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Unified and simple understanding for the evolution of conditional cooperators

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ABSTRACT

Cooperation is a mysterious phenomenon which is observed in this world. The potential explanation is a repeated interaction. Cooperation is established if individuals meet the same opponent repeatedly and cooperate conditionally. Previous studies have analyzed the following four as characters of conditional cooperators mainly. (i) niceness (i.e., when a conditional cooperator meets an opponent in the first place, he (she) cooperates or defects), (ii) optimism (when a conditional cooperator meets an opponent in the past, but he (she) did not get access to information about the opponent's behavior in the previous round, he (she) cooperates or defects), (iii) generosity (even when a conditional cooperator knows that an opponent defected in the previous round, he (she) cooperates or defects) and (iv) retaliation (a conditional cooperator cooperates with a cooperator with a higher probability than with a defector). Previous works deal with these four characters mainly. However, these four characters basically have been regarded as distinct topics and unified understanding has not been done fully. Here we, by studying the iterated prisoner's dilemma game (in particular, additive games) and using evolutionarily stable strategy (ESS) analysis, find that when retaliation is large, the condition under which conditional cooperators are stable against the invasion by an unconditional defector is loose, while none of "niceness", "optimism", and "generosity" makes impact on the condition under which conditional cooperators are stable against an invasion by an unconditional defector. Furthermore, we show that we can understand "niceness", "optimism", and "generosity" uniformly by using one parameter indicating "cooperative", and when the conditional cooperators have large "retaliation" enough to resist an invasion by an unconditional defector, natural selection favors more "cooperative" conditional cooperators to invade the resident conditional cooperative strategy. Moreover, we show that these results are robust even when taking the existence of mistakes in behavior into consideration.

1. Introduction

The existence of cooperation demands explanation [4,17,33,49]. One of the potential explanations for this mysterious phenomenon is a repeated interaction. Previous studies have revealed that cooperation is established if the interaction between the same individuals repeats and individuals cooperate conditionally based on the opponent's behavior [4,26,34,35,49] (but see also [9,25]).

Previous studies have analyzed the following four as characters of conditional cooperators mainly. (i) niceness (i.e., when a conditional cooperator meets an opponent in the first place, he (she) cooperates or defects [3,4,6,11,36,44,48,51,52,56]) (ii) optimism (when a conditional cooperator meets an opponent in the past, but he (she) did not get access to information about the opponent's behavior in the previous round, he (she) cooperates or defects [5,22,23,25]). (iii) generosity (even when a conditional cooperator knows that an opponent defected in the previous round, he (she) cooperates or defects [34]) (iv) retaliation (a conditional cooperator cooperates with a cooperator with a higher probability than with a defector [4,49]). Previous works deal with these four characters mainly. However, these four characters basically have been regarded as distinct topics and have been analyzed separately. And unified understanding has not been done fully. Here, we raise two questions: one is "How the conditional cooperators behave in these four situations facilitates the evolution of cooperation?" and the other is "Is unified understanding possible?" We examine these in this paper.

The rest of this paper is structured as follows. In Section 2, we describe a model and by using evolutionarily stable strategy (ESS) analysis, examine how conditional cooperators behave facilitates

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the evolution of cooperation most. In Section 3, we extend Model 1 to more general model which takes the existence of mistakes in behavior into consideration, and examine if the result obtained in Model 1 section is robust or not. In Section 4, we summarize the results and suggest some future works to be undertaken.

2. Model 1

Consider the iterated prisoner's dilemma game in which two individuals have to either cooperate or defect in each round. We assume that individuals are paired randomly, and assume that there is no age structure (see [30] for a work dealing with age structured population.). The probability that the individuals interact over t times in a given pair is w^t, where $0 < w < 1$ holds true. This assumption means that the expected number of interactions is $1/(1-w)$. An individual who cooperates will give an opponent an amount b at a personal cost of c, where $b > c > 0$. An individual who defects will give nothing. Furthermore, we consider the case wherein information is imperfect. We introduce a parameter e and let the parameter e denote the probability that information is somehow blocked, i.e., that an individual cannot get access to the information about an opponent's behavior, where $0 \le e \le 1$.

We consider two strategies: unconditional defection (ALLD) and reactive strategy ($R_{s,a,p,z}$), which is an extension of earlier works [4,22,25]. ALLD defects no matter what the opponent does. $R_{s,a,p,z}$ cooperates with probability s $(0 < s \le 1)$ in the first move and in the following rounds, $R_{s,a,p,z}$ cooperates with probability $p+z$ if $R_{s,a,p,z}$ can get access to information about the opponent's behavior *and* the opponent cooperated in the previous round, and cooperates with probability p if $R_{s,a,p,z}$ can get access to information about the opponent's behavior *and* the opponent defected in the previous round. If $R_{s,a,p,z}$ cannot get access to information about the opponent's behavior, $R_{s,a,p,z}$ cooperates with probability a $(0 \le a \le 1)$.

Here, s can be regarded as the index of "niceness". As the parameter s increases, the player trusts the opponent more and cooperates with the opponent in the first meeting with a higher probability. Similarly, a can be regarded as the index of "optimism". As the parameter a increases, the player cooperates with the opponent with a higher probability when the individuals does not get information about the opponent's behavior in the previous round. Similarly, p can be regarded as the index of "generosity". As the parameter p increases, the player cooperates with an opponent with a higher probability even when the opponent defected in the previous round (of course, when the opponent cooperated in the previous round). Similarly, z can be regarded as the index of "retaliation". As the parameter z increases, the player retaliates more for the opponent's behavior. Note that ALLD is the same as $R_{s,a,p,z}$ in the case wherein $s=a=p=z=0$ holds true.

Here, we consider the game between $R_{s,a,p,z}$ and ALLD. We specify the condition under which $R_{s,a,p,z}$ is a strict ESS against an invasion of ALLD. After algebraic calculation, it is shown that the condition under which $R_{s,a,p,z}$ is an ESS against an invasion of ALLD (i.e., $R_{s,a,p,z}$'s payoff against itself is larger than $R_{s,a,p,z}$'s payoff against ALLD) is

$$bwz(1-e) - c > 0. \tag{1}$$

This inequality becomes a special case of inequality (3) in [22] when substituting $z=1$ into (1). This inequality (1) indicates that when retaliation (z) is large, it is likely that $R_{s,a,p,z}$ is an ESS against an invasion of ALLD. And it is also apparent that inequality (1) does not contain s, a or p, which means that the parameter s, a, and p makes no impact on the condition under which $R_{s,a,p,z}$ is an ESS against an invasion of ALLD. The condition under which $R_{s,a,p,z}$ is not invaded by unconditional defectors is neither affected by whether conditional cooperators cooperate or defect in the first meeting nor affected by whether conditional cooperators cooperate or defect when information is not available or by whether conditional cooperators cooperate or defect when information is available.

Next, we consider the game between $R_{s1,a1,p1,z}$ and $R_{s2,a2,p2,z}$ where $R_{s1,a1,p1,z}$ cooperates in the first round with probability s_1 and cooperates in the following round with probability a_1 when information is unavailable in the previous round and cooperates with probability p_1+z if $R_{s1,a1,p1,z}$ can get access to information about the opponent's behavior *and* the opponent cooperated in the previous round, and cooperates with probability p_1 if $R_{s1,a1,p1,z}$ can get access to information about the opponent's behavior *and* the opponent defected in the previous round while $R_{s2,a2,p2,z}$ cooperates in the first round with probability s_2 and cooperates in the following round with probability a_2 when information is unavailable in the previous round and cooperates with probability p_2+z if $R_{s2,a2,p2,z}$ can get access to information about the opponent's behavior *and* the opponent cooperated in the previous round, and cooperates with probability p_2 if $R_{s2,a2,p2,z}$ can get access to information about the opponent's behavior *and* the opponent defected in the previous round, respectively.

After algebraic calculation (see Appendix A for detailed calculation), it is shown that the condition under which $R_{s1,a1,p1,z}$ is an ESS against an invasion of $R_{s2,a2,p2,z}$ is

$$[bwz(1-e)-c]\left[\frac{s_1+\frac{w}{1-w}ea_1+\frac{w}{1-w}(1-e)p_1}{\frac{1}{1-w}} - \frac{s_2+\frac{w}{1-w}ea_2+\frac{w}{1-w}(1-e)p_2}{\frac{1}{1-w}}\right] > 0. \tag{2}$$

This inequality becomes a special case of inequality (5) in [25] when substituting $s_1=s_2=1$, $p_1=p_2=0$, and $z=1$ into (2). Here, let us define v as

$$v \equiv \left[s+\frac{w}{1-w}ea+\frac{w}{1-w}(1-e)p\right]\Big/\left[\frac{1}{1-w}\right]. \tag{3}$$

How can the parameter v be interpreted? The expected number of interactions is given as $1/(1-w)$ as mentioned above. Among the number of interactions, $1/(1-w)$, the number of interactions wherein $R_{s,a,p,z}$ cooperates even when the conditional cooperators do not observe cooperation by the opponent is given as $s+\frac{w}{1-w}ea+\frac{w}{1-w}(1-e)p$ because of the definition of s, a, and p. Hence, the parameter v can be interpreted as the probability that even when the conditional cooperators do not observe cooperation by the opponent, they cooperate on average. Therefore, the parameter v can be regarded as the index of "“cooperative”". As the parameter v increases, the player becomes more "cooperative". It has also been found that the parameter v is over 0 and not more than 1 because of the domains of the parameter (a, s, p). Here, let us define v_1 and v_2, respectively, as

$$v_1 \equiv \left[s_1+\frac{w}{1-w}ea_1+\frac{w}{1-w}(1-e)p_1\right]\Big/\left[\frac{1}{1-w}\right] \tag{4}$$

$$v_2 \equiv \left[s_2+\frac{w}{1-w}ea_2+\frac{w}{1-w}(1-e)p_2\right]\Big/\left[\frac{1}{1-w}\right]. \tag{5}$$

Here, using (4) and (5), (2) becomes

$$[bwz(1-e)-c](v_1-v_2) > 0 \tag{6}$$

This inequality (6) indicates that when retaliation (z) is sufficient (i.e., more strictly speaking, larger than $c/[bw(1-e)]$), more "cooperative" strategy than the resident strategy can invade, while less "cooperative" strategy than the resident strategy cannot invade. On the other hand, this inequality (6) indicates that when retaliation (z) is not sufficient (i.e., more strictly speaking, smaller than $c/[bw(1-e)]$), less "cooperative" strategy than the resident strategy can invade, while more “cooperative” strategy than the resident strategy cannot invade. The important parameter is only v, which includes the information of s, a, and, p. Each of parameters (s, a, p) is unnecessary in knowing the direction of the evolution.

Combining (1) with (6), we know that in the situations wherein retaliation (z) is large enough to resist the invasion by unconditional defectors, natural selection favors the reactive cooperators which are more “cooperative” than the resident strategy to invade the resident strategy.

3. Model 2

In Section 2, we consider the case wherein mistakes in behavior are not present. However animals including humans are error-prone [24,31], and we take the existence of mistakes into consideration in this section. The strategies we consider are the same as ones we introduced in Model 1. We introduce a parameter μ and let the parameter μ denote the probability that an individual who intends to cooperate fails to do so, where $0 \le \mu < 1$.

We specify the condition under which $\mathrm{R}_{s,a,p,z}$ is a strict ESS against an invasion of ALLD. After algebraic calculation, the condition is that $\mathrm{R}_{s,a,p,z}$'s payoff against itself is larger than $\mathrm{R}_{s,a,p,z}$'s payoff against ALLD, given as

$$bwz(1-e)(1-\mu)-c>0. \tag{7}$$

This inequality reduces to (1) when substituting $\mu=0$ into (7). And, this inequality reduces to inequality (3) in [22] when substituting $s=0$, $p=0$, and $z=1$ into (7). And we can find that the existence of mistakes in behavior makes the condition more stringent.

Next, we consider the game between $\mathrm{R}_{s1,a1,p,z}$ and $\mathrm{R}_{s2,a2,p,z}$. After algebraic calculation (see Appendix B for detailed calculation), it is shown that the condition under which $\mathrm{R}_{s1,a1,p,z}$ is an ESS against an invasion of $\mathrm{R}_{s2,a2,p,z}$ is

$$[bwz(1-e)(1-\mu)-c]\left[\frac{s_1+\frac{w}{1-w}ea_1+\frac{w}{1-w}(1-e)p_1}{\frac{1}{1-w}} - \frac{s_2+\frac{w}{1-w}ea_2+\frac{w}{1-w}(1-e)p_2}{\frac{1}{1-w}}\right]>0. \tag{8}$$

This inequality reduces to inequality (5) in [25] when substituting $s_1=s_2=1$, $p_1=p_2=0$, and $z=1$ into (2).

Here, using (4) and (5), (8) becomes

$$[bwz(1-e)(1-\mu)-c](v_1-v_2)>0 \tag{9}$$

This inequality reduces to (6) when substituting $\mu=0$ into (9). We stated that in the situations wherein retaliation (z) is large enough to resist the invasion by unconditional defectors, natural selection favors the reactive cooperators which are more “cooperative” than the resident strategy to invade the resident strategy in Model 1. Using (9), we can state that the result is robust even taking the existence of mistakes in behavior into consideration.

4. Conclusion

In Model 1, we, by using ESS analysis, find that when retaliation is large (i.e., conditional cooperators cooperate with an individual who cooperated in the previous round with a higher probability than with an individual who defected in the previous round), the condition under which conditional cooperators are stable against the invasion by an unconditional defector is loose, while none of “niceness (i.e., conditional cooperators cooperate in the first move)”, “optimism (i.e., conditional cooperators cooperate with an opponent when information about the opponent's behavior in the previous round is absent)”, and “generosity (i.e., conditional cooperators cooperate with an opponent even when the opponent defected in the previous round)” makes impact on the condition under which conditional cooperators are stable against an invasion by an unconditional defector. Furthermore, we show that we can understand “niceness”, “optimism”, and “generosity” uniformly by using one parameter indicating “cooperative”, and when the conditional cooperators have large “retaliation” enough to resist an invasion by an unconditional defector, natural selection favors more “cooperative” conditional cooperators to invade the resident strategy. In Model 2, we have shown that these results are robust even when taking the existence of mistakes in behavior into consideration.

In this paper, we consider the case wherein payoffs are linear (i.e., the effects of behaviors are additive). Removing the assumption may sway the result (see [1,2,23,24,37,47] for relevant works). Further study on this issue is needed.

In this paper, we consider a memory-one game (i.e., the game in which the individuals remember the previous only one round). We do not analyze long-memory strategies (i.e., strategies whose memory length are more than 1 (e.g. [20,43])), but it may be important.

This paper considers the interaction between two individuals, however, some animals including humans, interact among more than the two individuals. In order to analyze such a group-wise interaction including group-wise cooperation, we have to extend two player games which we used in this article to n-player games [7,8,10,12,13–16,18,19,21,26–29,32,38–42,46,50,53–55,57]. Further study on this issue might be interesting.

This paper considers the following four characters: (i) niceness, (ii) optimism, (iii) generosity and (iv) retaliation. And we proposed a simple model and we tried to understand the relevance of the four main characters.

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Appendix A

Proof for (2)

In the first round, $\mathrm{R}_{s1,a1,p1,z}$ cooperates with probability s_1, while in the following rounds, $\mathrm{R}_{s1,a1,p1,z}$ cooperates with probability $(1-e)(p_1+z)+ea_1$ when the opponent cooperated in the last move and cooperates with probability $(1-e)p_1+ea_1$ when the opponent defected in the last move. Similarly, in the first round, $\mathrm{R}_{s2,a2,p2,z}$ cooperates with probability s_2, while in the following rounds, $\mathrm{R}_{s2,a2,p2,z}$ cooperates with probability $(1-e)(p_2+z)+ea_2$ when the opponent cooperated in the last move and cooperates with probability $(1-e)p_2+ea_2$ when the opponent defected in the last move.

Now using (3. 41) in [45], we can know that $\mathrm{R}_{s1,a1,p1,z}$'s payoff against itself is given as

$$\frac{(b-c)\left(s_1+\frac{w}{1-w}((1-e)p_1+ea_1)\right)}{(1-(1-e)wz)}.$$

And we can also know, by using (3. 41) in [45], that $\mathrm{R}_{s2,a2,p2,z}$'s payoff against $\mathrm{R}_{s1,a1,p1,z}$ is given as

$$-c\frac{(s_2+s_1(1-e)wz)+\frac{w}{1-w}((1-e)(p_2+p_1(1-e)wz)+e(a_2+a_1(1-e)wz))}{(1+(1-e)wz)(1-(1-e)wz)} +b\frac{(s_1+s_2(1-e)wz)+\frac{w}{1-w}((1-e)(p_1+p_2(1-e)wz)+e(a_1+a_2(1-e)wz))}{(1+(1-e)wz)(1-(1-e)wz)}.$$

Hence, the condition under which $R_{s1,a1,p1,z}$'s payoff against itself is larger than $R_{s2,a2,p2,z}$'s payoff against $R_{s1,a1,p1,z}$ is given as (2). This is the end of the proof.

Appendix B

Proof for (8)

In the first round, $R_{s1,a1,p1,z}$ cooperates with probability $s_1(1-\mu)$, while in the following rounds, $R_{s1,a1,p1,z}$ cooperates with probability $((1-e)(p_1+z)+ea_1)(1-\mu)$ when the opponent cooperated in the last move and cooperates with probability $((1-e)p_1+ea_1)(1-\mu)$ when the opponent defected in the last move. Similarly, in the first round, $R_{s2,a2,p2,z}$ cooperates with probability $s_2(1-\mu)$, while in the following rounds, $R_{s2,a2,p2,z}$ cooperates with probability $((1-e)(p_2+z)+ea_2)(1-\mu)$ when the opponent cooperated in the last move and cooperates with probability $((1-e)p_2+ea_2)(1-\mu)$ when the opponent defected in the last move.

Now using (3. 41) in [45], we can know that $R_{s1,a1,p1,z}$'s payoff against itself is given as

$$\frac{(b-c)(1-\mu)\left(s_1+\frac{w}{1-w}((1-e)p_1+ea_1)\right)}{(1-(1-e)(1-\mu)wz)}.$$

And we can also know, by using (3. 41) in [45], that $R_{s2,a2,p2,z}$'s payoff against $R_{s1,a1,p1,z}$ is given as

$$-c\frac{(1-\mu)(s_2+s_1(1-e)(1-\mu)wz)+\frac{w}{1-w}((1-e)(1-\mu)(p_2+p_1(1-e)(1-\mu)wz)+e(1-\mu)(a_2+a_1(1-e)(1-\mu)wz))}{(1+(1-e)(1-\mu)wz)(1-(1-e)(1-\mu)wz)}$$
$$+b\frac{(1-\mu)(s_1+s_2(1-e)(1-\mu)wz)+\frac{w}{1-w}((1-e)(1-\mu)(p_1+p_2(1-e)(1-\mu)wz)+e(1-\mu)(a_1+a_2(1-e)(1-\mu)wz))}{(1+(1-e)(1-\mu)wz)(1-(1-e)(1-\mu)wz)}.$$

Hence, the condition under which Rs1,a1,p1,z's payoff against itself is larger than Rs2,a2,p2,z's payoff against Rs1,a1,p1,z is given as (8). This is the end of the proof.

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