Game-Theoretic Analysis of Climate Change

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Abstract

Climate Change, today, is arguably the biggest problem faced by planet Earth. We are witnessing warmer global temperatures, rising sea levels, shrinking ice sheets and increasing number of extreme weather events. At the present rate, it is predicted that by mid-century, the arctic would become ice free, the ocean levels would rise by 1-4 feet submerging several, presently inhabited regions and an order of magnitude increase in the occurrence of droughts and heat waves. In the absence of a global governing body, there is a need for a set of self-enforcing rules and guidelines, that coerce nations to do their bit in moving toward sustainable development. In the face of this global challenge, representatives from countries around the world have been successful in negotiating a treaty which may be our only hope towards reversing climate change. Considering the fact that previous attempts to come at an agreement have failed, it has become imperative to critically analyze the status quo and work towards a robust agreement. We employ a game-theoretic approach to gather insight about the current situation.

1 Introduction

The last century has seen a drastic rise in average global temperatures. Especially, the past decade has seen an increased frequency in extreme weather patterns. Rising sea levels has resulted in a significant portion of several island nations being submerged under water. Though several people argue that this is a natural phenomenon, there is irrefutable evidence that rapid industrialization in the past century leading to increased emission of greenhouse gases(GHGs) has been largely responsible for a globally changing climate. If the present trends continue, average global temperatures are expected to rise from 2^o C to 5^o C in the next century. An increase at such a scale could create severe imbalances in the ecosystem and threaten the very existence of mankind.

Climate change is a global challenge and requires a global solution. Actions by one country to reduce emissions will do little to slow global warming and may even end up hurting the country unless other countries act as well. This leaves little or no incentive in taking any major steps towards curbing emissions, in the first place. Therefore, an effective strategy to reverse climate change will require commitments and action by all the countries across the globe. The recently adopted Paris Agreement is a major step in this direction. The treaty is the outcome of years of negotiation and several failed attempts.

Though scientists pointed out the threats of climate change as early as the 1950s, only in the 1990s did it begin to garner serious attention from governments across the world as a potential threat to the global economy. The Rio Earth Summit, held in 1992, was attended by more than 170 governments. A major outcome of the Earth Summit was the establishment of the U.N. Framework Convention on Climate Change (UNFCC), which became the home for all climate-related negotiations globally. It was decided that the framework would be followed by sessions of the Conference of the Parties (COP) and its subsidiary bodies to negotiate and agree upon further action.

Kyoto Protocol

The first attempt to broker a global treaty was made at COP3, held at Kyoto, Japan in 1992. As reports from the newly-formed Intergovernmental Panel on Climate (IPCC) began to form a scientific consensus on the problem, the threats of climate change became apparent.

The Kyoto Protocol was considered weak by many. Besides the glaring absence of the United States, and fellow major-polluter Australia, it put almost no limits on the ability of developing countries to emit CO_2. This meant that, even as countries in Europe and Japan slowed down their emissions, they were more than made up for by the boom in emissions from the global South, especially the rising powerhouse China, who in 2007 overtook the United States to become the world biggest carbon emitter. Global carbon emissions continued to rise throughout the early implementation of Kyoto.

Paris Agreement

After breakdown of the Kyoto Protocol and failed attempts at reaching a consensus at Copenhagen, the Paris Agreement was adopted at COP21 at Paris in Dec, 2015. The aim of the treaty is:

- Holding the increase in the global average temperature to well below 2^o C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5^o C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change.

- Increasing the ability to adapt to the adverse impacts of climate change and foster climate resilience and low greenhouse gas emissions development, in a manner that does not threaten food production.

- Making finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development.

According to the treaty, each country has to declare their Nationally Determined Contributions(NDC) which details the steps that they would take to meat the targets set by the treaty.

2 Related Work

There has been a lot of work in modeling various aspects of the problem previously. In [2], Green-house Gases, the cause of global warming and their levels have been modeled as variables, affected by the actions of nations in a dynamic game. In [3], environmental negotiations that resulted in the Kyoto Protocol and its aftermath are modeled as a coalition game.

2.1 Kyoto Protocol from Game-Theoretic Perspective

The paper analyses the Kyoto Protocol by modeling it as a game between countries, that are considered equal in all respect and comes to the conclusion that it is not stable, i.e. if one country leaves the treaty then the other countries obtain an incentive to leave too. This was also seen in reality as the treaty broke down after Canada left the Kyoto Protocol. It further discusses transfer of funds from developed to developing nations, threats that should be put in place to discourage countries from defaulting and other such issues to stabilise the treaty in a real setting.

2.2 Self-Enforcing Climate Change Treaties

The popular Kyoto treaty does not lay the base of a Self Enforcing Treaty. Such a treaty says that if a country expects other countries to abide by the treaty, then it is in it's self interest to abide by the treaty too. The work [1] by *Dutta et.al.* aims to come up with self-enforcing treaties by modeling the current negotiations as a suitably defined dynamic game, where the GHG emissions and the GDP as a function of time are taken as strategies and payoff of a country. They argue, that a self-enforcing treaty can be modeled as the Nash Equilibrium of such a game.

3 Two-Player Game

To begin with a simple case, we will try to model the climate change negotiations between only two players. This game is worth analysing since the two major polluters China and United States, together account for 44% of the emmissions. Considering this game would give us insight into the various intricacies involved in the creation of a successful pact. Another fact worth considering is that if the two major polluters disagree to cooperate and do not take steps to curb their greenhouse gas (GHG) emissions, then the less significant polluters would have no incentive to cooperate.

Let the two players involved in the game be A and B. For the sake of simplicity, we assume that both the players are equal in all respects. Though each player has a continuum of actions at its disposal, we will consider the availability of just two actions; cooperate and reduce emissions or defect and focus solely on economic development, even at the cost of environmental degradation. Several factors need to be taken into account before designing the payoff matrix. These include, the cost of taking steps towards reducing emissions; amount of exploitation of natural resources and its impact on the economy and the environment etc.

In the initial phase when the problem of pollution and its impacts were in their infancy, one would agree that the advantages of indiscriminate exploitation of natural resources for economic development far outweigh protection of the environment. The payoff matrix for this case would resemble Table 3

		Player B	
		Cooperate	**Defect**
Player A	**Cooperate**	1,1	1,3
	Defect	3,1	3,3

Table 1: The payoffs in the initial phases of a deteriorating environment

The narrow and short-sighted view of the future taken by human beings, that results in common problems such as procrastination, is the main culprit in this case too. All these factors will change in importance with time, as environmental degradation accelerates. As time progresses, the limited stock of natural resources will take a serious hit and deriving benefit from their exploitation would not remain as lucrative as investing in curbing emissions, renewable energy and protection of the environment. The payoff matrix would change drastically:

		Player B	
		Cooperate	**Defect**
Player A	**Cooperate**	1, 1	0.5, 0.5
	Defect	0.5, 0.5	0, 0

Table 2: The payoffs when the environment has been significantly deteriorated

Now consider a general case involving n players and a continuum of actions.

- The amount of resources consumed by the player i is $r_i(t)$
- The amount of emissions by a player i or in general its carbon footprint is e_i which is a function of r_i, say $e_i(t) = f_i(r_i(t))$
- A player's economic development is also a function of $r_i(t)$, say $D_i(r_i(t))$
- Finally the environmental loss due to emissions is a function of the collective emissions by all countries, $L_i(E(t))$ where $E(t) = \sum_{i=1}^{n} e_i(t)$

Note the fact that the functions D (amount of benefit derived from the given natural resources) and f (amount of damage caused to the ecosystem by the use of certain resources) depend upon the technology and policies adopted by the players.

The payoff for player i, $P_i(t)$ is as follows:

$$P_i(t) = D_i(r_i(t)) - \frac{L_i(E(t))}{n}$$

This is simply the gains from exploitation of natural resources versus the damage done to the environment.
After making the following reasinable assumptions, we can make useful inferences.

- D_i is an increasing function of r_i.
- L is an incr function of e_i, which is a decr function of r_i.
- Since r_i is limited and in general decreasing, with time $P_i(t)$ would decrease, if we assume the functions to be static.
- Options that will remain to maximise the payoffs and keep them from falling to very small values are:
  - Slow down decreasing $r(t)$, i.e. use resoures judiciously.
  - Improve function f and D_i, i.e. invest in technology and make policy decisions favouring the environment.

The rate at which we are currently polluting and damaging the ecosystem is unsustainable. The point is not far, when efforts of any magnitude will fail to revese the damage caused. This point may potentially occur before the payoffs tip the equilibrium favourably. The question therefore, is not whether an equlibrium, that is conducive towards sustainable development, be reached. A more pertinent question is wheher we can enforce mechanisms that can quicken the pace at which we move towards this equlibrium, before it is too late.

Another way of looking at the problem may be as a game between the environment and human beings. The aim of the environment being to maintain a stae of low energy and that of the human being to enusre his survival. Let the state of the environment be represented by s. Based on this state the human player calculates his payoffs p and determines and action α to be performed on the environment to maximise his payoff. This action performed by the player changes the state of the environment, and the cycle continues. Therefore at any time instant t, $s_t = f(s_{t-1}, \alpha_{t-1})$ and $p_t = g(s_t)$ is obtained on perfoming $\alpha_t = \alpha_{p_t}$.

4 The Coalition Perspective

4.1 Definitions and Assumptions

Assuming the game is being conducted between N countries. Consider the game $G = (N, X_i, u_i)$ where $i \in 1..N$ and X_i are set of strategy for player i and u_i is payoff of player i. A coalition structure is as follows: $\tau = \{C_1, C_2, ..C_m\}$, where $C_i \bigcap C_j = \phi$ for $i \neq j$ and $\bigcup_{i=1}^{m} C_i = N$. Consider a partition function $p : \tau \to \mathbb{R}^N$, which maps a coalition structure to the payoff of countries. $p(C_i, \tau)$ represents the payoff of a country when it belongs to C_i in the coalition structure τ.
Some key assumptions are as follows:

1. All countries decide their strategy simultaneously.
2. All counties/players are symmetric.
3. Inside a coalition, players work together to maximize the coalition surplus. This is similar to the co-operation game.
4. Each player in a coalition receives the same payoff as the other members, since countries are symmetric in the game.
5. Every country/player has only two choices, whether to sign the treaty or not.
6. Payoff increases monotonically with coalition size for the countries/players in coalition.

4.2 The Game

4.2.1 Instability of a Global Treaty

Climate is a public good and as a result it also suffers from **Tragedy of commons**.The tragedy of the commons is an economic theory of a situation within a shared-resource system where individual users acting independently according to their own self-interest behave contrary to the common good of all users by depleting or spoiling that resource through their collective action. Climate Change is a global phenomena and affects everyone, and hence all countries. Also, it is important to note that, taking actions for reducing emissions comes with a cost and affects the development and production within a country. Let us assume that every country signs the global treaty. Now, for a particular country, there will always be an incentive to defect from the treaty, since it will reap the benefits of other's efforts, without paying the cost of taking the steps. The payoff in defecting is thus, much greater than co-operating, for this country. This can be easily seen with the following model:

$N > 2$ $0 \leq x_i \leq 1$ be effort by a country and $b = 2\sum_{i=1}^{N} x_i$ is collective benefit of all countries.
$b_i = b/N$ be the benefit of individual country.
$\pi_i(x) = b/N - x_i$ be the payoff to a country.
Consider i=1 and it's difference of payoff for $x_1 = 0$ and $x_1* = x_1 (\neq 0)$ considering other player have same strategy
$2/N(\sum_{i=2}^{N} x_i) - 2/N(\sum_{i=1}^{N} x_i) + x_1$
$x_1(1 - 2/N)$,SO the dominated strategy for the player is $x_1 = 0$ and hence players will have tendency to defect. As a result the global treaty give a chance for emergence of **Free riders**. However if all countries put an effort $x_i = 1$ then the payoff is *Pareto optimal* and it's better off for individuals and collective society both.

4.2.2 Free Riders

The countries/players defecting and thus not a part of the coalition are called free-riders. Their are two different behaviors of free-riders:

- **Orthogonal:** Free Riders cannot damage the coalition and just benefit from the cooperative action of the coalition.
- **Non-Orthogonal:** Free Riders can damage the coalition by increasing their productions(and thus emissions) whenever, the players in coalition reduce theirs. This implies that the players in coalition lose in this case.

4.2.3 Stability

- **Internal Stability:** A coalition is internally stable if no player in that coalition is better off by defecting and playing as a singleton.

$$p(c;\tau) \geq p(1;\tau')$$

where $\tau = \{c, 1_{(n-c)}\}$ and $\tau' = \tau \backslash \{c\} \cup \{c-1, 1\}$

- **External Stability:** A coalition is externally stable if no singleton player is better off by joining the coalition.

$$p(1;\tau) > p(c';\tau')$$

where $\tau = \{c, 1_{(n-c)}\}$ and $\tau' = \tau \backslash \{c, 1\} \cup \{c+1\}$

A country/player, therefore, has the following **incentive function** to join a coalition c:

$$L(c) = p(c;\tau) - p(1;\tau')$$

where $\tau = \{c, 1_{(n-c)}\}$ and $\tau' = \{c-1, 1_{n-c+1}\}$ A stable coalition has the size $c*$, which is defined as $[\tilde{c}]$, where $L(\tilde{c}) = 0$ and $L'(\tilde{c}) < 0$.

4.2.4 Nash Equilibrium

We have seen that the countries benefit more from a larger coalition size, and may lose if the coalition size is less than a certain size. Let's say that the minimum size of a profitable coalition(where the member countries are better off) is c_m. It is easy to see that c_m is the minimum integer that satisfies:

$$p(c;\tau) > p(1;\tau^S)$$

where $\tau = \{c, 1_{(n-c)}\}$ and $\tau^S = \{1_n\}$(No coalition).

Consider the following Nash Equilibria Conditions:

- $c_m > c*$*:* When the minimum profitability size is more than the maximum stability size, then clearly the NE will be a singleton structure, i.e. $\tau = \{1_n\}$.
- $c_m \leq c*$: This is the case, when a single coalition with size $c*$ is more stable and profitable, i.e. $\tau = \{c*, 1_{n-c}\}$

Consider the following examples games. Figure 1 is the condition when all the free-riders are orthogonal. Here, the coalition is internally and externally stable for all $c \leq 3$. Also, the profitability is satisfied for all coalition sizes. The Nash Equilibrium for this game is thus $\tau = \{1, 1, 1, 3\}$.

In Figure 2, all the free riders are non-orthogonal, i.e., they can harm those in the coalition. Here, the profitable condition is satisfied only when the coalition size reaches 5. Also, the coalition is not internally stable for any $c \geq 1$. The Nash Equilibrium in this case is thus $\tau = \{1, 1, 1, 1, 1, 1\}$.

Coalition Structure	PayOff of the players					
1,1,1,1,1,1	0	0	0	0	0	0
1,1,1,1,2	2	2	2	2	0	0
1,1,1,3	6	6	6	2	2	2
1,1,4	12	12	4	4	4	4
1,5	20	8	8	8	8	8
6	12	12	12	12	12	12

Figure 1: Orthogonal Free-Riding [3]

Coalition Structure	PayOff of the players					
1,1,1,1,1,1	1/49	1/49	1/49	1/49	1/49	1/49
1,1,1,1,2	1/36	1/36	1/36	1/36	1/72	1/72
1,1,1,3	1/25	1/25	1/25	1/75	1/75	1/75
1,1,4	1/16	1/16	1/64	1/64	1/64	1/64
1,5	1/9	1/45	1/45	1/45	1/45	1/45
6	1/24	1/24	1/24	1/24	1/24	1/24

Figure 2: Non-Orthogonal Free-Riding [3]

4.2.5 Multiple Coalition

Now, lets allow multiple coalitions to form. Here, we need to consider one more factor of Stability:
Intra-Coalition Stability: A coalition is stable in a multi-coalition setup if none of the players is better off by joining a different coalition.

Figure 3 shows the case, where free-riders are orthogonal in a multi-coalition setup. Considering all the three factors of stability, there are two nash equilibrium coalition structures, $\tau = \{3, 3\}$ and $\tau = \{2, 2, 2\}$.

Coalition Structure	PayOff of the players					
1,1,1,1,1,1	0	0	0	0	0	0
1,1,1,1,2	2	2	2	2	0	0
1,1,1,3	6	6	6	2	2	2
1,1,4	12	12	4	4	4	4
1,5	20	8	8	8	8	8
6	12	12	12	12	12	12
1,2,3	8	6	6	4	4	4
2,2,2	4	4	4	4	4	4
3,3	8	8	8	8	8	8
2,4	12	12	6	6	6	6
1,1,2,2	4	4	2	2	2	2

Figure 3: Orthogonal Free-Riding Multiple coalition [3]

One can observe that the social welfare(total payoff) is more in the case of multiple coalitions, proving that local regional treaties can be more beneficial than a global treaty.

Also, Figure 4 looks at the multi-coalition perspective with respect to the leakage values for different country groups. The country groups analyzed are JAP - Japan, NA- North America, EU- European Union, EE+R - Eastern Countries and Russia, C+I- China and India.

Leakage in Country					Stable Coalitions
JAP	NA	EU	EE+R	C+I	Nash Bargaining
0	0	0	0	0	{JAP,NA,EU} {JAP,EU,EE+R} {JAP,NA,EE+R}
1%	7%	7%	15%	15%	No Equilibrium Condition
1%	7%	7%	15%	30%	No Equilibrium Condition
1%	7%	7%	30%	30%	No Equilibrium Condition
3%	7%	7%	15%	30%	{NA,EU}, {NA,EU,EE+R}
3%	7%	7%	30%	30%	{NA,EU}
5%	7%	7%	15%	15%	{JAP,NA,EU, EE+R}
5%	7%	15%	15%	15%	{JAP,NA,EU, EE+R, C+I}

Figure 4: Stable Coalitions and Leakage [3]

4.3 Transfers

As we discussed that any global treaty is unstable but also at the same time it is need of the hour.Due to unsymmetrical nature of the countries many of the LDCs and developing countries will loose by signing any of the global treaties. Since the Developed countries are those countries who exploited the natural resources and produced huge amount of GHG in industrial era which include EU, USA etc. SO it will be also unfair for the LDCs if they are forced to sign.**Price of fairness** is pretty high and in this case it is harming our planet earth's habitable conditions, this price can be O($\sqrt{n}$). In such scenario compensation from DCs to LDCs can be an option so that LDCs will show intent to move from conventional organic energy sources to carbon free resources. These transfers can be given in form of cash or resources to achieve a large stable coalition structure.Similar things happened is recent Paris treaty also, developed country agreed to collect a fund of **$100 Billion** in name of Green Climate Fund to help other LDCs.

4.4 Linkages

Seeing transfers as separate things will not make things look pretty, One need to see the co-relation of different things collectively to come up with a solution.Few major points are mentioned below.

- Business deals (import/export)
- Research and Development sharing
- Geographical differences
- Development level of countries
- Cultural and political priorities

4.5 Threats

Threats are important to achieve non Nash Equilibrium strategy as a strategy adopted by players in a game, Suppose all countries signed the treaty now a given country wants to quit the deal then other countries has two options- a) they also quit the deal and maintain status quo. b) Cut the business deals with that country so that profit gained by free riding is negated by loss in business deals. If quiting country is in LDCs then cutting business deals will not make a great help in such scenario other countries needed to cut the R&D helps and other transfers with that country and such threats are going to be very much effective in case of LDCs since they depend on other countries for technical helps. The threats leads to a **Self enforcing** global treaty.

5 Self Enforcing Treaty

5.1 Repeated Games

Consider the game with 6 players(discussed above). Now we will play a game between a 5 country coalition and a single country with following assumptions-

- Countries values future also rather than current profit. let δ be the discount factor for both players. Discount factor- suppose payoff is x by an strategy in table then payoff value of iteration i of game given same strategy set is to be considered x*δ^{i-1}.
- For simplicity assume δ to be same over iteration and for different players.
- Player A is a group of players and we write average payoff as payoff, which is same as individual payoff.
- Player A defects implies no treaty is signed then player B's Cooperation don't make any sense is such case.
- Now based on the trigger strategies and δ values of player we can decide weather the treaty is going to be signed or not.
- The game will repeat infinite time.

Now the game will proceed in this way. Both players will decide to play (C,C) initially. Now player B has a chance to defect and get a better output in current round, But based on the action of B, Player A may decide to punish B for his defection and will choose a **trigger strategy** based on his own valuations.

		Player B	
		Cooperate	**Defect**
Player A	**Cooperate**	12,12	8,20
	Defect	-	0,0

Table 3: Player A: coalition of n-1 countries, Player B: Single Defecting Country

5.2 Trigger Strategy

It is a class of strategy used in non co-operative repeated games. A player uses on the trigger strategy when the other player(s) who initially agree to co-operate now have shown certain level of defection.

5.2.1 Grim Trigger

In this strategy once the opponent defects the player A will defect in all coming round in future, by such action player A may not maximize his payoff but can minimize payoff of B, and this threat will be very credible for B if he had a feeling that A can take decision at his own cost.
For given δ, for Player B, Cooperation gives 12/(1-δ) payoff and Defection gives 20. So clearly for $\delta \geq 2/5$ cooperation is better.

5.2.2 Tit for Tat

In this strategy Player A is more liberal and wanted the treaty to be continued so it will penalize for next round after B defects and then again continues to cooperate.
For given δ, for Player B, Cooperation gives 12/(1-δ) while defection gives 20 + 12/δ^2(1-δ). So their no δ for which we get cooperation as a better strategy.

6 Classic Externalities

With unequal real world countries it is very difficult to generalize any of the environmental effects. While the global average temperature is rising drastically as compared to entire history but it is being observed that average temperature is not going upwards in all places in the world. In such scenario there may be fer countries who are not suffering by temperature increase. Also their may be countries who are getting benefit out of boiling earth, though this profit may not be applicable in long term but *In the long term we all are dead.*
The presence of such externalities makes very difficult to design a single global treaty which will incorporate all these factors. The mood of a country is decided by ruling party/person and signing such agreements depends a lot on the priority of the government of a given country. *It's easier to fool people then convince them they have been fooled.*

7 World Government

A world government with powers adequate to guarantee security is not a remote ideal for the distant future.It is urgent necessity if our civilization is to survive- Albert Einstein
We shall have world government weather you like it or not, By conquest or consent - James Warburg
All the problems regarding any global or local treaties were due to priorities of country and views of their leadership. The idea of world government will lead to a stable solution for this problem. Since the government will treat the states(currently countries) equally and will not hesitate to take decision in global importance. In current world countries do a lot of under-table things in the name of securities, a lot of foreign policies shows the hypocrisy of the ruling party, it may be regarding criminals handover or oil acquisition etc.

8 Conclusion

We have discussed that climate change is accepted as one of the biggest problems for our planet. Majority of countries have accepted it as a problem and that there is a need of a global treaty to tackle with the problem. So, in our discussion we conclude that a global treaty is unstable due to the *tragedy of commons.* The rational players will always have a tendency to defect from such a treaty. In the mean time, we also need to address the problem, so that the status quo should not be maintained. We show that, instead of a global treaty we can have a few local treaties, where we can find an optimal partition of countries and can have a Nash equilibrium strategy.

Now, one needs to increase the size of coalitions in a coalition structure. This can be achieved by mutual cooperation in terms of funds and technology transfer to increase the fuel efficiency of LDCs and, also incorporate the fact that developed countries have already depleted the environment in the industrial era. Threats of business and technology alienation can also be used to enforce LDCs to sign such treaties.

Coming up with a self enforcing global treaty is our main goal, which can be achieved if players are farsighted. If a player values future highly, then it can be shown by the repeated game model that the player will stick to cooperation given that other players have strict trigger strategies.

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