Reactive strategies with longer memory

Nikoleta E. Glynatsi, Ethan Akin, Martin Nowak, Christian Hilbe

1 Formal Model

We consider infinitely repeated games among two players, player p and player q. Each round, they engage in the donation game with payoff matrix

$$\begin{pmatrix} b-c & -c \\ b & 0 \end{pmatrix}. \tag{1}$$

Here b and c denote the benefit and the cost of cooperation, respectively. We assume $b > c > 0$ throughout. Therefore, payoff matrix (1) is a special case of the prisoner's dilemma with payoff matrix,

$$\begin{pmatrix} R & S \\ T & P \end{pmatrix}, \tag{2}$$

where $T > R > S > P$ and $2R > T + S$. Here, R is the reward payoff of mutual cooperation, T is the temptation to defect payoff, S is the sucker's payoff, and P is the punishment payoff for mutual defection.

We assume in the following, that the players' decisions only depend on the outcome of the previous n rounds. To this end, an *n-history for player p* is a string $h^p = (a^p_{-1}, \ldots, a^p_{-n}) \in \{C, D\}^n$. An entry a^p_{-k} corresponds to player p's action k rounds ago. Let H^p denote the space of all n-histories of player p. Analogously, let H^q as the set of n-histories h^q of player q. Sets H^p and H^q contain $|H^p| = |H^q| = 2^n$ elements each.

A pair $h = (h^p, h^q)$ is called an *n-history of the game*. We use $H = H^p \times H^q$ to denote the space of all such histories. This set contains $|H| = 2^{2n}$ elements.

Memory-n strategies. A *memory-n* strategy is a vector $\mathbf{m} = (m_h)_{h \in H} \in [0, 1]^{2n}$. Each entry m_h corresponds to the player's cooperation probability in the next round, depending on the outcome of the previous n rounds. If the two players use memory-n strategies $\mathbf{m}$ and $\mathbf{m}'$, one can represent the interaction as a Markov chain with a $2^{2n} \times 2^{2n}$ transition matrix M. Let $\mathbf{v} = (v_h)_{h \in H}$ be an invariant distribution of this Markov chain. Based on the invariant distribution $\mathbf{v}$, we can also compute the players' payoffs. To this end, let $\mathbf{S}^k = (S^k_h)_{h \in H}$ denote the vector that returns for each h the one-shot payoff that player p obtained k rounds ago,

$$S^k_h = \begin{cases} b-c & \text{if } a^p_{-k} = C \text{ and } a^q_{-k} = C \\ -c & \text{if } a^p_{-k} = C \text{ and } a^q_{-k} = D \\ b & \text{if } a^p_{-k} = D \text{ and } a^q_{-k} = C \\ 0 & \text{if } a^p_{-k} = D \text{ and } a^q_{-k} = D \end{cases} \tag{3}$$

Then we can define player p's repeated-game payoff $s_{\mathbf{m},\mathbf{m}'}$ as

$$s_{\mathbf{m},\mathbf{m}'} = \mathbf{v} \cdot \mathbf{S}^1 = \mathbf{v} \cdot \mathbf{S}^2 = \ldots = \mathbf{v} \cdot \mathbf{S}^n. \tag{4}$$

The equalities $\mathbf{v} \cdot \mathbf{S}^1 = \ldots = \mathbf{v} \cdot \mathbf{S}^n$ correspond to the intuition that it does not matter which of the past n rounds we use to define average payoffs. The payoff $s_{\mathbf{m}',\mathbf{m}}$ of player q can be defined analogously.

Let's provide definitions for some additional terms that will be used in this manuscript.

Nash Strategies. A strategy $\mathbf{m}$ for player p, is a *Nash strategy*, if player q never receives a payoff higher than that of the mutual cooperation payoff. Irrespective of q's strategy. Namely if,

$$s_{\mathbf{m}',\mathbf{m}} \le (b - c) \ \forall \ m' \ \in [0, 1]^{2n}. \tag{5}$$

Nice Strategies. A player's strategy is *nice*, if the player is never the first to defect. A nice strategy against itself receives the mutual cooperation payoff, $(b - c)$.

Partner Strategies. For player p, a *partner strategy* is a strategy which is both nice and Nash.

Partners strategies are of interest because they are strategies that strive to achieve the mutual cooperation payoff of $(b-c)$ with their co-player. However, if the co-player doesn't cooperate, they are prepared to penalize them with lower payoffs. Partner strategies, by definition, are best responses to themselves, making them Nash strategies [Hilbe et al., 2015]. All partner strategies are Nash strategies, but not all Nash strategies are partner strategies.

Previously, the work of [Akin, 2016] characterized all partner strategies in the case of memory-one strategies. For higher memory values $(n > 1)$, a few works ([Hilbe et al., 2017]) have managed to characterize subsets of memory$-n$ partner strategies. This difficulty arises from the fact that as memory increases, obtaining analytical results becomes more challenging. In this work, we focus on reactive strategies instead of memory$-n$ strategies. Reactive strategies, a subset of memory$-n$ strategies, are formally introduced in Section 3. We characterize all reactive partner strategies for $n = 2$ and $n = 3$, and present a series of results starting from Section 3.1. In the following section, we will discuss a series of results for the case of memory$-n$.

2 An Extension of Akin's Lemma

Akin's Lemma. The work of [Akin, 2016] focuses on the case of memory-one strategies, thus for $n = 1$. A memory-one strategy of player p is represented by the vector $\mathbf{m} = (m_1, m_2, m_3, m_4)$, and and when played against a co-player with strategy $\mathbf{m}'$, the resulting stationary distribution is denoted as $\mathbf{v} = (v_1, v_2, v_3, v_4)$. Akin's lemma states the following,

Lemma 2.1 (Akin's Lemma). Assume that player p uses the memory-one strategy $\mathbf{m} = (m_1, m_2, m_3, m_4)$, and q uses a strategy that leads to a sequence of distributions $\{\mathbf{v}^k, k = 1, 2, ...\}$ with $\mathbf{v}^k$ representing the distribution over the states in the kth round of the game. Let $\mathbf{v}$ be the associated stationary distribution, then,

$$\lim_{n \to \infty} \frac{1}{n} \sum_{k=1}^{n} \mathbf{v}^k \cdot (\mathbf{m} - (1, 1, 0, 0)) = 0, \text{ and therefore } \mathbf{v} \cdot (\mathbf{m} - (1, 1, 0, 0)) = 0. \tag{6}$$

Akin's Lemma for $1 \leq k \leq n$.

One special case of memory$-n$ strategies are the round$-k-$repeat strategies for some $1 \leq k \leq n$. Player p uses a *round-k-repeat strategy* $\mathbf{m}^{k-\text{Rep}}$ if in any given round, the player chooses the same action as k rounds ago. That is, if the game's n-history is such that $a^p_{-k} = C$, then $m_h^{k-\text{Rep}} = 1$; otherwise $m_h^{k-\text{Rep}} = 0$.

With the same method as in [Akin, 2016], one can show *Akin's Lemma*: For each k with $1 \leq k \leq n$, the invariant distribution $\mathbf{v}$ satisfies the following relationship,

$$\mathbf{v} \cdot (\mathbf{m} - \mathbf{m}^{k-\text{Rep}}) = \sum_{h \in H} v_h (m_h - m_h^{k-\text{Rep}}) = 0. \tag{7}$$

The intuition for this result is that $\mathbf{v} \cdot \mathbf{m}$ and all $\mathbf{v} \cdot \mathbf{m}^{k-\text{Rep}}$ are just different (but equivalent) expressions for player p's average cooperation rate. For example, $\mathbf{v} \cdot \mathbf{m}$ corresponds to a setup in which one first draws a history h according to the invariant distribution $\mathbf{v}$; then one takes player p's probability m_h to cooperate in the next round; the expectation of this procedure is $\sum_{h \in H} v_h m_h$.

%ToDo Do we need a proof here? The intuition is summarising the proof.

Zero-determinant strategies. Based on Akin's Lemma, we can derive a theory of zero-determinant strategies analogous to the case of memory-one strategies. In the following, we say a memory-n strategy $\mathbf{m}$ is a zero-determinant strategy if there are k_1, k_2, k_3 and α, β, γ such that $\mathbf{m}$ can be written as

$$\mathbf{m} = \alpha \mathbf{S}^{k_1} + \beta \tilde{\mathbf{S}}^{k_2} + \gamma \mathbf{1} + \mathbf{m}^{k-\text{Rep}}, \tag{8}$$

where $\mathbf{1}$ is the vector for which every entry is 1. By Akin's Lemma and the definition of payoffs,

$$0 = \mathbf{v} \cdot (\mathbf{m} - \mathbf{m}^{k-\text{Rep}}) = \mathbf{v} \cdot (\alpha \mathbf{S}^{k_1} + \beta \tilde{\mathbf{S}}^{k_2} + \gamma \mathbf{1}) = \alpha s_{\mathbf{m}, \mathbf{m}'} + \beta s_{\mathbf{m}', \mathbf{m}} + \gamma. \tag{9}$$

That is, payoffs satisfy a linear relationship.

One interesting special case arises if $k_1 = k_2 = k_3 =: k$ and $\alpha = -\beta = 1/(b+c)$ and $\gamma = 0$. In that case, the formula (8) yields the strategy

$$m_h = \begin{cases} 1 & \text{if } a^q_{-k} = C \\ 0 & \text{if } a^q_{-k} = D \end{cases} \tag{10}$$

That is, this strategy implements Tit-for-Tat (for $k = 1$) or delayed versions thereof (for $k > 1$). These strategies are partners strategies that also satisfy a stronger relationship. By Eq. (9), the enforced payoff relationship is $s_{\mathbf{m}, \mathbf{m}'} = s_{\mathbf{m}', \mathbf{m}}$.

Another interesting special case arises if $k_1 = k_2 = k_3 =: k$ and $\alpha = 0$, $\beta = -1/b$, $\gamma = 1 - c/b$. In that case Eq. (8) yields the strategy

$$m_h = \begin{cases} 1 & \text{if } a^q_{-k} = C \\ 1 - c/b & \text{if } a^q_{-k} = D \end{cases} \tag{11}$$

That is, the generated strategy is GTFT (if $k = 1$), or delayed versions thereof (for $k > 1$). By Eq. (9), the enforced payoff relationship is $s_{\mathbf{m}', \mathbf{m}} = b - c$. In particular, these strategies are partner strategies.

3

3 Reactive Partner Strategies

A *reactive$-n$ strategy* is denoted by a vector $\mathbf{p} = (p_h)_{h \in H^q} \in [0,1]^{2n}$. Each entry p_h corresponds to the player's cooperation probability in the next round, based on the co-player's action(s) in the previous n rounds. Therefore, n-bit reactive strategies exclusively rely on the co-player's n-history, remaining unaffected by the focal player's own actions during the past n rounds. From this point onward, we distinguish between memory-n strategies and reactive-n strategies, using notations $\mathbf{m}$ and $\mathbf{p}$ respectively for each set of strategies.

To begin, let's introduce some additional notation. Suppose player p adopts are reactive$-n$ strategy $\mathbf{p}$, and suppose player q adopts an arbitrary memory-n strategy. Let $\mathbf{v} = (v_h)_{h \in H}$ be an invariant of the game between the two players. We define the following marginal distributions with respect to the possible n-histories of player q,

$$v_h^q = \sum_{h^p \in H^p} v_{(h^p, h^q)} \; \forall \; h^q \in H^q. \tag{12}$$

These entries describe how often we observe player q to choose actions h^q, in n consecutive rounds (irrespective of the actions of player p). Note that,

$$\sum_{h \in H^q} v_h^q = 1. \tag{13}$$

Similarly, the cooperation rate of player q can also be defined irrespective of the actions of player p. Let H_k^q be the subset of H^q, for which,

$$H_k^q = \{h \in H^q : h_{-k} = C\}. \tag{14}$$

Let $\rho_{\mathbf{m}}$ be the cooperation rate of player q playing an arbitrary memory-n strategy $\mathbf{m}$ when playing against player p with a reactive strategy,

$$\rho_{\mathbf{m}} = \sum_{h \in H_1^q} v_h^q = \sum_{h \in H_2^q} v_h^q = \ldots = \sum_{h \in H_n^q} v_h^q. \tag{15}$$

Equality (15) correspond to the intuition that it does not matter which of the past n rounds player q cooperated to define the cooperation rate.

We can also express player p's average cooperation rate $\rho_{\mathbf{p}}$ in terms of v_h^q by noting that,

$$\rho_{\mathbf{p}} = \sum_{h \in H^q} v_h^q \cdot p_h. \tag{16}$$

Because we consider simple donation games, we note that these two quantities, $\rho_{\mathbf{m}}$ *and* $\rho_{\mathbf{p}}$, are sufficient to define the payoffs of the two players,

$$\begin{aligned} s_{\mathbf{p},\mathbf{m}} &= b\,\rho_{\mathbf{m}} - c\,\rho_{\mathbf{p}} \\ s_{\mathbf{m},\mathbf{q}} &= b\,\rho_{\mathbf{p}} - c\,\rho_{\mathbf{m}}. \end{aligned} \tag{17}$$

3.1 Sufficiency of Self reactive strategies

To characterize all partner reactive-n strategies, one would usually need to check against all pure memory-n strategies McAvoy and Nowak [2019]. However, we demonstrate that when player p uses a reactive-n strategy, it is sufficient to check only against self-reactive-n strategies. This is a direct outcome of Lemma 3.1.

Self-reactive-n strategies are also a subset of memory-n strategies. They only consider the focal player's own n-history, and ignore the co-player's. Formally, a self-reactive-n strategy is a vector $\tilde{\mathbf{p}} = (\tilde{p}_h)_{h \in H^p} \in [0,1]^{2n}$. Each entry $\tilde{p}_h$ corresponds to the player's cooperation probability in the next, depending on the player's own action(s) in the previous n rounds.

Lemma 3.1. Let $\mathbf{p}$ be an reactive$-n$ strategy for player p. Then, for any memory$-n$ strategy $\mathbf{m}$ used by player q, player p's score is exactly the same as if q had played a specific self-reactive memory-n strategy $\tilde{\mathbf{p}}$.

Proof.   □

Note that Lemma 3.1 aligns with the previous result by Press and Dyson [2012]. They discussed the case where one player uses a memory-one strategy and the other player employs a longer memory strategy. They demonstrated that the payoff of the player with the longer memory is exactly the same as if the player had employed a specific shorter-memory strategy, disregarding any history beyond what is shared with the short-memory player. The result here follows a similar intuition: if there is a part of history that one player does not observe, then the co-player gains nothing by considering the history not shared with the short-memory player.

More specifically, the play of a self-reactive player solely relies on their own previous actions. Hence, describing the self-reactive player's play can be achieved through a Markov process with a $2^n \times 2^n$ transition matrix $\tilde{M}$ instead. The stationary distribution $\tilde{\mathbf{v}}$ of $\tilde{M}$ has the following property:

$$\tilde{u}_h = u_h^q \ \forall \ h \in H^q. \tag{18}$$

From hereupon we will use the notation $\mathbf{m}, \mathbf{p}$, and $\tilde{\mathbf{p}}$ to denote memory-n, reactive-n, and self-reactive-n strategies.

3.2 Reactive-Two Partner Strategies

In this section, we focus on the case of $n = 2$. Reactive-two strategies are denoted as a vector $\mathbf{p} = (p_{CC}, p_{CD}, p_{DC}, p_{DD})$ where p_{CC} is the probability of cooperating in this turn when the co-player cooperated in the last 2 turns, p_{CD} is the probability of cooperating given that the co-player cooperated in the second to last turn and defected in the last, and so forth. A nice reactive-two strategy is represented by the vector $\mathbf{p} = (1, p_{CD}, p_{DC}, p_{DD})$.

Theorem 3.2 ("Reactive-Two Partner Strategies")**.** A reactive-two strategy $\mathbf{p}$, is a partner strategy if and only if, it's nice ($p_{CC} = 1$) and the remaining entries satisfy the conditions:

$$p_{DD} < 1 - \frac{c}{b} \quad and \quad \frac{p_{CD} + p_{DC}}{2} < 1 - \frac{1}{2} \cdot \frac{c}{b}. \tag{19}$$

There are two independent proves of Theorem 3.2. The first prove is in line with the work of [Akin, 2016], and the second one relies on Lemma 3.1. Here, we discuss both.

Proof One. Suppose player p adopts a reactive-two strategy $\mathbf{p} = (p_{CC}, p_{CD}, p_{DC}, p_{DD})$. Moreover, suppose player q adopts an arbitrary memory-2 strategy $\mathbf{m}$. Let $\mathbf{v} = (v_h)_{h \in H}$ be an invariant distribution of the game between the two players.

We define the following four marginal distributions with respect to the possible two-histories of player q,

$$
\begin{aligned}
v_{CC}^q &= \sum_{h^p \in H^p} v_{(h^p, CC)} \\
v_{CD}^q &= \sum_{h^p \in H^p} v_{(h^p, CD)} \\
v_{DC}^q &= \sum_{h^p \in H^p} v_{(h^p, DC)} \\
v_{DD}^q &= \sum_{h^p \in H^p} v_{(h^p, DD)}.
\end{aligned}
\tag{20}
$$

These four entries describe how often we observe player q to choose actions CC, CD, DC, DD in two consecutive rounds (irrespective of the actions of player p). We can define player q's average cooperation rate $\rho_{\mathbf{m}}$ as

$$
\rho_{\mathbf{m}} := v_{CC}^q + v_{CD}^q = v_{CC}^q + v_{DC}^q.
\tag{21}
$$

Here, the second equality holds because it does not matter whether we define player q's cooperation rate based on the first or the second round of each 2-history. In particular, we can use this equality to conclude

$$
v_{CD}^q = v_{DC}^q.
\tag{22}
$$

Similarly, we can express player p's average cooperation rate $\rho_{\mathbf{p}}$ in terms of v_{CC}^q, v_{CD}^q, v_{DC}^q, v_{DD}^q by noting that

$$
\begin{aligned}
\rho_{\mathbf{p}} &= v_{CC}^q \, p_{CC} + v_{CD}^q \, p_{CD} + v_{DC}^q \, p_{DC} + v_{DD}^q \, p_{DD} \\
&= v_{CC}^q \, p_{CC} + v_{CD}^q \, (p_{CD} + p_{DC}) + v_{DD}^q \, p_{DD}.
\end{aligned}
\tag{23}
$$

Here, the second equality is due to Eq. (22).

Proof. A reactive-two strategy $\mathbf{p} = (p_{CC}, p_{CD}, p_{DC}, p_{DD})$ can only be a Nash equilibrium if *no* other strategy yields a larger payoff, in particular neither AllD nor the Alternator strategy must yield a larger payoff, where AllD$= (0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0)$ and Alternator$= (0,0,1,1,0,0,1,1,0,0,1,1,0,0,1,1)$. Thus, $\mathbf{p}$ can only form a Nash equilibrium if

$$
\pi(\text{AllD}, \mathbf{p}) \leq b - c \quad \text{and} \quad \pi(\text{Alternator}, \mathbf{p}) \leq b - c,
$$

or equivalently, if

$$
p_{DD} \leq 1 - \frac{c}{b} \quad \text{and} \quad p_{CD} + p_{DC} \leq 1 + \frac{b-c}{c}.
\tag{24}
$$

Now, suppose player q has some strategy $\mathbf{m}$ such that $s_{\mathbf{m},\mathbf{p}} > b-c$. It follows that

$$
\begin{aligned}
0 \quad &< \quad s_{\mathbf{m},\mathbf{p}} - (b-c) \\
&\stackrel{Eq.\ (17)}{=} \quad b\rho_{\mathbf{p}} - c\rho_{\mathbf{m}} - (b-c) \\
&\stackrel{Eqs.\ (21),(23),(13)}{=} \quad b\left(v_{CC}^q p_{CC} + v_{CD}^q(p_{CD}+p_{DC}) + v_{DD}^q p_{DD}\right) - c\left(v_{CC}^q + v_{CD}^q\right) - (b-c)\left(v_{CC}^q + 2v_{CD}^q + v_{DD}^q\right) \\
&= \quad v_{CC}^q\, b\,(p_{CC}-1) + v_{CD}^q\left(b(p_{CD}+p_{DC}) + c - 2b\right) + v_{DD}^q\left(bp_{DD} - (b-c)\right).
\end{aligned}
\tag{25}
$$

Condition (25) can hold only if,

$$
b\,(p_{CD}+p_{DC}) + c - 2b > 0, \qquad b\,p_{DD} - (b-c) > 0.
\tag{26}
$$

Thus, Eq. (24) reassures that $\mathbf{p}$ is Nash strategy, and given that $p_{CC} = 1$, it is a partner strategy.

$\square$

Proof Two. Suppose player p adopts a nice reactive-two strategy $\mathbf{p} = (1, p_{CD}, p_{DC}, p_{DD})$. For $\mathbf{p}$ to be a Nash strategy,

$$
s_{\mathbf{m},\mathbf{p}} \leq (b-c),
\tag{27}
$$

must hold against all pure memory-2 strategies ($\mathbf{m} \in \{0,1\}^{4^2}$). Due to Lemma 3.1, it is sufficient to check only against pure self-reactive strategies, and in the case of $n = 2$ there can be only 16 such strategies. We refer to them as $\tilde{\mathbf{q}}^i$ for $i \in 1, \ldots, 16$. The strategies are as follow,

- $\tilde{\mathbf{q}}^0 = (0, 0, 0, 0)$
- $\tilde{\mathbf{q}}^4 = (0, 1, 0, 0)$
- $\tilde{\mathbf{q}}^8 = (1, 0, 0, 0)$
- $\tilde{\mathbf{q}}^{12} = (1, 1, 0, 0)$

- $\tilde{\mathbf{q}}^1 = (0, 0, 0, 1)$
- $\tilde{\mathbf{q}}^5 = (0, 1, 0, 1)$
- $\tilde{\mathbf{q}}^9 = (1, 0, 0, 1)$
- $\tilde{\mathbf{q}}^{13} = (1, 1, 0, 1)$

- $\tilde{\mathbf{q}}^2 = (0, 0, 1, 0)$
- $\tilde{\mathbf{q}}^6 = (0, 1, 1, 0)$
- $\tilde{\mathbf{q}}^{10} = (1, 0, 1, 0)$
- $\tilde{\mathbf{q}}^{14} = (1, 1, 1, 0)$

- $\tilde{\mathbf{q}}^3 = (0, 0, 1, 1)$
- $\tilde{\mathbf{q}}^7 = (0, 1, 1, 1)$
- $\tilde{\mathbf{q}}^{11} = (1, 0, 1, 1)$
- $\tilde{\mathbf{q}}^{15} = (1, 1, 1, 1)$

Proof. Suppose player p plays a nice reactive-two strategy $\mathbf{p} = (1, p_{CD}, p_{DC}, p_{DD})$, and suppose the co-player q plays a pure self-reactive-two strategy $\tilde{\mathbf{q}}$. The possible payoffs for $\tilde{\mathbf{q}} \in \{\tilde{\mathbf{q}}^0, \ldots, \tilde{\mathbf{q}}^{16}\}$ are:

$$s_{\tilde{\mathbf{q}}^i,\mathbf{p}} = \quad b \cdot p_{DD} \qquad\qquad for \ \ i \in \quad \{0,2,4,6,8,10,12,14\}$$

$$s_{\tilde{\mathbf{q}}^i,\mathbf{p}} = \quad \frac{b \cdot (p_{CD}+p_{DC}+p_{DD})}{3} - \frac{1}{3}\cdot c \qquad for \ \ i \in \quad \{1,9\}$$

$$s_{\tilde{\mathbf{q}}^i,\mathbf{p}} = \quad \frac{b \cdot (p_{CD}+p_{DC}+p_{DD}+1)}{4} - \frac{1}{2}\cdot c \qquad for \ \ i \in \quad \{3\}$$

$$s_{\tilde{\mathbf{q}}^i,\mathbf{p}} = \quad \frac{b \cdot (p_{CD}+p_{DC})}{2} - \frac{1}{2}\cdot c \qquad for \ \ i \in \quad \{4,5,12,13\}$$

$$s_{\tilde{\mathbf{q}}^i,\mathbf{p}} = \quad \frac{b \cdot (p_{CD}+p_{DC}+1)}{3} - \frac{2}{3}\cdot c \qquad for \ \ i \in \quad \{6,7\}$$

$$s_{\tilde{\mathbf{q}}^i,\mathbf{p}} = \quad b - c \qquad\qquad for \ \ i \in \quad \{8,9,10,11,12,13,14,15\}$$

Setting the payoff expressions of $s_{\tilde{\mathbf{q}}^i,\mathbf{p}}$ to smaller or equal to $(b-c)$ we get the following unique conditions,

$$p_{DD} \leq 1 - \frac{c}{b} \tag{28}$$

$$\frac{p_{CD}+p_{DC}+p_{DD}}{3} \leq 1 - \frac{2}{3}\cdot\frac{c}{b} \tag{29}$$

$$\frac{p_{CD}+p_{DC}}{2} \leq 1 - \frac{1}{2}\cdot\frac{c}{b} \tag{30}$$

$$\tag{31}$$

Note that condition (30) is the sum of conditions (29) and (31). Thus, only conditions (29) and (31) are necessary.

$\square$

3.3 Reactive-Three Partner Strategies

In this section, we focus on the case of $n = 3$. Reactive-three strategies are denoted as a vector $\mathbf{p} = (p_{CCC}, p_{CCD}, p_{CDC}, p_{CDD}, p_{DCC}, p_{DCD}, p_{DDC}, p_{DDD})$ where p_{CCC} is the probability of cooperating in round t when the co-player cooperates in the last 3 rounds, p_{CCD} is the probability of cooperating given that the co-player cooperated in the third and second to last rounds and defected in the last, and so forth. A nice reactive-three strategy is represented by the vector $\mathbf{p} = (1, p_{CCD}, p_{CDC}, p_{CDD}, p_{DCC}, p_{DCD}, p_{DDC}, p_{DDD})$.

Theorem 3.3 ("Reactive-Three Partner Strategies"). A reactive-three strategy $\mathbf{p}$, is a partner strategy if and only if, it's nice ($p_{CCC} = 1$) and the remaining entries satisfy the conditions:

$$\frac{p_{CCD}+p_{CDC}+p_{DCC}}{3} < 1-\frac{1}{3}\cdot\frac{c}{b} \qquad \frac{p_{CDD}+p_{DCD}+p_{DDC}}{3} < 1-\frac{2}{3}\cdot\frac{c}{b} \qquad p_{DDD} < 1-\frac{c}{b} \tag{32}$$

$$\frac{p_{CCD}+p_{CDD}+p_{DCC}+p_{DDC}}{4} < 1-\frac{1}{2}\cdot\frac{c}{b} \qquad \frac{p_{CDC}+p_{DCD}}{2} < 1-\frac{1}{2}\cdot\frac{c}{b} \tag{33}$$

Once again, there are two independent proves of Theorem 3.3, and we will present both.

Proof One. Suppose player p adopts a reactive-three strategy $\mathbf{p}$, and suppose player q adopts an arbitrary memory-three strategy $\mathbf{m}$. Let $\mathbf{v} = (v_h)_{h\in H}$ be an invariant distribution of the game between the two players.

We define the following eight marginal distributions with respect to the possible three-histories of player q,

$$
\begin{aligned}
v_{CCC}^q &= \sum_{h^p \in H^p} v_{(h^p, CCC)} \\
v_{CCD}^q &= \sum_{h^p \in H^p} v_{(h^p, CCD)} \\
v_{CDC}^q &= \sum_{h^p \in H^p} v_{(h^p, CDC)} \\
v_{CDD}^q &= \sum_{h^p \in H^p} v_{(h^p, CDD)} \\
v_{DCC}^q &= \sum_{h^p \in H^p} v_{(h^p, DCC)} \\
v_{DCD}^q &= \sum_{h^p \in H^p} v_{(h^p, DCD)} \\
v_{DDC}^q &= \sum_{h^p \in H^p} v_{(h^p, DDC)} \\
v_{DDD}^q &= \sum_{h^p \in H^p} v_{(h^p, DDD)}.
\end{aligned}
\tag{34}
$$

These eight entries describe how often we observe player q to choose actions CCC, CCD, CDC, CDD, DCC, DCD, DDC, DDD in three consecutive rounds (irrespective of the actions of player p). We can define player q's average cooperation rate $\rho_{\mathbf{m}}$ as

$$
\rho_{\mathbf{m}} := v_{CCC}^q + v_{CCD}^q + v_{DCC}^q + v_{DCD}^q.
\tag{35}
$$

In the case of $n = 3$ the following equalities hold,

$$
\begin{aligned}
v_{CCD}^q &= v_{DCC}^q & (36) \\
v_{DDC}^q &= v_{CDD}^q & (37) \\
v_{CCD}^q + v_{DCD}^q &= v_{CDC}^q + v_{DDC}^q \Rightarrow & \\
v_{CCD}^q &= v_{CDC}^q + v_{CDD}^q - v_{DCD}^q & (38)
\end{aligned}
$$

The average cooperation rate of p's is given by

$$
\begin{aligned}
\rho_{\mathbf{p}} \quad = \quad & v_{CCC}^q\, p_{CCC} + v_{CCD}^q\, p_{CCD} + v_{CDC}^q\, p_{CDC} + v_{CDD}^q\, p_{CDD} + v_{DCD}^q\, p_{DCD} + \\
& + v_{DDC}^q\, p_{DDC} + v_{DDD}^q\, p_{DDD} \\
\overset{Eqs.\ (36),(37)}{=} \quad & v_{CCC}^q\, p_{CCC} + v_{CCD}^q\, (p_{CCD} + p_{DCC}) + v_{CDC}^q\, p_{CDC} + v_{CDD}^q\, (p_{CDD} + p_{DDC}) + \\
& v_{DCD}^q\, p_{DCD} + v_{DDD}^q\, p_{DDD}
\end{aligned}
\tag{39}
$$

Proof. A reactive-three strategy $\mathbf{p}$ can only be a Nash equilibrium if *no* other strategy yields a larger payoff, in particular neither AllD nor the following self-reactive-three strategies, $\tilde{\mathbf{q}}^{15} = (0,0,0,0,1,1,1,1)$, $\tilde{\mathbf{q}}^{17} = (0,0,0,1,0,0,0,1)$, $\tilde{\mathbf{q}}^{51} = (0,0,1,1,0,0,1,1)$ and $\tilde{\mathbf{q}}^{102} = (0,1,1,0,0,1,1,0)$. Thus, $\mathbf{p}$ can only form a Nash equilibrium if

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$$\pi(\text{AllD}, \mathbf{p}) \le b-c \quad and \quad \pi(\tilde{\mathbf{q}}^{15}, \mathbf{p}) \le b-c \quad and \quad \pi(\tilde{\mathbf{q}}^{17}, \mathbf{p}) \le b-c \quad and$$

$$\pi(\tilde{\mathbf{q}}^{51}, \mathbf{p}) \le b-c \quad and \quad \pi(\tilde{\mathbf{q}}^{102}, \mathbf{p}) \le b-c$$

or equivalently, if

$$\frac{p_{CCD} + p_{CDC} + p_{DCC}}{3} < 1 - \frac{1}{3} \cdot \frac{c}{b} \qquad \frac{p_{CDD} + p_{DCD} + p_{DDC}}{3} < 1 - \frac{2}{3} \cdot \frac{c}{b} \qquad\qquad p_{DDD} < 1 - \frac{c}{b} \quad (40)$$

$$\frac{p_{CCD} + p_{CDD} + p_{DCC} + p_{DDC}}{4} < 1 - \frac{1}{2} \cdot \frac{c}{b} \qquad \frac{p_{CDC} + p_{DCD}}{2} < 1 - \frac{1}{2} \cdot \frac{c}{b} \qquad\qquad (41)$$

Now, suppose player q has some strategy $\mathbf{m}$ and player p has a reactive-two strategy such that $s_{\mathbf{m},\mathbf{p}} > b-c$. It follows that

$$
\begin{aligned}
0 \quad &\le \quad s_{\mathbf{m},\mathbf{p}} - (b-c) \\[4pt]
&\overset{Eq.\ (17)}{=} \quad b\rho_{\mathbf{p}} - c\rho_{\mathbf{m}} - (b-c) \\[4pt]
&\overset{Eqs.\ (39),(13)}{=} \quad b\left(v_{CCC}^q p_{CCC} + v_{CCD}^q (p_{CCD} + p_{DCC}) + v_{CDC}^q p_{CDC} + v_{DDC}^q (p_{CDD} + p_{DDC}) + v_{DCD}^q p_{DCD} + v_{DDD}^q p_{DDD}\right) \\
&\qquad\quad - c\left(v_{CCC}^q + 2v_{CCD}^q + v_{DCD}^q \right) - (b-c)\left(v_{CCC}^q + 2v_{CCD}^q + v_{CDC}^q + 2v_{DDC}^q + v_{DCD}^q + v_{DDD}^q \right) \\[4pt]
&= \quad b\, v_{CCC}^q (p_{CCC} - 1) + v_{CCD}^q (b\,(p_{CCD} + p_{DCC} - 2)) + v_{CDC}^q (b\,(p_{CDC} - 1) + c) + \\
&\qquad\quad v_{CDD}^q (b\,(p_{CDD} + p_{DDC} - 2) + 2\,c) + v_{DCD}^q (b\,(p_{DCD} - 1)) + v_{DDD}^q (b\,(p_{DDD} - 1) + c) \\[4pt]
&\overset{Eq.\ (38)}{=} \quad b\, v_{CCC}^q (p_{CCC} - 1) + v_{DDD}^q (b\,(p_{DDD} - 1) + c) + v_{CDC}^q (b\,(p_{CCD} + p_{DCC} + p_{CDC} - 3) + c) + \\
&\qquad\quad v_{CDD}^q (b\,(p_{CDD} + p_{DDC} + p_{CCD} + p_{DCC} - 4) + 2\,c) + v_{DCD}^q (b\,(p_{DCD} - 1) - b\,(p_{CCD} + p_{DCC}) - 2) \\
&\hspace{12cm} (42)
\end{aligned}
$$

Condition (42) holds only for,

$$b\,(p_{DDD} - 1) + c < 0, \quad b\,(p_{CCD} + p_{DCC} + p_{CDC} - 3) + c$$

$$b\,(p_{CDD} + p_{DDC} + p_{CCD} + p_{DCC} - 4) + 2\,c < 0 \Rightarrow -b\,(p_{CCD} + p_{DCC} - 2) > b\,(p_{CDD} + p_{DDC} - 2) + 2\,c$$

$$b\,(p_{DCD} - 1) - b\,(p_{CCD} + p_{DCC}) - 2 < 0 \Rightarrow b\,(p_{DCD} + p_{CDD} + p_{DDC} - 3) + 2\,c < 0.$$

Thus, conditions Eq. (40) reassure that $\mathbf{p}$ is Nash strategy, and given that $p_{CC} = 1$, it is a partner strategy.

$\square$

Proof Two. Consider all the pure self-reactive-three strategies. There is a total of 256 such strategies. These are given in the Section 5. The payoff expression for each of these strategies against a nice reactive-three strategies can be calculated explicitly. We use these expressions to obtain the conditions for partner strategies similar to the previous subsection.

Proof. The payoff expressions for a nice reactive-three strategy p against all pure self-reactive-three strategies are as follows,

$$
\begin{aligned}
s_{\tilde{\mathbf{q}}^i,\mathbf{p}} &= b\,p_{DDD} & for\ \ i &\in\ [0,2,4,6,\ldots,250,252,254]\\[4pt]
s_{\tilde{\mathbf{q}}^i,\mathbf{p}} &= \frac{b\cdot(p_{CDD}+p_{DCD}+p_{DDC}+p_{DDD})}{4}-\frac{1}{4}\cdot c & for\ \ i &\in\ \{1,9,33,41,65,73,97,105,129,137,161,\\
& & & \quad\ 169,193,201,225,233\}\\[4pt]
s_{\tilde{\mathbf{q}}^i,\mathbf{p}} &= \frac{b\cdot(p_{CCD}+p_{CDD}+p_{DCC}+p_{DDC}+p_{DDD})}{5}-\frac{2}{5}\cdot c & for\ \ i &\in\ \{3,7,35,39,131,135,163,167\}\\[4pt]
s_{\tilde{\mathbf{q}}^i,\mathbf{p}} &= \frac{b\cdot(p_{CDC}+p_{DCD})}{2}-\frac{1}{2}\cdot c & for\ \ i &\in\ \{4-7,12-15,20-23,28-31,68-71,\\
& & & \quad\ 76-79,84-87,92-95,132-135,\\
& & & \quad\ 140-143,148-151,156-159,\\
& & & \quad\ 196-199,204-207,212-215,220-223\}\\[4pt]
s_{\tilde{\mathbf{q}}^i,\mathbf{p}} &= \frac{b\cdot(p_{CCD}+p_{CDD}+p_{DCC}+p_{DDC}+p_{DDD}+1)}{6}-\frac{1}{2}\cdot c & for\ \ i &\in\ \{11,15,43,47\}\\[4pt]
s_{\tilde{\mathbf{q}}^i,\mathbf{p}} &= \frac{b\cdot(p_{CDD}+p_{DCD}+p_{DDC})}{3}-\frac{1}{3}\cdot c & for\ \ i &\in\ \{16,17,24,25,48,49,56,57,80,81,88,\\
& & & \quad\ 89,112,113,120,121,144,145,152,153,\\
& & & \quad\ 176,177,184,185,208,209,216,217,\\
& & & \quad\ 240,241,248,249\}\\[4pt]
s_{\tilde{\mathbf{q}}^i,\mathbf{p}} &= \frac{b\cdot(p_{CCD}+p_{CDD}+p_{DCC}+p_{DDC})}{4}-\frac{1}{2}\cdot c & for\ \ i &\in\ \{18,19,22,23,50,51,54,55,146,147,\\
& & & \quad\ 150,151,178,179,182,183\}\\[4pt]
s_{\tilde{\mathbf{q}}^i,\mathbf{p}} &= \frac{b\cdot(p_{CCD}+p_{CDD}+p_{DCC}+p_{DDC}+1)}{5}-\frac{3}{5}\cdot c & for\ \ i &\in\ \{26,27,30,31,58,59,62,63\}\\[4pt]
s_{\tilde{\mathbf{q}}^i,\mathbf{p}} &= \frac{b\cdot(p_{CCD}+p_{CDC}+p_{CDD}+p_{DCC}+p_{DCD}+p_{DDC}+p_{DDD})}{7}-\frac{3}{7}\cdot c & for\ \ i &\in\ \{37,67,165,195\}\\[4pt]
s_{\tilde{\mathbf{q}}^i,\mathbf{p}} &= \frac{b\cdot(p_{CCD}+p_{CDC}+p_{CDD}+p_{DCC}+p_{DCD}+p_{DDC}+p_{DDD}+1)}{8}-\frac{1}{2}\cdot c & for\ \ i &\in\ \{45,75\}\\[4pt]
s_{\tilde{\mathbf{q}}^i,\mathbf{p}} &= \frac{b\cdot(p_{CCD}+p_{CDC}+p_{CDD}+p_{DCC}+p_{DCD}+p_{DDC})}{6}-\frac{1}{2}\cdot c & for\ \ i &\in\ \{52,53,82,83,180,181,210,211\}\\[4pt]
s_{\tilde{\mathbf{q}}^i,\mathbf{p}} &= \frac{b\cdot(p_{CCD}+p_{CDC}+p_{CDD}+p_{DCC}+p_{DCD}+p_{DDC}+1)}{7}-\frac{4}{7}\cdot c & for\ \ i &\in\ \{60,61,90,91\}\\[4pt]
s_{\tilde{\mathbf{q}}^i,\mathbf{p}} &= \frac{b\cdot(p_{CCD}+p_{CDC}+p_{DCC})}{3}-\frac{2}{3}\cdot c & for\ \ i &\in\ \{96-103,112-119,224-231,240-247\}\\[4pt]
s_{\tilde{\mathbf{q}}^i,\mathbf{p}} &= \frac{b\cdot(p_{CCD}+p_{CDC}+p_{DCC}+1)}{4}-\frac{3}{4}\cdot c & for\ \ i &\in\ \{104-111,120-127\}\\[4pt]
s_{\tilde{\mathbf{q}}^i,\mathbf{p}} &= (b-c) & for\ \ i &\in\ [128,255]
\end{aligned}
\tag{43}
$$

Setting these to smaller or equal than the mutual cooperation payoff $(b-c)$ give the following ten conditions,

$$
p_{DDD}\le 1-\frac{c}{b},\quad \frac{p_{CDC}+p_{DCD}}{2}\le 1-\frac{1}{2}\cdot\frac{c}{b},\quad \frac{p_{CDD}+p_{DCD}+p_{DDC}}{3}\le 1-\frac{2}{3}\cdot\frac{c}{b},
\tag{44}
$$

$$
\frac{p_{CCD}+p_{CDC}+p_{DCC}}{3}\le 1-\frac{1}{3}\cdot\frac{c}{b},\quad \frac{p_{CCD}+p_{CDD}+p_{DCC}+p_{DDC}}{4}\le 1-\frac{1}{2}\cdot\frac{c}{b}
\tag{45}
$$

$$
\frac{p_{CDD}+p_{DCD}+p_{DDC}+p_{DDD}}{4}\le 1-\frac{3}{4}\cdot\frac{c}{b},
\tag{46}
$$

$$
\frac{p_{CCD}+p_{CDC}+p_{CDD}+p_{DCC}+p_{DCD}+p_{DDC}+p_8}{7}\le 1-\frac{4}{7}\cdot\frac{c}{b},
\tag{47}
$$

$$
\frac{p_{CCD}+p_{CDD}+p_{DCC}+p_{DDC}+p_8}{5}\le 1-\frac{3}{5}\cdot\frac{c}{b},
\tag{48}
$$

$$
\frac{p_{CCD}+p_{CDC}+p_{CDD}+p_{DCC}+p_{DCD}+p_{DDC}}{6}\le 1-\frac{1}{2}\cdot\frac{c}{b}
\tag{49}
$$

Note that only conditions (44) and (45) are unique. The remaining conditions can be derived from the sums of two or more of these conditions. $\qquad\square$

3.4 Reactive Counting Partner Strategies

A special case of reactive strategies is reactive-counting strategies. These are strategies that respond to the co-player's actions, but they do not distinguish between when cooperations/defections occurred; they solely consider the count of cooperations in the last n turns. A reactive-counting-n strategy is represented by a vector $\mathbf{r} = (r_i)_{i \in [0,n]}$, where the entry r_i indicates the probability of cooperating given that the co-player cooperated i times in the last n turns.

Reactive-Counting-Two Partner Strategies. These are denoted by the vector $\mathbf{r} = (r_2, r_1, r_0)$ where r_i is the probability of cooperating in after i cooperations in the last 2 turns. We can characterise reactive-counting-two partner strategies by setting $r_2 = 1$, and $p_{CD} = p_{DC} = r_1$ and $p_{DD} = r_0$ in conditions (19). This gives us the following result.

Lemma 3.4. A nice reactive-counting-two strategy $\mathbf{r} = (1, r_1, r_0)$ is a partner strategy if and only if,

$$r_1 < 1 - \frac{1}{2} \cdot \frac{c}{b} \quad and \quad r_0 < 1 - \frac{c}{b}. \tag{50}$$

Reactive-Counting-Three Partner Strategies. These are denoted by the vector $\mathbf{r} = (r_3, r_2, r_1, r_0)$ where r_i is the probability of cooperating in after i cooperations in the last 3 turns. We can characterise reactive-counting-three partner strategies by setting $r_3 = 1$, and $p_{CCD} = p_{CDC} = r_2, p_{DCD} = p_{DDC} = r_1$ and $p_{DDD} = r_0$ in conditions (32). This gives us the following result.

Lemma 3.5. A nice reactive-counting-three strategy $\mathbf{r} = (1, r_2, r_1, r_0)$ is a partner strategy if and only if,

$$r_2 < 1 - \frac{1}{3} \cdot \frac{c}{b}, \quad r_1 < 1 - \frac{2}{3} \cdot \frac{c}{b} \quad and \quad r_0 < 1 - \frac{c}{b}. \tag{51}$$

In the case of counting reactive strategies, we generalise to the case of n.

Given a reactive-counting-n strategy $\mathbf{r} = (r_n, r_{n-1}, \ldots, r_0)$, in the strategy's eyes the game can end up in n states. Each u_i state represents the state that the co-player cooperated i times in the last n turns with,

$$\sum_{i=0}^{n} u_i = 1 \Rightarrow \sum_{k=0}^{n} u_{n-k} = 1. \tag{52}$$

Thus the cooperation ratio of the strategy is,

$$\rho_{\mathbf{p}} = \sum_{k=0}^{n} r_{n-k} \cdot u_{n-k}. \tag{53}$$

the probability of cooperating given that the co-player cooperated i times. The co-player can use any self-reactive-n strategy, and thus the co-player differentiates between when the last cooperation/defection occurred. However, we can still express the co-player's cooperation rate as a function of u_i. More specifically, the co-player's cooperation rate is,

$$\rho_{\tilde{\mathbf{p}}} = \sum_{k=0}^{n} \frac{n-k}{n} \cdot u_{n-k}. \tag{54}$$

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With this we have all the required tools to prove the following theorem.

Theorem 3.6 ("Reactive-Counting Partner Strategies"). A reactive-counting$-n$ strategy $\mathbf{r} = (r_i)_{i \in [0,n]}$, is a partner strategy if and only if, the r_i entries satisfy the conditions:

$$r_n = 1, \text{ and } r_{n-k} < 1 - \frac{k}{n} \cdot \frac{c}{b}, \text{ for } k \in [1, n]. \tag{55}$$

Proof. Consider a set of alternating self-reactive-n strategies that defect after cooperating i times. Since $i \in [0, n]$, there can be only $n + 1$ such strategies. We will denote this set as $A = \{\mathbf{A^0}, \mathbf{A^1}, \ldots, \mathbf{A^n}\}$. The payoff of an alternating self-reactive-n against a counting-reactive$-n$ $\mathbf{r}$ is given by,

$$s_{\mathbf{A^i},\mathbf{r}} = b \cdot r_i - \frac{i}{n} \cdot c \ \ for \ \ i \in [0, n]. \tag{56}$$

The intuition behind Eq. (56) is that in the long term of the gave the strategies end up in a state where $\mathbf{A^i}$ has cooperated i times in the last n turns. Thus, here the co-player will cooperate, and provide the benefit b with a probability r_i. Whilst in return the alternating strategy cooperated $\frac{i}{n}$ and pays the cost. As we have already discussed previously, a strategy can only be Nash if the payoff of the co-player does not exceed $(b - c)$. Thus for $\mathbf{p}$ to be Nash against each strategy in set A (for $i \in [0, n]$),

The intuition behind Eq. (56) is that in the long term, the strategies end up in a state where $\mathbf{A^i}$ has cooperated i times in the last n turns. Thus, the co-player will cooperate and provide the benefit b with a probability r_i, while in return, the alternating strategy has cooperated $\frac{i}{n}$ times and pays the cost. As we have already discussed previously, a strategy can only be a Nash equilibrium if the payoff of the co-player does not exceed $(b - c)$. Therefore, for p to be a Nash equilibrium against each strategy in set A (for $i \in [0, n]$),

$$s_{\mathbf{A^i},\mathbf{r}} \leq b - c \tag{57}$$

$$b \cdot r_i - \frac{i}{n} \cdot c \leq b - c \tag{58}$$

$$r_i \leq 1 - \frac{i}{n} \cdot \frac{c}{b} \tag{59}$$

Now, suppose player q has some strategy $\mathbf{m}$ and player p has a reactive-counting strategy such that $s_{\mathbf{m},\mathbf{p}} > b\text{–}c$. It follows that

$$
\begin{aligned}
0 \qquad &\leq \qquad s_{\mathbf{m},\mathbf{p}} - (b\text{–}c) \\
&\overset{Eq.\ (17)}{=} \quad b\rho_{\mathbf{p}} - c\rho_{\mathbf{m}} - (b\text{–}c) \\
&\overset{Eqs.\ (52),(53),(54)}{=} \quad b \sum_{k=0}^{n} r_{n-k} \cdot u_{n-k} - c \sum_{k=0}^{n} \frac{n-k}{n} \cdot u_{n-k} - (b-c) \sum_{k=0}^{n} u_{n-k} \\
&\qquad\qquad u_n \Big(b\,(r_n - 1) \Big) + \sum_{k=1}^{n} u_{n-k} \Big(b \sum_{k=1}^{n} r_{n-k} - c \sum_{k=0}^{n-1} \frac{n-k}{n} - (b-c) \sum_{k=0}^{n-1} 1 \Big)
\end{aligned}
\tag{60}
$$

This condition holds only if,

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$$\left(b \, r_{n-k} - c \, \frac{n-k}{n} - (b-c) \right) < 0 \Rightarrow \tag{61}$$

$$b \, (r_{n-k} - 1) + (1 - \frac{n-k}{n}) \, c < 0 \Rightarrow \tag{62}$$

$$r_{n-k} < 1 - \frac{n}{k} \cdot \frac{c}{b}. \tag{63}$$

for $k \in [0, n]$. Thus, any counting strategy that satisfies conditions (57) is Nash, and if it is nice, it's also a partner strategy. □

4 Prisoner's Dilemma

To characterise partner strategies for the general prisoner's dilemma, we can use the method based on Lemma 3.1. Here we discuss this result in the case of $n = 2$.

There are 16 pure-self reactive strategies in $n = 2$. To calculate the explicit payoff expressions for each pure strategy against a nice reactive-two strategy $\mathbf{p} = (1, p_{CD}, p_{DC}, p_{CD})$ we use the method discussed in Section 3.1. More specifically, for a self-reactive strategy $\mathbf{q}$, we calculate where the strategy is in the long term using the transition matrix,

$$\tilde{M} = \begin{bmatrix} \tilde{p}_1 & 1 - \tilde{p}_1 & 0 & 0 \\ 0 & 0 & \tilde{p}_2 & 1 - \tilde{p}_2 \\ \tilde{p}_3 & 1 - \tilde{p}_3 & 0 & 0 \\ 0 & 0 & \tilde{p}_4 & 1 - \tilde{p}_4 \end{bmatrix} \tag{64}$$

Using the stationary vector $\tilde{\mathbf{v}}$ we can define the payoffs in the general prisoner's dilemma as follows:

$$\mathbf{s_{q,p}} = a_R \cdot R + a_S \cdot S + a_T \cdot T + a_P \cdot P, \quad where$$

$$a_R = \tilde{v}_{CC} \, p_{CC} \, \tilde{q}_{CC} + \tilde{v}_{CD} \, p_{CD} \, \tilde{q}_{CD} + \tilde{v}_{DC} \, p_{DC} \, \tilde{q}_{DC} + \tilde{v}_{DD} \, p_{DD} \, \tilde{q}_{DD},$$

$$a_S = \tilde{v}_{CC} \, p_{CC} \, (1 - \tilde{q}_{CC}) + \tilde{v}_{CD} \, p_{CD} \, (1 - \tilde{q}_{CD}) + \tilde{v}_{DC} \, p_{DC} \, (1 - \tilde{q}_{DC}) + \tilde{v}_{DD} \, p_{DD} \, (1 - \tilde{q}_{DD}),$$

$$a_T = \tilde{v}_{CC} \, (1 - p_{CC}) \, \tilde{q}_{CC} + \tilde{v}_{CD} \, (1 - p_{CD}) \, \tilde{q}_{CD} + \tilde{v}_{DC} \, (1 - p_{DC}) \, \tilde{q}_{DC} + \tilde{v}_{DD} \, (1 - p_{DD}) \, \tilde{q}_{DD},$$

$$a_P = \tilde{v}_{CC} \, (1 - p_{CC}) \, (1 - \tilde{q}_{CC}) + \tilde{v}_{CD} \, (1 - p_{CD}) \, (1 - \tilde{q}_{CD}) + \tilde{v}_{DC} \, (1 - p_{DC}) \, (1 - \tilde{q}_{DC}) + \tilde{v}_{DD} \, (1 - p_{DD}) \, (1 - \tilde{q}_{DD}).$$

This gives the following payoff expressions:

$$s_{\tilde{\mathbf{q}}^i,\mathbf{p}} = \qquad\qquad P(1-p_{DD}) + Tp_{DD} \qquad\qquad for \quad i \in \{0,2,4,6,8,10,12,14\}$$

$$s_{\tilde{\mathbf{q}}^i,\mathbf{p}} = \quad \frac{-P(p_{CD}+p_{DC}-2)+Rp_{DD}-S(p_{DD}-1)+T(p_{CD}+p_{DC})}{3} \qquad for \quad i \in \{1,9\}$$

$$s_{\tilde{\mathbf{q}}^i,\mathbf{p}} = \quad \frac{P(1-p_{CD})+R(p_{DC}+p_{DD})-S(p_{DC}+p_{DD}-2)+T(p_{CD}+1)}{4} \qquad for \quad i \in \{3\}$$

$$s_{\tilde{\mathbf{q}}^i,\mathbf{p}} = \quad \frac{P(1-p_{DC})+Rp_{CD}-S(p_{CD}-1)+Tp_{DC}}{2} \qquad for \quad i \in \{4,5,12,13\}$$

$$s_{\tilde{\mathbf{q}}^i,\mathbf{p}} = \quad \frac{R(p_{CD}+p_{DC})-S(p_{CD}+p_{DC}-2)+T}{3} \qquad for \quad i \in \{6,7\}$$

$$s_{\tilde{\mathbf{q}}^i,\mathbf{p}} = \qquad\qquad R \qquad\qquad for \quad i \in \{8,9,10,11,12,13,14,15\}$$

Setting the above expressions to smaller than R gives the following conditions,

$$p_{DD} < \frac{P-R}{P-T}, \qquad p_{CD} + p_{DC} < \frac{2P+R(p_{DD}-3)-S(p_{DD}+1)}{P-T}, \qquad p_{CD} + p_{DC} < \frac{3R-2S-T}{R-S}$$

$$p_{DC} + p_{DD} < \frac{P(p_{CD}-1)+4R-2S-T(p_{CD}+1)}{R-S}, \qquad p_{CD}(R-S) + p_{DC}(T-P) < 2R-S-P$$

Consider the case where $T = 1$ and $S = 0$,

$$p_{DD} < \frac{P-R}{P-1}, \qquad p_{CD} + p_{DC} < \frac{2P+R(p_{DD}-3)}{P-1}, \qquad p_{CD} + p_{DC} < \frac{3R-1}{R}$$

$$p_{DC} + p_{DD} < \frac{P(p_{CD}-1)+4R-p_{CD}-1}{R}, \qquad p_{CD} R + p_{DC}(1-P) < 2R-P.$$

There are five conditions, however note that

$$p_{CD} < \frac{2R-P-p_{DC}(1-P)}{R} \tag{65}$$

$$p_{CD} < \frac{3R-1}{R} - p_{DC} \tag{66}$$

by setting (66) greater ti 65 we get,

$$(1-P) < R$$

which is always true and thus we can only consider condition 66, as condition 65 will also be satisfied.

Similarly by setting (64) greater ti 61 we get,

$$\frac{2P+Rp_{DD}-3R}{P-1} < \frac{3R-1}{R} \tag{67}$$

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5 Pure Self-Reactive-Three Strategies

The 256 pure self-reactive-three strategies and their vectors are as follows,

- $\tilde{\mathbf{q}}^0 = (0, 0, 0, 0, 0, 0, 0, 0)$
- $\tilde{\mathbf{q}}^1 = (0, 0, 0, 0, 0, 0, 0, 1)$
- $\tilde{\mathbf{q}}^2 = (0, 0, 0, 0, 0, 0, 1, 0)$
- $\tilde{\mathbf{q}}^3 = (0, 0, 0, 0, 0, 0, 1, 1)$
- $\tilde{\mathbf{q}}^4 = (0, 0, 0, 0, 0, 1, 0, 0)$
- $\tilde{\mathbf{q}}^5 = (0, 0, 0, 0, 0, 1, 0, 1)$
- $\tilde{\mathbf{q}}^6 = (0, 0, 0, 0, 0, 1, 1, 0)$
- $\tilde{\mathbf{q}}^7 = (0, 0, 0, 0, 0, 1, 1, 1)$
- $\tilde{\mathbf{q}}^8 = (0, 0, 0, 0, 1, 0, 0, 0)$
- $\tilde{\mathbf{q}}^9 = (0, 0, 0, 0, 1, 0, 0, 1)$
- $\tilde{\mathbf{q}}^{10} = (0, 0, 0, 0, 1, 0, 1, 0)$
- $\tilde{\mathbf{q}}^{11} = (0, 0, 0, 0, 1, 0, 1, 1)$
- $\tilde{\mathbf{q}}^{12} = (0, 0, 0, 0, 1, 1, 0, 0)$
- $\tilde{\mathbf{q}}^{13} = (0, 0, 0, 0, 1, 1, 0, 1)$
- $\tilde{\mathbf{q}}^{14} = (0, 0, 0, 0, 1, 1, 1, 0)$
- $\tilde{\mathbf{q}}^{15} = (0, 0, 0, 0, 1, 1, 1, 1)$
- $\tilde{\mathbf{q}}^{16} = (0, 0, 0, 1, 0, 0, 0, 0)$
- $\tilde{\mathbf{q}}^{17} = (0, 0, 0, 1, 0, 0, 0, 1)$
- $\tilde{\mathbf{q}}^{18} = (0, 0, 0, 1, 0, 0, 1, 0)$
- $\tilde{\mathbf{q}}^{19} = (0, 0, 0, 1, 0, 0, 1, 1)$
- $\tilde{\mathbf{q}}^{20} = (0, 0, 0, 1, 0, 1, 0, 0)$
- $\tilde{\mathbf{q}}^{21} = (0, 0, 0, 1, 0, 1, 0, 1)$
- $\tilde{\mathbf{q}}^{22} = (0, 0, 0, 1, 0, 1, 1, 0)$
- $\tilde{\mathbf{q}}^{23} = (0, 0, 0, 1, 0, 1, 1, 1)$
- $\tilde{\mathbf{q}}^{24} = (0, 0, 0, 1, 1, 0, 0, 0)$
- $\tilde{\mathbf{q}}^{25} = (0, 0, 0, 1, 1, 0, 0, 1)$
- $\tilde{\mathbf{q}}^{26} = (0, 0, 0, 1, 1, 0, 1, 0)$
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