to relative income or power. As Russell Hardin puts it, "one cannot view the criterion of Pareto superiority as a principle of rational choice in general. The criterion is rationally objectionable because it presumes consent in situations in which conflict can arise over potential allocations. Because my future opportunities may depend on how we allocate things now, my interests now depend on my future prospects" (Hardin, 2008, pp. 68–69).

Alibi: 412		
	Abate	Pollute
Abate	3, 4	1, 3
Pollute	4, 1	2, 2 * +
Row's DS = Pollute		

Alibi: 221		
	Abate	Pollute
Abate	4, 3	1, 4
Pollute	3, 1	2, 2 * +
Column's DS = Pollute		

* Nash Equilibrium
+ Maxi-min Equilibrium
DS = Dominant Strategy

Fig. 5. Climate games similar to the Prisoner's Dilemma.

		Column's Strategy	
		Abate	Pollute
Row's Strategy	Abate	4, 4 *	1, 3
	Pollute	3, 1	2, 2 *,+

* ***Two*** Nash equilibria
+ Maxi-min equilibrium

Fig. 6. Climate policy as a Coordination problem: 322.

Other ways out of the PD focus on creating incentives to stay at the Pareto-superior outcome in which both Abate, by bringing in rewards and punishments that are outside the structure of the game's payoffs. Public goods (such as pollution abatement) are provided within States by enforcing environmental laws with the police power — there are civil and criminal penalties for those who pollute. In the international arena, treaties can be designed that impose trade sanctions on countries that do not join and comply. The pressure to comply can take softer forms as well. Polluters may be subject to opprobrium and shame if they do not conform to the preferences of the "world community." Pariah status can also be the first step towards more tangible punishments, but it must be kept in mind that sovereign states are often quite willing to bear up against international disapproval if they feel their vital interests are threatened. It is also possible to imagine that appeals to moral principles or equity could carry some weight. For either external or internal political reasons, defecting from an equitable climate change accord might be difficult, although factoring in within-country politics would run counter to the Realist abstraction from domestic political considerations.

In the climate context, defectors might be denied green technology transfers. If the game were played repeatedly, then a "tit for tat" punishment/reward strategy could be employed to train all the parties in the benefits of cooperation.[15] Repeated interactions do not necessarily require playing the same game over and over; it might entail the linkage of seemingly unrelated issues. Help in one sphere (for example, fighting terrorism or suppressing the illegal drug trade) could be offered in return for cooperation on climate.

The PD is the most well known of the games having this sort of payoff structure, but Robinson and Goforth's NPT reveals that there are other games with payoff structures quite similar to the PD and having the same logic. The two climate-relevant ones are shown in Fig. 5. As in the PD, the outcome if both play Abate is Pareto-superior to the Nash and Maxi-min equilibria. However, Pollute is a dominant strategy for one of the players in each game, so that player always has an incentive to defect from the (Abate, Abate) outcome. As in the PD, both countries' least-preferred outcome is to Abate while the other Pollutes; both care deeply about the outcome of the geopolitical economic/military competition.

The PD "neighborhood" of games is a good candidate for characterizing the real-world situation because greenhouse gas controls mainly would have to take the form of cutting the carbon dioxide emitted when fossil fuels are burned. Fossil fuels currently constitute the bulk of the world's energy supply, and energy is central to modern industrial power. Intervention in the energy sector therefore strikes close to the heart of an industrialized nation's economic strength, so that countries with global influence fear that they would be weakened if required to scale back their energy production and consumption or substitute more expensive primary energy sources for fossil fuels. However, it is a remarkable fact that there is another climate-relevant game that shows the same kind of priority given to geopolitical competition as the PD games, and yet offers a much greater possibility for international cooperation.

4. The Coordination Game

Consider a slight modification to the PD payoff structure in which both countries are highly averse to playing Abate while their rival plays Pollute, but where the very best outcome for both is jointly to play Abate. This eliminates the incentive to defect, *provided an agreement by both parties to play Abate can first be reached* (Fig. 6). The worst outcome for either country is to abate while the other pollutes, just as in the PD. One country's playing Abate while the other plays Pollute leads to losing out in the short-run geopolitical competition (because continuing business as usual in the short run has no short-run economic or military cost) and eventually results in disastrous destabilization of the atmosphere also. Avoiding a high probability of exceeding a 2 °C temperature increase requires the world as a whole to reach zero net emissions this century; there is no room in the atmosphere for any major economy to continue business as usual without running the risk of "dangerous anthropogenic interference with the climate system" for everyone (Ackerman et al., 2009b). The next-to-worst outcome for both Great Powers is that they both pollute; in this case there is significant risk that the planet is destroyed but at least, as the line in the Tom Lehrer song puts it, "we will all go together when we go." Neither gains geopolitical advantage in the short run. The best outcome for both is that they both abate. In this case, neither Great Power is disadvantaged politically nor does the planet run the risk of climate catastrophe.

In this game, there are two Nash equilibria: Either both countries play Abate or both play Pollute. The diplomatic problem here is one of *equilibrium choice*. If the system could be gotten to (Abate, Abate) it would stay there.[16] The payoff structure is such that an international climate agreement would be self-enforcing. Equity considerations might well play a role in the equilibrium choice, because the Pareto-superior outcome in which both players Abate would be one in which the world environment is more benign, and nations might therefore be more likely and more able to devote resources to other objectives like poverty elimination or sustainable development.

The game structure depicted in Fig. 6 is sometimes referred to as "Stag Hunt." The story is that two individuals can cooperate to hunt a stag, or each can go his own way and hunt a hare. Without cooperation, the stag hunt is guaranteed to fail, but either hunter can easily bag a hare on his own. A stag hunt is not particularly familiar to most people today; the terminology stems from an example given by Rousseau. A similar situation in which there is a substantial payoff to social cooperation is Hume's example of two occupants of a boat who can make progress only

15 See Axelrod (1984).

16 Unless, that is, the players were to begin playing Maxi-min strategies.

by rowing together.[17] We will use the more contemporary terminology of "Coordination Game" to describe the payoff structure of Fig. 6.

The Coordination Game is *fundamentally different* from the Prisoner's Dilemma, even though Great Power rivalry and concern over the relative payoffs are built into the payoff structures of both games. Both games exhibit the classic collective action problem, in that the worst outcome for a player is to abate (i.e., contribute to paying for the public good) while the other player is a free rider. The difference is that in the Coordination Game, the highest-valued outcome for both parties is achieved when they cooperate, while in the Prisoner's Dilemma the best outcome for a party is to Pollute while the other Abates.

Is global climate protection more like a Prisoner's Dilemma or a Coordination Game? The answer depends on how severe the risk of catastrophic climate change is considered to be. The presence of a (4, 4) payoff means that, if it can be reached, neither party will have an incentive to defect. If one reads the science as saying that climate change is an existential threat to humanity and civilization, at a non-zero probability of sufficient magnitude that it cannot be ignored, then the world is in a Coordination Game. Even if Great Power rivalries and geopolitical competition are strong, there is still sufficient advantage to cooperation to make (Abate, Abate) a sustainable and self-enforcing equilibrium, provided it can first be reached. On the other hand, if *nothing*, not even survival, is more important than winning geopolitical advantage over the other competing powers, the PD characterizes the situation and the outlook for cooperation is dim.

This simple comparison between the Prisoner's Dilemma and the Coordination Game demonstrates that the overriding barrier to achieving an international agreement to protect the climate may be a *failure of the leading governments to grasp the seriousness of the climate risk*. That the governments of all Great Powers care deeply about their relative power and survival in the short run is a given. If we are playing a Coordination Game with the climate, however, it is entirely plausible that self-interest (perhaps reinforced by equity considerations) could help push the system into the Pareto-optimal (Abate, Abate) equilibrium.[18] Economic theory does not offer a clear or firm answer to the problem of equilibrium choice when there are multiple equilibria.[19]

[17] These philosophical and historical precedents of the "Stag Hunt" game are given in Skryms (2001), who recognizes that it expresses one of the fundamental social dilemmas. Stag Hunt is also called the Coordination Game or the Assurance Game (the latter terminology in Sen (1967)). In the 2×2 games with completely ranked ordinal payoffs, all of the following six Coordination Games have the same Nash equilibria as Stag Hunt, but do not satisfy the climate-relevancy criterion that pollution imposes a negative externality (for example, in 333 if Row is Polluting, its payoff is higher if Column also Pollutes than if Column Abates):

Coordination games that are not climate-relevant

Pure coordination: 334			Pure coordination: 343		
	Abate	Pollute		Abate	Pollute
Abate	4, 4*	1, 1	Abate	4, 4*	2, 2+
Pollute	2, 2+	3, 3*	Pollute	1, 1	3, 3*
Coordination: 333			Coordination: 344		
	Abate	Pollute		Abate	Pollute
Abate	4, 4*	1, 2	Abate	4, 4*,+	2, 1
Pollute	2, 1	3, 3*,+	Pollute	1, 2	3, 3*
Asymmetric coordination: 323			Asymmetric coordination: 332		
	Abate	Pollute		Abate	Pollute
Abate	4, 4*	1, 2	Abate	4, 4*	1, 3
Pollute	3, 1	2, 3*,+	Pollute	2, 1	3, 2*,+
Asymmetric coordination: 324			Asymmetric coordination: 342		
	Abate	Pollute		Abate	Pollute
Abate	4, 4*	1, 1	Abate	4, 4*	2, 3+
Pollute	3, 2+	2, 3*	Pollute	1, 1	3, 2*

*Nash equilibria.
+Maxi-min equilibrium.

[18] There have been situations in which international public goods have been provided without an international political regime (see Kindleberger, 1986 for historical examples, although equity concerns were not a focus of Kindleberger's arguments).

[19] There are numerous examples of multiple equilibria in market systems (DeCanio, 2003).

Column's Strategy

		Abate	Pollute
Row's Strategy	Abate	3, 3 +	2, 4 *
	Pollute	4, 2 *	1, 1

* Nash Equilibria
\+ Maxi-min equilibrium

Fig. 7. Climate negotiations as the game of "Chicken": 122.

Nevertheless, if the Coordination Game corresponds to the real-world situation, intelligent diplomacy holds the promise of being able to reach the Pareto-optimal outcome of (Abate, Abate). It is easy to imagine the world's initially being in the (Pollute, Pollute) Nash equilibrium because awareness of the climate change problem is so recent, and that considerable effort and adjustment would be required to attain mutual Abatement. Relatively sudden realization of the magnitude of a global environmental risk is consistent with the history of the negotiation and subsequent success of the Montreal Protocol.

5. Chicken and Related Games

So far, the (Abate, Abate) outcome has been a Nash equilibrium (the Coordination Game and the No Conflict games) or has been Pareto-superior to the Nash equilibrium (the Prisoner's Dilemma family). There are, however, other climate-relevant games for which the Nash equilibrium is for one party to pollute while the other abates. As we noted above, however, the Nash equilibrium is not the only possible equilibrium concept. Risk-aversion is usually thought of as being a characteristic of the agents' *preferences*, but it may alternatively describe their choice of *strategies*. Preferences here are being represented only in ordinal terms, which are invariant under positive monotonic transformations. Thus, the curvature of the "utility function" may be either positive or negative and still have the same rank-ordering, so it makes no sense to talk about risk aversion as a characteristic of the preferences in this context. However, the agents may operationalize their risk aversion by selecting Maxi-min strategies. Risk-averse parties behaving in this way can arrive at an equilibrium different from the Nash equilibrium.

Consider the game of Chicken. Inspection of the payoff matrix in Fig. 7 shows that this game is climate-relevant; Row's payoffs are lower if Column plays Pollute than if Column plays Abate, and vice-versa. The name comes from the "game" in which two teenagers race their cars head-on; the winner is the one who does not swerve aside. First, notice that Chicken has two Nash equilibria — one party Pollutes while the other Abates. Teenage males are not noted for being particularly risk-averse, however, and the outcome when both parties play Maxi-min

426			262		
	Abate	Pollute		Abate	Pollute
Abate	3, 4 +	2, 2	Abate	4, 3 +	3, 4 *
Pollute	4, 3 *	1, 1	Pollute	2, 2	1, 1
Column's DS = Abate			Row's DS = Abate		
421			**212**		
	Abate	Pollute		Abate	Pollute
Abate	3, 4 +	2,3	Abate	4, 3 +	2, 4 *
Pollute	4, 2 *	1, 1	Pollute	3, 2	1, 1
Column's DS = Abate			Row's DS = Abate		

* Nash equilibrium
\+ Maxi-min equilibrium
DS = Dominant Strategy

Fig. 8. Asymmetric games like Chicken.

strategies is (Abate, Abate). In other words, highly risk-averse parties might reach this outcome rather than one of the Nash equilibria.

There are four other climate-relevant games having the same logic as Chicken, in which in the Nash equilibria one party pollutes and the other abates but that have (Abate, Abate) as the Maxi-min equilibrium. These games with their Robinson and Goforth numbers are shown in Fig. 8. In all four of these games (and in Chicken as well), the least-favored outcome for both parties is (Pollute, Pollute). This coupled with the risk-averse choice of Maxi-min strategy leads to the (Abate, Abate) outcome. Note that in Games 426 and 421, Column has a dominant strategy of Abate, while in 262 and 212, Row has Abate as its dominant strategy. Neither party has a dominant strategy in Chicken.

As in the case of the Coordination Game, it is possible to reach a mutual abatement equilibrium without any side payments or changes in the countries' preferences if greater understanding of the risks of climate change were to induce both to adopt a Maxi-min strategy. The presence of a dominant strategy for one of the parties in 426, 421, 262, and 212 means that only the country not having the dominant strategy would have to play a Maxi-min strategy to get to the (Abate, Abate) outcome. As with the Coordination Game, it is quite possible to imagine negotiations serving the function of persuading the country inclined to pollute of the dire risks posed by uncontrolled climate change.

There is a downside to the Maxi-min strategy in these games, however: One party (or both parties in Chicken) has an incentive to defect from the Maxi-min equilibrium. The defecting party can, in effect, exploit the risk averseness of the Maxi-min player. For example, in #212 Abate is the dominant strategy for Row and (Abate, Abate) is the Maxi-min equilibrium. However, by defecting from this outcome and Polluting, Column can improve its payoff from 3 to 4. In addition, the new outcome, (Abate, Pollute), is a Nash equilibrium. This means that although Row's payoff declines from 4 to 2, Row has no incentive to deviate unilaterally from (Abate, Pollute). While playing a Maxi-min strategy can be attractive to a risk-averse player, it may allow a more ruthless competitor to gain the advantage by defecting from the Maxi-min equilibrium.

6. "Unhappy" Games in Which It Is Difficult to Get to an Agreement to Abate

There are six games in which both the Nash equilibrium and the Maxi-min agreement are for one country to pollute while the other abates. These profoundly "unhappy" games are shown in Fig. 9. Four of these games, 261, 211, 416, and 411 are the category of "Type" games as defined by Robinson and Goforth. As they colorfully put it,

> these are games in which the players are asymmetric in the strongest way. One player always gains by making the other better off; the other always loses by making her partner better off. Unlike Chicken and Stag Hunt, in which both players have mixed interests, the motives of players in these Type games are absolutely unmixed.
>
> In Type games the players live in different moral universes. One type is never led into temptation, the other is never free of temptation. One needs no moral instruction, the other must be restrained by law. One freely casts his bread upon the water and the Lord provides, while the other must live by theft. These games seem perfectly suited for exploring a whole class of morally ambiguous situations — cases in which agents may debate morality from fundamentally different material situations (2005, p. 124).[20]

If Climate is one of these games, the prospect of reaching an agreement by both parties to Abate is bleak. For example, Abate is a dominant

[20] Robinson and Goforth note that Type games have appeared previously in the literature, in Schelling (1963) and Licht (1999). There appears to be no previously standard terminology to denote this class of games, so we follow Robinson and Goforth in calling them "Type" games.

121		
	Abate	Pollute
Abate	3, 3	2, 4 *,+
Pollute	4, 1	1, 2

112		
	Abate	Pollute
Abate	3, 3	1, 4
Pollute	4, 2 *,+	2, 1

The Four Climate-Relevant "Type" Games

261		
	Abate	Pollute
Abate	4, 3	3, 4 *,+
Pollute	2, 1	1, 2

211		
	Abate	Pollute
Abate	4, 3	2, 4 *,+
Pollute	3, 1	1, 2

416		
	Abate	Pollute
Abate	3, 4	1, 2
Pollute	4, 3 *,+	2, 1

411		
	Abate	Pollute
Abate	3, 4	1, 3
Pollute	4, 2 *,+	2, 1

* Nash equilibrium
\+ Maxi-min equilibrium

Fig. 9. The six "unhappy" Climate-relevant games.

strategy for Row in #261 and #211 and Column is better off when Row abates than if Row were to pollute in both games. However, Pollute is Column's dominant strategy in both of these games, and furthermore, Column's playing Pollute hurts Row in both games. Row's dominant strategy benefits Column, but Column's dominant strategy harms Row. The players "live in different moral universes." It is possible to visualize the climate debate in these terms, listening to the rich developed nations and the poor developing countries "talk past each other." If this payoff structure prevails in the real world, abatement is the dominant strategy for the rich nations and benefits the developing nations as well, while Pollute (i.e., putting economic growth above anything else) is the dominant strategy for the developing countries and harms the already-developed nations. Note that the outcome (Pollute, Pollute) is not ranked worst by Column (the developing countries in this illustration). Climate stabilization could be achieved in this case only by some combination of carrot and stick (side payments and coercion) to change Column's ranking of the outcomes.

7. Games with no Pure-Strategy Nash Equilibrium

There is one final pair of games to be counted. These are called Cycle, and in both of them there is no pure-strategy Nash equilibrium. The Maxi-min equilibrium is one in which one country Pollutes and the other Abates (Fig. 10). These two games are symmetrical, and they tell a story of futility. Suppose both Row and Column start out playing Pollute in #422. It would be in Row's interest to switch its strategy and begin playing Abate. But from (Abate, Pollute), it would be in Column's interest to start playing Abate. Then from (Abate, Abate) it would be in Row's interest to switch to Pollute. This would in turn give Column an incentive to go back to Pollute, and the game would be at the (Pollute, Pollute) outcome where it started. The cycle would repeat without ending. Ironically, the outcome (Abate, Abate) is Pareto-superior to the Maxi-min equilibrium of (Abate, Pollute), but it is not self-sustaining. An international agreement with incentives and/or enforcement provisions outside the payoff matrix would be necessary to maintain (Abate, Abate).

Cycle: 422		
	Abate	Pollute
Abate	3, 4	2, 3 +
Pollute	4, 1	1, 2

Cycle: 222		
	Abate	Pollute
Abate	4, 3	1, 4
Pollute	3, 2 +	2, 1

\+ Maxi-min equilibrium

Fig. 10. Games with no Pure-Strategy Nash Equilibrium.

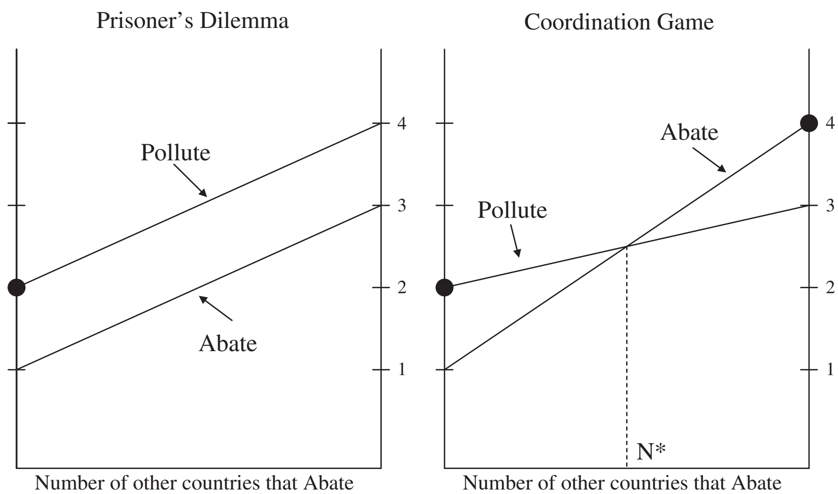

Fig. 11. The Prisoner's Dilemma and Coordination in N-player games.

8. Multi-player Climate Games

We have concentrated on 2×2 ordinal games because it is possible to treat them exhaustively. Quite clearly, the complexity of the topology would increase dramatically with the number of players and strategic options.[21] Following Barrett (2003), it is much easier to discuss generalizations to *N*-player games if the players are identical and the payoffs can be expressed as cardinal measures. If this is the case, it is possible to represent the payoffs for a particular player succinctly in a graphical format. In Fig. 11 (using Barrett's graphical representation),[22] the vertical axis gives the payoffs for any country to abate or pollute, as a function of how many other countries abate. It is clear why the payoff to both polluting and abating increases with the number of other countries that abate. This simply illustrates our second condition that there be a negative externality to polluting. Additionally, the benefits from abating might increase with the number of countries abating if countries following the same environmental path benefit from the spillovers of technological change coming about because of the abatement policies, and increased trade accompanies both the diffusion of abatement technologies and adoption of standards that favor the cleaner technologies.

In the Prisoner's Dilemma half of Fig. 11 the Pollute payoff line lies everywhere above the Abate payoff line.[23] What turns the situation into a Coordination Game is if the Abate line crosses the Pollute line. In the Prisoner's Dilemma case, there is only one Nash equilibrium (represented by the heavy black dot on the left-hand vertical axis), but in the case of the Coordination Game, there are two Nash equilibria, one in which all countries pollute and the other in which all abate (shown by the two heavy dots in the right-hand half of Fig. 11). In the Coordination Game, the best strategy depends on what other countries do. If fewer than N^* countries initially abate, then the payoff for each country to abate is less than the payoff to pollute, and all countries will (eventually) settle toward the equilibrium in which all pollute. However, if more than N^* countries abate, then the payoff to Abate is greater than the payoff to Pollute for each country, and the countries will settle toward the equilibrium in which all abate. In a dynamic negotiation setting, what matters is whether a critical mass of countries can agree to abate. If that kind of agreement can be reached, the payoff structure induces all the remaining countries to abate as well.

Therefore, it is critically important to know whether countries face a situation that better resembles an N-player Prisoner's Dilemma or an N-player Coordination Game. If each country's business-as-usual emissions have negligible effect on the climate, it might be the case that the payoff to polluting will always exceed the payoff to abating no matter what other countries do. Then countries would be stuck in the Prisoners' Dilemma where the dominant strategy is always to pollute. However, there are two strong reasons for doubting that this accurately describes the situation with respect to climate change.

First, any major country (e.g., the United States or China) is large enough that its business-as-usual emissions alone would eventually disrupt the climate with potential for catastrophic global damage. In 2009 US CO_2 emissions from energy use were 18% of the world's total, and China's were 25% (U.S. Energy Information Administration, 2011). In the case or large countries, the imperative to avoid the risk of disaster may well outweigh other economic factors in the country's decision-making process. With the biggest emitters accounting for such large fractions of global emissions, a model that treats each country as identical and only a minor contributor to the externality is inapplicable.

Second, this perspective, in which the avoidance of catastrophic risks is of paramount importance, is increasingly being recognized as central to the economic analysis of climate change. For example, Weitzman (2009) rigorously develops "a basic theoretical principle that holds under positive relative risk aversion and potentially unlimited exposure. In principle, what might be called the catastrophe insurance aspect of such a fat-tailed unlimited-exposure situation, which can never be fully learned away, can dominate the social-discounting aspect, the pure-risk aspect, and the consumption-smoothing aspect" (2009, p. 18). In this Special Issue of *Ecological Economics*, Chanel and Chichilnisky (2011-this issue)[24] offer experimental evidence showing that the conventional expected utility framework mischaracterizes how people respond to potential catastrophes. Chichilnisky's axiomatic framework formalizes "a theory of choice under uncertainty where rare but catastrophic events (such as death) are given a treatment in symmetry with the treatment of frequent events" (Chanel and Chichilnisky, 2011-this issue). The consequence is a policy approach much more consistent with both common sense

[21] Computing a Nash equilibrium in which each player obtains an expected payoff of at least a certain level and determining the uniqueness of a Nash equilibrium are NP-hard problems, i.e., are computationally intractable (Gilboa and Zemel, 1989; see also Borgs et al., 2008). Interestingly, the problem of finding a "correlated equilibrium" as defined by Aumann (1974) is computationally tractable (Gilboa and Zemel, 1989).

[22] Barrett (2003) credits the idea for this type of figure to Schelling (1978).

[23] It should be noted that the lines representing the payoffs do not need to be straight. The logic is the same for any monotonic payoff functions.

[24] They draw on prior theoretical work by Chichilnisky (2000, 2009).

and experimental evidence. A "new climate economics" must assimilate the implications of these kinds of results.

An international agreement also could transform a PD into a Coordination Game through positive or negative incentives that would shift upward, increase the slope, or change the shape of the Abate and Pollute payoff functions, to transform the Prisoners' Dilemma into a Coordination Game. It would be possible to design an agreement that builds in excludable benefits to signatories. This is the approach favored by Barrett (2003). If the Abate strategy line were shifted up, the critical mass of countries needed to ensure that mutual abatement was a stable equilibrium would decrease. What kinds of exclusionary benefits could be included in an international climate change treaty? Clearly, different sorts of countries might be attracted by different sorts of benefits. Transfers of wealth from rich countries to poor countries are a very important example of exclusionary benefits (although Barrett dismisses per capita allocation of emissions rights as a political impossibility in rich countries (p. xiv)). Such transfers would not necessarily have to benefit one Great Power at the expense of another if the recipient countries are not major players on the global political stage. Transfers to Angola, Palau, or the Dominican Republic are not equivalent to transfers to China, although all three of the former countries have per capita incomes close to China's (Central Intelligence Agency, 2011). Given continuing Great Power rivalry, it is important to distinguish between small developing countries that would have difficulty mobilizing resources for clean energy investments and the "Other Major Economies" (OMEs), to use the terminology of the IEA.[25]

It certainly must be the case that low-carbon energy has to be a component of sustainable development for poor countries currently seeking to improve their standards of living. The big question, then, is what benefits could a climate treaty offer rich countries in exchange for dramatically cutting their emissions and providing investment funds and technology to poor countries? Barrett's proposals suggest that there could be some exclusionary benefits to joint work on technological innovation and the setting of standards. If a critical mass of participating countries agreed to invest together in R&D and share the successes exclusively among participants, the benefits of participation may outweigh the costs for each individual country. Trade advantages could be extended to participants, and/or trade sanctions imposed on non-participants. More broadly, participants might formally or informally agree to work together on a range of international issues, with non-participants treated as rogue states. This is not so far-fetched. The failure to ratify the Kyoto Protocol by the United States arguably made it more difficult for us to find allies on other issues, such as the wars in Afghanistan and Iraq (Chayes, 2008). Larger groups of countries make more technological discoveries, and offer the possibility of more valuable alliances. Finally, investments in advanced non-fossil energy technologies in developing countries could be a means by which Great Powers seek to expand their influence.

9. Discussion and Summary

We have examined the entire set of 25 climate-relevant 2 × 2 order games — eight of the "no conflict" variety, the Prisoner's Dilemma and its two related Alibi games, the Coordination Game, Chicken and its four related asymmetric relatives, the six "unhappy" games in which it is difficult to reach an agreement to Abate, and the two Cycle games that have no pure-strategy Nash equilibrium. Instead of picking one or more examples on an ad hoc basis, we have covered every possibility for describing the strategic interactions that might characterize the international climate negotiations.

Our exhaustive treatment of the climate-relevant 2 × 2 order games suggests several general conclusions. The first, and perhaps the most important, is that *there is no reason to assume that the Prisoner's Dilemma is the best description of the climate negotiations*. The most favorable situation would be if the climate game were of the "no conflict" variety. If it were, there should be no barrier to an agreement, although negotiations might still be necessary to overcome Maxi-min tendencies and achieve the Pareto-optimal outcome. The absence of progress in the negotiations suggests, however, that the "no conflict" payoff structure is not the real-world situation. However, a payoff structure that is entirely consistent with the current state of scientific knowledge is that of the Coordination Game. If this is the true state of the world, reaching a global agreement boils down to a problem of *equilibrium choice*. While economics can offer some help in this (by ruling out wasteful, inconsistent, or self-defeating approaches), solution to the equilibrium choice problem falls at least partly outside the realm of economics. In particular, fairness could have a bearing on selecting the equilibrium.

Second, *the Nash equilibrium is not the only possible solution concept*. Risk aversion and a lack of trust can lead countries to adopt a Maxi-min strategy, although under some payoff configurations this runs the risk of being exploited by the other player. Again, there is no hard-and-fast guideline here. Economists have tended to favor the Nash equilibrium because of its correspondence to Walrasian general equilibrium, but the Nash solution is prone to exhibit multiplicities. Maxi-min strategies often reach a Nash equilibrium, but sometimes they do not. In any case, Nash equilibrium should not simply be equated with "rationality" on the part of the players.

Third, for the climate problem *it may be that different countries are operating in different moral universes, or that their material circumstances are so divergent that cooperation on climate is very difficult*. The existence of climate-relevant Type games raises this possibility. If this is indeed the situation, or if the climate game really is a Prisoner's Dilemma, then a range of incentives and inducements to cooperate may be needed to reach an acceptable international agreement. Even in the games in which the players are as oppositely motivated as possible (the Type games) it is possible that a well-thought-out negotiating strategy coupled with suitable side payments and negative incentives could bring about an agreement to Abate.

Fourth, *slight changes in the preferences of the players can dramatically change the prospects for a climate agreement*. This is equivalent to Perlo-Freeman's conclusion that "a small change in the preference ordering by one player can lead to a radical change in the resulting Nash equilibrium" (2006, p. 2). In the context of climate, we have shown how slight modification of the preferences giving rise to the Prisoner's Dilemma can transform the situation into a Coordination Game. As long as the preference orderings are subject to modification through the diffusion of scientific information and diplomatic negotiations, there is room for optimism that a solution to the climate problem can be reached.

Given the imperatives of economic development and poverty reduction, it seems likely that transfers from rich countries to poor countries, in the form of low-carbon or zero-carbon energy supply technologies, will be essential to induce the poorest developing countries to participate. However, there is no reason that the investments in low-carbon energy technologies made in these countries have to disrupt or destabilize Great Power relationships. Such investments could be part of a relatively healthy form of Great Power competition, because diffusion of the technologies could contribute to the spread of a powerful nation's influence without resort to coercion or war.

[25] The OMEs are "[t]he largest emitting countries outside OECD+ (based on their total emissions of energy-related CO_2 in 2007), with gross domestic product (GDP) per capita that is expected to exceed $13,000 in 2020. The countries belonging to this group are China, Russia, Brazil, South Africa, and the countries of the Middle East." The OECD+ includes the members of the EU that are not part of the OECD, and Middle Eastern countries are Bahrain, the Islamic Republic of Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syrian Arab Republic, the United Arab Emirates and Yemen, as well as the neutral zone between Saudi Arabia and Iraq (International Energy Agency, 2009, pp. 201 and 672).

The game-theoretic examples do demonstrate, however, that a unilateral approach to emissions reduction may not be the best strategy for a country like the United States. In both the PD and the Coordination Game, the least-preferred outcome for either party is if it abates while the other pollutes. Of course, it is possible that early action to abate emissions will confer an advantage in the development of clean energy technologies. In the Coordination Game, unilateral adoption of the Abate strategy by one of the major countries or blocs may increase the incentive for others to abate or be a signal to others that moving to the (Abate, Abate) Nash equilibrium would beneficial for all. But if one of the Great Powers (or set of GPs) holds as its highest goal the short-run maximization of its relative power, domestic abatement measures by the others will be in vain. Business as usual by either the US or China (or, for that matter, the EU, India, or the rest of the world collectively) will threaten climate stability no matter what actions are taken by any one country or subset of countries. In the Chicken family of games, prior commitment to Abate by the nation whose dominant strategy is Abate guarantees that the other will Pollute. Only if the other nation follows a Maxi-min strategy can the (Abate, Abate) outcome be obtained, and this will not happen if the first party announces in advance of the play of the game that it will Abate.

The most serious difficulties in reaching a global climate protection agreement arise if one of the major countries (the ones whose emissions alone are enough to produce dangerous anthropogenic interference with the climate) ranks highest the outcome in which it pollutes while the rest of the world abates. All of the “unhappy” games as well as the PD and the Chicken family have this feature. In the Chicken games, all parties playing Maxi-min can lead to mutual Abatement, although one party's playing Maxi-min can be exploited by the other. In the “unhappy” games both the Nash equilibrium and the Maxi-min equilibrium risk climate catastrophe.

The NPT for order games may be helpful in pointing the way to resolving the diplomatic impasse. Bruns (2010, 2011) notes how “swaps,” defined as switching the ranks of outcomes for a player, can transform one climate-relevant game into another. Some games are transformed rather easily; all of our “unhappy” games can be converted into games with a (4, 4) Nash equilibrium by swapping the payoffs 3 and 4 for either one or both players. For example, the Type game 261 becomes the No-conflict game 362 if Column's rankings 3 and 4 are swapped, and Chicken becomes No-conflict game 311 if payoffs 3 and 4 are swapped for both Row and Column. As noted earlier, one possible way a government's rankings can change is through greater understanding of the science that underlies assessment of the risks of climate change. Side payments or negative incentives such as trade sanctions are also feasible instruments, but because we are discussing only ordinal games we cannot say how large the side payments (or side-punishments) would have to be to make these transformations. Of course, there is no way to force sovereign governments to accept the science. As a character in one of Schiller's (1801) plays said long ago, “Mit der Dummheit kämpfen Götter selbst vergebens.”

Practical policy will come down to (1) how serious the long-term climate risk is considered to be, (2) whether the governments of the Great Powers (i.e., the nations that decisively shape the negotiations) genuinely care about future generations, (3) whether climate abatement policies can be devised that do not give an advantage to one or a subset of the Great Powers, and (4) whether suitable instruments can induce the necessary investments in clean energy and efficient end-use technologies while simultaneously promoting economic growth in the poorest developing countries.

The greatest reason for optimism is that science is universal; understanding the risks of climate change can eventually bring all major governments to realize that Abatement is in their long-run interest. Diplomacy also can work to create incentives that will push the governments towards cooperation. Like economics more generally, game theory can offer guidance for the successful navigation of these diplomatic shoals, but is not by itself able to demonstrate the solution.

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References

Ackerman, Frank, DeCanio, Stephen J., Howarth, Richard B., Sheeran, Kristen, 2009a. Limitations of integrated assessment models of climate change. Climatic Change 95, 297–315.

Ackerman, Frank, Stanton, Elizabeth A., DeCanio, Stephen J., Goodstein, Eban, Howarth, Richard B., Norgaard, Richard B., Norman, Catherine S., Sheeran, Kristen A., 2009b. The Economics of 350: The Benefits and Costs of Climate Stabilization. Economics for Equity and Environment. http://www.e3network.org/papers/Economics_of_350.pdf (accessed 6-20-10).

Aumann, Robert J., 1974. Subjectivity and correlation in randomized strategies. J. Mathematical Economics 1, 67–95.

Axelrod, Robert, 1984. The Evolution of Cooperation. Basic Books, New York.

Barrett, Scott, 2003. Environment & Statecraft: The Strategy of Environmental Treaty-Making. Oxford University Press, Oxford.

Borgs, Christian, Chayes, Jennifer, Immorlica, Nicole, Kalai, Adam Tauman, Mirrokni, Vahab, Papadimitriou, Christos, 2008. The myth of the Folk Theorem. STOC '08. Proceedings of the 40th Annual ACM Symposium on Theory of Computing, pp. 365–372. May 17–20.

Brams, Steven, 1977. Deception in 2×2 games. J. Peace Science [Conflict Management and Peace Science] 2, 177–203.

Brams, Steven, 1983. Superior Beings. Springer-Verlag, New York.

Bruns, Bryan, 2010. Transmuting Social Dilemmas into Win–Win Games: Payoff Families in the Topology of 2×2 Ordinal Games. http://www.bryanbruns.com/Bruns,%20Bryan%202010%20Transmuting%20social%20dilemmas%20into%20win-win%20games100722.pdf (accessed 4-7-2011).

Bruns, Bryan, 2011. Personal communication 3–22–2011.

Central Intelligence Agency, 2011. The World Factbook. https://www.cia.gov/library/publications/the-world-factbook/rankorder/2004rank.html (accessed 4-7-2011).

Chanel, Olivier, Chichilnisky, Graciela, 2011-this issue. Valuing life: experimental evidence using sensitivity to rare events. Ecological Economics.

Chayes, Antonia, 2008. How American treaty behavior threatens national security. International Security 33, 45–81.

Chichilnisky, Graciela, 2000. An axiomatic approach to choice under uncertainty with catastrophic risks. Resource and Energy Economics 22, 221–231.

Chichilnisky, Graciela, 2009. The topology of fear. J. Mathematical Economics 45, 807–816.

DeCanio, Stephen J., 2003. Economic Models of Climate Change: A Critique. Palgrave Macmillan, New York.

Donnelly, Jack, 2000. Realism and International Relations. Cambridge University Press, Cambridge.

Gilboa, Itzhak, Zemel, Eitan, 1989. Nash and correlated equilibria: some complexity considerations. Games and Economic Behavior 1, 80–93.

Hardin, Russell, 2008. Indeterminacy and basic rationality. In: Ciprut, Jose V. (Ed.), Indeterminacy: The Mapped, the Navigable, and the Uncharted. The MIT Press, Cambridge.

Holcombe, Randall G., Sobel, Russell S., 2001. Public policy toward pecuniary externalities. Public Finance Review 29, 304–325.

Ingrao, Bruna, Israel, Giorgio, 1990. The Invisible Hand: Economic Equilibrium in the History of Science. The MIT Press, Cambridge.

International Energy Agency (IEA), 2009. World Energy Outlook 2009. OECD/IEA, Paris.

Kindleberger, Charles, 1986. International public goods without international government. Am. Econ. Rev. 76, 1–13.

Licht, Amir N., 1999. Games commissions play: 2×2 games of international securities regulation. Yale J. International Law 24, 61–128.

Nash, John, 1950. Equilibrium points in n-person games. Proceedings of the National Academy of Sciences 36, 48–49.

Nash, John, 1951. Non-cooperative games. Annals Mathematics 54, 286–295.

Perlo-Freeman, Sam, 2006. The Topology of Conflict and Co-operation. Bristol, UK: Discussion Papers 0609, University of the West of England, Department of Economics. http://ideas.repec.org/p/uwe/wpaper/0609.html (accessed 8-30-2010).

Rapoport, Anatol, Guyer, Melvin, 1966. A taxonomy of 2×2 games. General Systems Yearbook of the Society for General Systems Research 11, 203–214.

Robinson, David, Goforth, David, 2005. The Topology of the 2×2 Games: A New Periodic Table. Routledge, New York.

Schelling, Thomas C., 1963. The Strategy of Conflict. Oxford University Press, Oxford.

Schelling, Thomas C., 1978. Micromotives and Macrobehavior. W. W. Norton & Company, Inc, New York.

Schiller, Johann Christoph Friedrich von, 1801. The Maid of Orleans. Cited in http://en.wikipedia.org/wiki/Friedrich_Schiller (accessed 4-7-2011).
Sen, Amartya, 1967. Isolation, assurance, and the social rate of discount. Quarterly J. Economics 81, 112–124.
Shubik, Martin, 1983. Game Theory in the Social Sciences: Concepts and Solutions. The MIT Press, Cambridge.
Skryms, Brian, 2001. The Stag Hunt. Presidential Address, Pacific Division of the American Philosophical Association. http://www.lps.uci.edu/home/fac-staff/faculty/skyrms/StagHunt.pdf (accessed 6-20-10).
Stanton, Elizabeth A., 2010. Negishi welfare weights in integrated assessment models: the mathematics of global inequality. Climatic Change. doi:10.1007/s10584-010-9967-6.
Stein, A.A., 1990. Why Nations Cooperate: Circumstance and Choice in International Relations. Cornell University Press, Ithaca.
Sunstein, Cass, 2007. Of Montreal and Kyoto: a tale of two protocols. Harvard Environmental Law Review 31, 1–65.
U.S. Energy Information Administration, 2011. International Emissions. http://www.eia.doe.gov/environment/data.cfm (accessed 4-15-2011).
Velders, Guus J.M., Andersen, Stephen O., Daniel, John S., Fahey, Daniel W., McFarland, Mack, 2007. The importance of the Montreal Protocol in protecting climate. Proceedings of the National Academy of Sciences USA 104, 4814–4819.
von Neumann, John, 1928. Zur Theorie der Gesellschaftsspiele [On the Theory of Parlor Games]. Mathematische Annalen 100, 295–300.
von Neumann, John, Morgenstern, Oskar, 1944. Theory of Games and Economic Behavior. Princeton University Press, Princeton.
Weitzman, Martin, 2009. On modeling and interpreting the economics of catastrophic climate change. The Review of Economics and Statistics 91, 1–19.