# SPACE DEBRIS REMOVAL: GLOBAL PUBLIC GOOD GAME

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*Abstract*. Since the late fifties when the USSR launched Sputnik, the first artificial satellite to orbit the earth, space activities have exploded: we have set foot on the moon, our robotic spacecrafts have reached Mars and asteroids; and satellites have much improved our lives, providing indispensable services for communication, navigation, and weather forecasting, just to name a few. Unfortunately, along with these achievements, dangerous space debris have accumulated and become a serious hurdle to future space activities. So far little has been done or planned to ameliorate the problem. This paper considers the global public good aspect of the space-debris removal problem. Other than the typical private incentive of an individual contributing country to remove some space debris, an additional issue prevents private contributions to clean up a public good. Namely, a "benefiting" country may have incentives to object to the specific removal behavior. We explain this "forbidding" behavior and attempt a game theoretical analysis of these interacting issues to stress that much international negotiation, agreement, and collaboration with the rest of the world is needed to solve this imminent space trash problem.

*JEL*. H87 International Public Goods
D62 Externalities
C72 Noncooperative Games
F55 International Institutional Arrangements

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## Introduction

- In the last six decades, space activities have exploded.
- Along the way of launching rockets and satellites to outer space, we left a lot of debris such as non-performing satellites, boosters or spent parts of a rocket, forgotten tools, paint chips, and debris from former debris breaking up or colliding with other debris.
- According to the European Space Agency, there are now 25,000 objects in orbit. Fifty five percent of these reside in the Low Earth Orbit (LEO), at altitudes lower than 1,240 miles where most satellites reside.
- Satellites now provide indispensable services to people all over the world. Circling the Earth at 17,000 miles per hour, these stray bullets can induce serious collisions anytime, withholding or destroying services provided to us by satellites.
- With the plans for constellations of satellites to be launched in the future, the problem will become more serious. A resolution to the problem needs to be found as soon as possible.

## Debris Mitigation versus Debris Remediation

- Mitigation effort: Currently most countries have regulations dictating how a company will make sure that a forthcoming satellite to be launched should be taken out of LEO at the end of its service, minimizing the likelihood of increasing the amount of debris in outer space.
- Remediation effort: if nothing is done, accumulated debris will stay in LEO for decades or even hundreds of years. But the cleaning up of the existing debris has proved to be difficult, technologically speaking and in terms of efforts attempted. This paper tries to investigate this aspect of the problem.

## Disastrous Collison in outer space can happen anytime

- The International Space Station has carried out collision maneuver many times to avoid being hit by flying debris.
- Some large space debris have fallen to Earth, fortunately no one was injured.

## The most serious consequences of a collision may be the disruption of services provided by satellites.

- In October 2021, Facebook's services were interrupted for four hours. It impacted billions of people worldwide, causing many people not being able to perform their business. Imagine what would happen when a few satellites collide and for days some services do not work, such as not being able to use GPS, to withdraw money from an ATM, to buy or sell stocks, to call your friends, or have no power or water.
- Even a short interruption resulting from an outage of the carmaker's app, Tesla drivers found it very inconvenient because they were unable to start their cars!
- It is impossible to imagine a large scale loss in services due to collisions of some important satellites.
- But many fear that the possibility is there. It is a matter of when.

**Status of the debris removal problems**

- There are some attempts in using different technologies to remove some specific kind of flying debris. But large international collaborative effort is needed. Some UN sanctioned discussions are underway, while moving at a glacial speed.
- It is felt that if the space debris problem and its potential disastrous consequences are widely known, international cooperation on the matter may result. This paper offers a theoretical game model to analyze the problem.

**(The above is a rough draft of what will be added in the paper. The following section is written with more care, explaining the model. But more should be discussed in words to introduce the development of the model.)**

## The Theoretical Game Model

This paper attempts to use a game model to explain why there may or may not be an agreement to have a treaty to cooperate to clean up some space debris (for simplicity, denote these as *T* and *NT*).[2] We use *T* to mean two things: that a country is willing to partake in a treaty and that it is willing to clean up or contribute to clean up some space debris; *NT* to mean that a country would not join a treaty as it does not allow space debris removal of its defunct property. We want to highlight the fact that none of the space powers are very receptive to the idea of space debris removal presently. The disincentive issues of different countries to participate in cleaning up can be due to different reasons: it takes private resources from other space and economic activities; it cannot capture all the social benefits since a cleaner outer space is a public good enjoyed by all countries; and more importantly, the country may not want the technology embedded in the discarded part of its booster or a stage of its rocket or a defunct satellite to be detected by other countries.

In Figure 1 we start the model with two space-faring countries, A and B, who contributed space trash in the past through their space-faring activity. To facilitate our discussion, all (private net) benefits will be denoted as V, with a superscript representing the country, as in $V^A$. Following common convention, the payoffs for the strategy profile are presented in the order of row country (A), column country (B), and matrix country if there is a third country (C) later in our analysis. Thus, $V^A(T, NT)$ = 4 and $V^B(T, NT)$ = 2 are the benefits of the countries A and B as indicated in the second row (*T* chosen by A) and first column (*NT* chosen by B).

| A \ B | *NT* | *T* |
|---|---|---|
| *NT* | 6, 6 | 5, 5 |
| *T* | 4, 2 | 3, 4 |

| | | |
|---|---|---|
| | | |
| | | |

***Table 1: No third country***

[2] We denote strategies by italic letters.

A country's preference and choice will be determined by the relative magnitude under different strategies, given another country's strategy. Thus, numbers presented are meant to be ordinal numbers: only the relative order of the numbers matter.

In Table 1, we assume that countries A and B have somewhat different preferences. In particular, we assume that **A has a strict preference of *NT***, or, A has a dominant strategy of *NT*, as choosing *NT* is always better than *T* no matter what choices B adopts:

$$V^A(NT, \bullet) > V^A(T, \bullet) \text{ whatever strategy B chooses.}$$

Meanwhile, **B has an accommodating preference**: when A chooses *NT*, B prefers *NT* as well. When A chooses *T*, then B also prefers *T*:

$$V^B(NT, NT) > V^B(NT, T);\ V^B(T, T) > V^B(T, NT).$$

This scenario may happen if, for example, A has many superior space technologies embedded in its spacecrafts. No matter what others want, it does not want another country to be able to detect any leak in its technology while capturing its space-wandering discarded stage of a rocket in the name of cleaning up.[3] On the other hand, B has not polluted as much as A so far, so leaking the space technology is less damaging. Or it may be because the technology embedded in B's defunct spacecrafts are less advanced, so the concern over keeping the secrecy of the technology is less strong, relative to the future safety-benefit of sending many constellations of satellites to space.[4]

In the model, the preferences for A and B are made with the space debris-removal, a global public good, behind the picture. Here, we assume that the public good property of a cleaner outer space implies that no country should have a strict preference for *T*, that a country should not be willing to allow debris clean-up no matter what other countries choose, because the country cannot guarantee what would happen to its technical junk left in space.[5] *T* is an abbreviation of some agreement between/among countries to have joint effort to clean up the space debris. The specific detail of the treaty agreement and agreed cleanup amount or procedure is not the subject of study in this model.

Returning to Table 1, the Nash equilibrium occurs at (*NT*, *NT*). Since A strictly prefers *NT*, and the accommodating B chooses *NT* when A chooses *NT*, both countries choose no treaty *NT* at equilibrium. Thus, there is no agreement among countries and there is no removal of any space debris.[6]

We now add a third party, country C. C realizes that no space debris clean-up may lead to collisions in outer space, resulting in much of its business and daily activities suffering serious damage. It now takes an intense interest in participating in the process of forming a treaty. While we assume C is a single country in our model, C may represent many other countries who have not had much space-

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[3] The case in which no country has a strict preference in *NT* is presented in the Appendix.

[4] Cases in which both A and B have similar preferences are considered in the Appendix.

[5] If a country has a strict preference for *T*, representing an agreement to the production of a public good, as in debris-cleanup in our case, no matter what the other country's preference is, then there will be production of the public good and game-theoretical analysis is not useful.

[6] A similar outcome would occur under the usual public good consideration if contributions can be made *only if* everyone agrees to be a contributor to the public good. Otherwise, no contribution and no provision to public good can be made.

faring experience but are keenly aware of the dangers imposed on the world by the fast-moving, wandering, and menacing space debris. When citizens of these other countries as well as the two space-faring countries A and B become aware of the dangerous situation and potential devastation space debris may impose, the net benefits to the two countries under different strategies will change for the worse. We assume that the countries recognize these changes from the influence of C and act accordingly. We now extend the previous simple two country model by first observing how the two countries' net benefits should change.

The previous case is now embedded in Table 2, with the heading of **NC** (the left hand matrix). While the benefits of country **C** will not appear explicitly in Table 2, we concentrate on the serious impact of C on net benefits of countries A and B from debris-cleaning here.

| **NC**: No interested third country C | | | **C**: With a third country C | | |
|---|---|---|---|---|---|
| A \ B | *NT* | *T* | A \ B | *NT* | *T* |
| *NT* | 6, 6 * | 5, 5 | *NT* | 5, 2 | 1, 4 |
| *T* | 4, 2 | 3, 4 | *T* | 3, 1 | 2, 3 # |

***Table 2: Without and with an interested third country C (the benefits of C will be added later)***

We now introduce and abuse a notation, by adding **NC** and **C** in the description of the benefit of a country to distinguish between no third country interference and the presence of a third country. To proceed, observe that Table 2 shows that every benefit for country A with the presence of C and its induced negative publicity (in the right hand matrix with the heading **C**) is lower than before when there was no negative publicity.

$$V^A(\mathbf{NC}|\, NT, \bullet) > V^A(\mathbf{C}|\, NT, \bullet) \text{ and } V^A(\mathbf{NC}|\, T, \bullet) > V^A(\mathbf{C}|\, T, \bullet)\,. \qquad (1)$$

A is worse off with any strategy chosen by B when **C** is around to exert its influence.

Astute readers may observe that the *fall* in benefit for A is largest under strategy profile (*NT*, *T*), from 5 to 1, when B is willing to join a treaty while A still resists treaty even with international pressure: international scorn diminishes prestige of a space power the most. Further, without joining a treaty, A loses the power of monitoring the cleaning process and the danger of leaking its space technology. This leads to a change in preference of A when B sticks with *T* under outside influence.

$$V^A(\mathbf{C}|\, T, T) > V^A(\mathbf{C}|\, NT, T). \qquad (2)$$

This important implication is that, unlike before, now A is better off choosing *T* with **C** around when B chooses *T*, even though A still prefers *NT* if B also chooses *NT*. A no longer has a dominant strategy with *NT*.

Likewise, country B is worse off with any strategy chosen by A when **C** is present, convincing the general public of the imminent danger of the voluminous amount of space debris.

$$V^B(\mathbf{NC}|\, \bullet, NT) > V^B(\mathbf{C}|\, \bullet, NT) \text{ and } V^B(\mathbf{NC}|\, \bullet, T) > V^B(\mathbf{C}|\, \bullet, T). \qquad (3)$$

Recall that previously, B choses *NT* when A chooses *NT*. (And B chooses *T* when A chooses *T*.) Now, with the influence of international pressure from C, B's conviction for no space debris-cleaning *NT* weakens even when A chooses *NT*. B finds that choosing *T* is superior to choosing *NT* even when A prefers *NT*:

$$V^{B}(\mathbf{C}|\, NT, T) > V^{B}(\mathbf{C}|\, NT, NT). \qquad (4)$$

This is the most important impact on the behavior of B with country C around, exerting negative publicity on the potential devastating effects of space debris. That is, even when A is not amenable to space debris-removal *NT*, B now prefers *T* as *T* becomes B's dominant strategy with C around.

This model begins by assuming that countries other than those embroiled heavily in space-faring activities are not willing to minimize the danger imposed by space debris accumulated in outer space, as illustrated by the Nash equilibrium (*NT*, *NT*) * in the left-matrix of Figure 2, without outside influence. We stress that this undesirable equilibrium could be altered with actions from the rest of the world, represented by country C in the model, if C can exert enough influence on the space-faring countries preferences (as shown in equations (1) and (3)). And if the influence is strong enough to take away the dominant strategy *NT* of the country that was vehemently against debris-cleaning (A) and to increase the commitment strategy of the accommodating country (B) to make a space-cleaning treaty a dominant strategy under C's influence, then a potential Nash equilibrium, without taking Country C's preference into consideration yet, will locate at (*T*, *T*) # in Figure 2's right-matrix.

At this point, it is worthy to note that assumptions (1) and (3) are easy to understand. Assumptions (2) and (4), requiring major impacts on the payoffs of countries A and B with C around, may be overlooked easily. But it is important for these assumptions to hold to break the no-treaty equilibrium with the addition of country C.

Now we take the preference of country C into consideration. Payoffs for C under different strategy profiles are presented as the third number in any triplet in Table 3. The absence of C in previous consideration is treated as C choosing not to interfere. In general, it is assumed that when C decides not to interfere with the space debris problem by choosing *NT*, his highest preference occurs when there is a treaty to fix the space debris problem without its interference (3), and the lowest preference is when no country is willing to participate in joining a treaty for space-removal (1). Comparing the payoffs of C in the left-matrix with those in the right-matrix in Table 3, C's payoffs increase when C tries to influence the international outcome. The larger payoffs for C represent the potential and positive influence from C on international affairs as well as prestige bestowed on C. In particular, note that C's payoff increases from the case in which no one wants a treaty at (*NT*, *NT*, *NT*) to the case when C is the only country pushing for a cleanup effort internationally at (*NT*, *NT*, *T*), from 1 to 2.

C: *NT*

| A \ B | *NT* | *T* |
|---|---|---|
| *NT* | 6, 6, 1 | 5, 5, 2 |
| *T* | 4, 2, 2 | 3, 4, 3 |

C: *T*

| A \ B | *NT* | *T* |
|---|---|---|
| *NT* | 5, 2, 2 | 1, 4, 3 |
| *T* | 3, 1, 3 | 2, 3, 4 # |

***Table 3: With an interested third country C and its benefits included***

But why should C's payoff increase when every country agrees to a treaty now (4) relative to the case that there is a treaty without C's influence/participation (3)? One important reason under the problem investigated is that if C does not participate in being a treaty signatory, there may be no compensation from the offending country that is responsible for an accident if C is not part of the Convention or Treaty. Further, with the participation of C in the treaty, it may help determine the way the compensation amount is determined in case of disasters. This would have an indirect impact on the payoffs of the space-faring countries.

Given this representation of preferences, it is now clear that (*T*, *T*, *T*) # will become the Nash equilibrium with the influence and participation of country C.[7]

Thus, we investigated the necessary impact of a third country, or the rest of the world, required to alter the outcome of the current space debris cleaning problem. The most important observation is that meager impact from a third country involved will not be able to solve the problem. From the incentive point of view, this particular global public good problem can only be solved with the heavy influence of other non-space faring countries.

**Miscellaneous issues**

- Different countries are racing to send lots of satellites to space, trying to claim some spectrum still available.
- FCC, whose responsibility does not involve solving the space debris issues, and probably with the support of the Congress and NASA, generously grant lots of leeway for SpaceX to send up thousands of satellites.
- This is possible as there is no international agreement for dealing with the issue of congestion in outer space. The launching of satellites now is kind of the Wild-Wild-West in outer space.

**Concluding Section to be added ---**

We stress that our analysis focuses on the important assumptions or criterion needed so that an international agreement dealing with space debris can be made, while there is no international cooperation presently. In this case of space debris removal and the need for countries to keep their space technology secrets, it is important that we have a very strong coalition of other countries (a general country C in our model) to insert heavy influence on the space-faring countries. Otherwise, we are afraid that things will not move until a huge disaster happens in the near future.

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[7] The strategy profile (*NT*, *NT*, *NT*) is not a Nash equilibrium because of the important influence and objection of country C.

***Appendix: When preferences of A and B are symmetric to each other***

**NC**: No interested third C

| A \ B | *NT* | *T* |
|---|---|---|
| *NT* | 6, 6 * | 2, 5 |
| *T* | 5, 2 | 4, 4 * |

**C**: With a third country C

| A \ B | *NT* | *T* |
|---|---|---|
| *NT* | 2, 2 | 1, 4 |
| *T* | 4, 1 | 3, 3 # |

***Table A1: Regular Public Good Case (No serious objection to free-rider from A or B)***

First consider the case in which B is somewhat willing to contribute to clean up, not particularly worrying about exposing its space technology to the rest of the world, if the other party is willing to form a treaty. But since the private benefit of cleanup falls short of the aggregate public benefit of cleanup, B is not willing to join a treaty if the other party is not. A's preference is similar to that of B. (B's payoffs stay the same as those in Table 2, both without and with country C. Payoffs to A change symmetrically to those of B.)

When there is no third country C, there are two Nash equilibria: when both A and B are willing to join a treaty, making contributions toward space junk cleaning (*T*, *T*), and when neither are willing to make any contribution towards the provision of the public good of cleaner space orbit: (*NT*, *NT*). The Nash equilibria are identified by * in *A1* left-matrix.

With the influence of the third country C, choosing T becomes the dominant strategy for both A and B; with the additional strong preference for T from country C, (*T*, *T*, *T*) becomes the Nash equilibrium, identified by # in *A1* right matrix. (C's payoffs are absent from Table A1.)

**NC**: No interested third C

| A \ B | *NT* | *T* |
|---|---|---|
| *NT* | 6, 6 * | 5, 4 |
| *T* | 4, 5 | 3, 3 |

**C**: With a third country C

| A \ B | *NT* | *T* |
|---|---|---|
| *NT* | 5, 5 | 1, 3 |
| *T* | 3, 1 | 2, 2 # |

***Table A2: Regular Public Good Case (Both A and B have serious objection to free-rider)***

Next, consider the case in which A has a strict preference not to participate in forming a treaty to clean up space debris. Likewise, B has a preference similar to that of A. (In this case, the payoffs to A stay the same as those in Table 2 in both panels. Payoffs to B change symmetrically to those of A.)

Without the presence of C, neither A nor B are inclined to choose *T*, thus (*NT*, *NT*) is the Nash equilibrium, as identified by * in *A2* left-matrix.

With the presence of C but without considering the explicit preference of C, both (*NT*, *NT*) and (*T*, *T*) for countries A and B could be part of the 3-country Nash equilibrium. However, C's payoff with participation in the game is assumed to exceed its payoff without its participation, making (*NT*, *NT*, *T*) not a Nash equilibrium with 3 countries. This leaves (*T*, *T*, *T*) to be the single Nash equilibrium with three players, as identified by # in *A2* right-matrix.