

# Cooperation with a competition for partners

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## Abstract

A finitely repeated prisoner's dilemma game has a unique, defective Nash equilibrium. This paper shows that, in contrast, cooperation can be achieved in a subgame-perfect Nash equilibrium of a *finitely* repeated prisoner's dilemma game when players can choose their partners. Partner choices of all players produce an endogenous network in which a multi-player prisoner's dilemma is played. Cooperation is shown to be possible when players face linking costs or constraints that leads them to compete for possible partners.

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# 1 Introduction

The prisoner's dilemma game is a paradigm for the failure to achieve cooperation in groups of rational and informed players. The finitely repeated prisoner's dilemma, the multi-player prisoner's dilemma and the prisoner's dilemma played on a fixed network are some of the examples of games where the unique equilibrium consists of strategies that prescribe defection in each of the periods even though mutual cooperation benefits each of the players. Cooperative equilibria exist only in infinitely repeated prisoner's dilemma games or in those with random ending.

In this paper I investigate whether cooperation can be achieved in equilibrium under standard assumptions, if the players are free to choose their interaction partners themselves. For this I introduce a prisoner's dilemma game played on a network that is endogenously formed by the players. To facilitate the analysis of strategic behavior I follow Myerson (1991) and model network formation as a strategic game. I refer to the resulting games as the *network dilemma games*.

I study network dilemma games with either mutual or unilateral link formation. Standard equilibrium concepts from non-cooperative game theory, such as the Nash equilibrium and the subgame-perfect equilibrium, can straightforwardly be applied to network dilemma games with unilateral linking (see Bala and Goyal, 2000). However, these concepts are too weak for network dilemma games with mutual linking. I analyze such games by supplementing the requirement of Nash equilibrium with that of network stability. I define the concepts of a *linking-proof equilibrium* and a *linking-proof subgame-perfect equilibrium* which may be seen as extensions of the concept of pairwise-stable equilibrium (Goyal and Joshi, 2003, Calvó-Armengol, 2004) to network dilemma games.

In sections 3 and 4 I investigate network dilemma games between players that face linking constraints. In many real-life situations agents are strictly constrained in the maximal number of other agents with whom they can interact. One such example is the human social network: people have relatively few contacts compared to the number of all other people in their reference group, such as school class or job environment. I show that constraining the number of links that players can propose or establish has a dramatic effect for cooperation in network dilemma games, especially when the outside option is relatively unattractive. I say that a player's linking constraint is strict when she can not simultaneously establish links with all other players. In this paper I show that cooperation can be achieved in a (linking-proof) subgame-perfect equilibrium as long as (i) the players prefer to be in a network of defectors than to be isolated and (ii) at least two players have a strict linking constraint. I also identify network dilemma games in which cooperation can be achieved only through threats with exclusion. I show that this is possible if linking constraints are relatively severe, that is, if each player's upper bound on the number of her neighbors is relatively small. The human social network is again a suitable example.

The intuition behind my results is as follows. If linking is strictly constrained and outside option is less valuable than mutual defection then the players can structure their interaction into several different *equilibrium* networks. In some equilibrium networks all players establish their maximal number of links, but in others some players establish less or even no links. We could say that some equilibrium networks are efficient and others are inefficient. Naturally, in the final period of a finitely repeated game all rational players defect. However, because their interaction in the final period can be structured into different networks they can condition the structure of the final-period interaction on the actions taken in the previous periods. The fear from final-period exclusion can then sustain cooperation during the previous periods.

In section 5 I focus on network dilemma games with linking costs. I say that a player

*sponsors* a link if she proposed it and it is established. Linking is not constrained but sponsored links are costly. For each player the marginal cost of a link increases with the number of sponsored links, so that each additional link is costlier than the previous one. Such linking costs can be seen as the opportunity costs of spending time on social interactions rather than on some alternative profitable activity. The analysis of network dilemma games with linking costs is facilitated by the analysis of network dilemma games with linking constraints. I use the relation between these two classes of network dilemma games to characterize the following sufficient condition for cooperation in a (linking-proof) subgame-perfect equilibrium: if all players defect then each must be willing to sponsor at least two links but not all of them. However, more links can be established if some players cooperate and the networks among cooperators are denser than those among defectors.

My results hold both for mutual and unilateral link formation models. This is interesting in view of the considerable differences between the two models. For example, if linking is mutual then any link can be removed unilaterally. A player is induced to cooperate through threats of exclusion. On the other hand, if linking is unilateral then punishment by removing a link may not be possible. A player in this model cooperates because this attracts free links, sponsored by the other players.

My results can be related to the existing literature about subgame-perfect equilibria in finitely repeated games. Friedman (1985), Benoit and Krishna (1985), and Smith (1995) have proven limit Folk theorems for finitely repeated games when their set of static equilibrium payoffs has sufficient dimensionality. For a review of related results in a unified framework see Benoit and Krishna (2000). This paper contributes to this literature by highlighting the possibility that dimensionality of equilibrium payoffs can be increased by endogenizing the interaction structure. When the interaction structure is fixed then in some games, such as the prisoner's dilemma, only the static equilibrium outcomes can be sustained in a subgame-perfect equilibrium. I demonstrate that this may change if interaction network is endogenous: outcomes other than static equilibria may be achieved in a subgame-perfect equilibrium of the network dilemma game under any of the two models of link formation. Furthermore, given that the concept of a subgame-perfect equilibrium is too weak for games with mutual linking I show that, when linking is constrained, the above results hold also under the additional requirement of linking-proofness.

My study is one of relatively few that consider situations where agents form the network and also determine its value through behavior in the network interactions (see Jackson, 2004 for a comprehensive overview of the models of network formation). Droste et al. (2000), Jackson and Watts (2002) and Goyal and Vega-Redondo (2005) study games of coordination in endogenous networks, assuming either unilateral or mutual link formation. These games can be seen as equivalent to my network dilemma games for situations where interaction over the network has a character of a coordination game instead of the prisoner's dilemma game. All three papers consider an adaptive dynamic process with myopic best-responding players, and study the long-run stability of different conventions in relation to the linking costs. Evolutionary dynamics is the preferred approach also in studies of social dilemmas on endogenous interaction structures (see e.g. Smucker et al., 1994, Yamagishi et al., 1994, Ashlock et al., 1996, Hayashi and Yamagishi, 1998, Hauk, 2001, Vega-Redondo, 2002 and Outkin, 2003). These studies assume that behavior spreads via imitation rather than the best response, ostensibly because defection is the unique best response in social dilemma situations. In contrast, I assume in this paper that finitely repeated network dilemma games are played by rational players with perfect foresight and show that cooperation can be sustained in a subgame-perfect equilibrium through strategic linking behavior.

I am aware of two other studies of strategic behavior in similar situations. Hirshleifer and Rasmusen (1989) study a finitely repeated  $n$ -player prisoner's dilemma game with possibility of ostracism. Hirshleifer and Rasmusen show that cooperation can be achieved in the initial periods of a subgame-perfect equilibrium if ostracism in the last period of the game is costly only for the ostracized player. They do not deal with individual exclusion but assume that each individual conforms to the outcome of a vote. The other related result is about two particular finitely repeated prisoner's dilemma games with outside option, analyzed in Hauk and Nagel (2001). Hauk and Nagel assume that the outside option is more valuable than mutual defection and show that cooperation can be achieved in a Nash equilibrium of the repeated game if link formation is unilateral, but not if link formation is mutual. They stop short of showing that cooperation can be achieved also in a subgame-perfect equilibrium of one of the repeated games. This can be deduced from results in Section 4.

This is how to read the paper. For each class of games I first characterize the equilibrium networks of one-shot games and then the subgame-perfect equilibria of the repeated games. A number of proofs use lengthy combinatorics, mostly to deal with existence of networks having specific properties. These proofs are not essential and I gather them in the appendix. The proofs that carry important arguments are placed in the main sections. To support the intuition I supplement formal analysis with a sequence of simple examples. Numerical examples are often escorted also by graphical illustrations. A quick, but not comprehensive, overview of my results can be acquired by reading through descriptions of the models and following my analysis through the examples.

## 2 Network dilemma games

I consider an  $n$ -person prisoner's dilemma game with endogenous partner choice. In this game each of the  $n$  players simultaneously makes two decisions:

**LINKING DECISION:** Each player proposes links between herself and other players. Proposing links is costless. Each player can propose a link to any other player in the group. Proposing a link may or may not be sufficient to establish it. When a link between two players is established I say the players are neighbors.

**CHOICE OF ACTION:** Each player chooses an action in a prisoner's dilemma game. One game is played by each pair of neighbors. Players, however, cannot discriminate in their action choices. They can either cooperate with all their neighbors or defect on all of them. A player receives an outside option for each player she is not linked to.

At most one link can be established between each pair of players. I assume in this and the following two sections that establishing a link is costless. In this case the payoff to a player is the sum of the earnings from the prisoner's dilemma games played with her neighbors and of the outside options received for not playing with the remaining players.

I say that linking is *unconstrained* when each player is free to propose and establish any number of links, up to  $n - 1$ . Otherwise I say that linking is *constrained*. Let  $k_i$  be the integer denoting the maximal number of links that player  $i$  can propose. I refer to  $\mathbf{k} = (k_1, \dots, k_n)$  as the vector of linking constraints of players  $N = \{1, \dots, n\}$ . Proposing and establishing links is costless. A player  $i$  can propose a link to any other player in the group and can propose up to  $k_i$  links.

To distinguish between different kinds of choices I use the following notation:

- a *linking choice* describes the links proposed by a player,

- an *action* refers to a player's choice between cooperation and defection,
- a *move* consists of a linking choice and an action and thus describes all choices made by the player in the game described above.

Let  $N = \{1, \dots, n\}$  be the set of players. The linking choice of player  $i$  can be captured by a binary vector

$$p_i = (p_{ij})_{j \in N} \in \{0, 1\}^n, \text{ such that } p_{ii} = 0 \text{ and } \sum_{j \in N} p_{ij} \leq k_i.$$

If player  $i$  proposed a link to player  $j$  then  $p_{ij} = 1$ , otherwise  $p_{ij} = 0$ . The constraint  $p_{ii} = 0$  is assumed for convenience, and indicates that a player cannot establish a link with herself. If  $p_{ij} = 0$  I say that player  $i$  *refused to link* to player  $j$ . Linking choice  $p_i$  is *trivial* if  $p_{ij} = 0$  for all  $j$ , that is, when no links are proposed by player  $i$ .

For each profile of linking choices  $p = (p_1, \dots, p_n)$  let  $g(p)$  denote the corresponding *network of established links*. I consider two models of link formation. Each describes how the network is established from a profile of proposed links. The two models of link formation are formalized as follows:

**MUTUAL LINK FORMATION:** A link between players  $i$  and  $j$  is established when  $p_{ij} = 1$  and  $p_{ji} = 1$ . That is,  $g_{ij} = \min\{p_{ij}, p_{ji}\}$ .

**UNILATERAL LINK FORMATION:** A link between players  $i$  and  $j$  is established when  $p_{ij} = 1$  or  $p_{ji} = 1$ . That is,  $g_{ij} = \max\{p_{ij}, p_{ji}\}$ .

In the mutual linking model consent of both players is needed to establish a mutual link. That is, a link between two players is established if and only if it is proposed by both players. In the unilateral linking model no second party consent is needed to establish a link. A link between two players is then established whenever it is proposed by at least one of them.

Whenever a link between two players is established each of them interacts with the other, regardless of how the link was established and by whom it was proposed. For each network  $g$  let  $L_i(g) = \{j \mid g_{ij} = 1\}$  be the set neighbors of player  $i$  and let  $l_i(g) = |L_i(g)|$  be the size of her neighborhood. I say that two players without an established link are *separated*, that is, they are not neighbors. For convenience I use the shorthand notation  $L_i(p) \equiv L_i(g(p))$  and  $l_i(p) \equiv l_i(g(p))$  for a profile of linking choices  $p$ .

The action of player  $i$  in the prisoner's dilemma game is denoted by  $a_i \in \{C, D\}$ . Let  $v(a_i, a_j)$  denote the payoff to player  $i$  choosing action  $a_i$  for playing the game with player  $j$  choosing action  $a_j$ , where the payoff function  $v$  is given by the following payoff matrix,

		Player $j$	
		C	D
Player $i$	C	$c, c$	$e, f$
	D	$f, e$	$d, d$

where  $f > c > d > e$  and  $2c > e + f$ . As mentioned above, player  $i$  plays a prisoner's dilemma game with all her neighbors and receives an *outside option* for each other player that is not her neighbor. For simplicity (and with no loss of generality) I assume that  $o = 0$ . Let  $o \in \mathbb{R}$  be the value of the outside option. An outside option is *high* if  $d < 0$ , i.e. if it is more valuable than mutual defection, and *low* if  $d > 0$ , i.e. if it is less valuable than mutual defection.

A *move* of player  $i$  is a pair  $(a_i, p_i)$ , where  $a_i$  is her action and  $p_i$  her linking choice. The *profile of moves* is the  $n$  tuple of pairs denoted by  $(a, p) = ((a_1, p_1), \dots, (a_n, p_n))$ . The components of a profile of moves,  $a = (a_1, \dots, a_n)$  and  $p = (p_1, \dots, p_n)$ , are the *action profile* and the *linking profile*, respectively. Two particular profiles of actions are convenient to define. Let  $\mathbf{D} = (D, \dots, D)$  and  $\mathbf{C} = (C, \dots, C)$  denote the profiles of uniform defection and of uniform cooperation, respectively.

Let  $A_i = \{C, D\}$  be the set of actions and let  $P_i(k_i) = \{p_i \in \{0, 1\}^n \mid p_{ii} = 0, \sum_{j \in N} p_{ij} \leq k_i\}$  be the set of linking choices of player  $i$ . The *set of moves* of player  $i$  is denoted by  $J_i(k_i) = A_i \times P_i(k_i)$ . Let  $J(\mathbf{k}) = \times_{i \in N} J_i(k_i)$ . Let  $(a_{-i}, p_{-i})$  denote a profile of moves of player  $i$ 's opponents  $N \setminus \{i\}$ , and let  $J_{-i}(\mathbf{k}) = \times_{j \in N \setminus \{i\}} J_j(k_j)$  be the set of all such profiles. For each profile  $(a, p) \in J(\mathbf{k})$  the payoff to player  $i$  is given by her payoff function  $\pi_i : J(\mathbf{k}) \rightarrow \mathbb{R}$ , defined by

$$\pi_i(a, p) = \sum_{j \in L_i(p)} v(a_i, a_j) = \sum_{j \in N} v(a_i, a_j) g_{ij}(p).$$

Let  $\pi : J(\mathbf{k}) \rightarrow \mathbb{R}^n$  be defined as the function whose  $i$ -th component is  $\pi_i$ .

The set  $L_i(p)$  and its size  $l_i(p)$  by definition depend only on the links that are established. By implication, for a given action profile  $a$  the payoff  $\pi_i(a, p)$  of player  $i$  also depends only on the network of established links. With this in mind I slightly abuse notation and define  $\pi_i(a, g)$ , for each network  $g$ , by

$$\pi_i(a, g) = \sum_{j \in L_i(g)} v(a_i, a_j) = \sum_{j \in N} v(a_i, a_j) g_{ij}. \quad (1)$$

I refer to the stage game  $\Gamma(\mathbf{k}) = \langle N, J(\mathbf{k}), \pi \rangle$  as the *network dilemma game with linking constraints*, or shortly, the *dilemma game*.

An established link between two cooperative players represents a *cooperative relation*. An established link between a cooperative and a defective player represents a *semi-cooperative relation*. An established link between two defective players represents a *defective relation*.

I do not consider the possibility that players may randomize in their choices. Randomization can be analytically useful, e.g. to smooth the response functions, to make the action sets convex and, consequently, to ensure the existence of Nash equilibria. In my view there is no need for this in the analysis of network dilemma games, because at least one Nash equilibrium in pure strategies always exists. Including equilibria in mixed strategies would add little to my results but significantly complicate the notation and analysis. Furthermore, in repeated games the mixed strategies are difficult to enforce because deviations from mixed strategies cannot be detected. This is usually resolved either by assuming that each randomization process itself can be observed or that players condition their moves on the outcome of some public randomization mechanism. However, for the games in this paper it seems more intuitive to assume that only pure strategies are used.

Move  $(a_i^*, p_i^*) \in J_i(\mathbf{k})$  is a *best response of player  $i$*  to the profile of moves  $(a_{-i}, p_{-i}) \in J_{-i}(\mathbf{k})$  if

$$\pi_i(a_i^*, p_i^*, a_{-i}, p_{-i}) \geq \pi_i(a_i', p_i', a_{-i}, p_{-i})$$

for any  $(a_i', p_i') \in J_i(\mathbf{k})$ . A *Nash equilibrium* of game  $\Gamma(\mathbf{k})$  is a profile of moves  $(a^*, p^*) \in J(\mathbf{k})$  such that for each player  $i$ ,

$$\pi_i(a^*, p^*) \geq \pi_i(a_i, p_i, a_{-i}^*, p_{-i}^*) \quad (2)$$

for any  $(a_i, p_i) \in J_i(k_i)$ . Network  $g$  is an *equilibrium network* if there exists a Nash equilibrium  $(a^*, p^*)$  such that  $g = g(p^*)$ .

## 2.1 Finitely repeated network dilemma game

The game obtained when a network dilemma game with linking constraints  $\Gamma(\mathbf{k})$  is repeated  $T$ -times is denoted by  $\Gamma^T(\mathbf{k}) = \langle N, J(\mathbf{k}), \pi, T \rangle$ . Recall that when discussing a repeated game  $\Gamma^T$  the constituent game  $\Gamma$  is the *stage game* and the equilibria of  $\Gamma$  are the *static equilibria*. I refer to the repeated game  $\Gamma^T(\mathbf{k})$  as the *repeated dilemma game*.

The profile of moves at  $t$  is denoted by  $(a^t, p^t)$ . The action of player  $i$  in period  $t$  is  $a_i^t$  and her linking choice at  $t$  is  $p_i^t$ . The history at the end of time  $t$  is the sequence of moves  $h^t = ((a^1, p^1), \dots, (a^t, p^t))$ . The total payoff to player  $i$  at the end of the repeated dilemma game is determined by the terminal history  $h^T$  and given by

$$\Pi_i(h^T) = \sum_{t=1}^T \pi_i(a^t, p^t).$$

A strategy for player  $i$  in the game  $\Gamma^T(\mathbf{k})$  is a function  $\sigma_i$  which selects, for any history of play, an element of  $J_i(\mathbf{k})$ . I say that a strategy profile is *semi-cooperative* if at least one semi-cooperative relation is established in an outcome of at least one period. Otherwise, I say it is *defective*. I say that a strategy profile is *cooperative* if, in an outcome of at least one period, (i) each player has at least one neighbor and (ii) all players cooperate.

The concept of a subgame perfect equilibrium (Selten, 1965) is the standard equilibrium concept in repeated games. The following proposition describes some obvious properties of subgame perfect equilibria of network dilemma games. It states that in any such equilibrium all players defect in the last period of the game. Therefore, a subgame-perfect equilibrium is cooperative only if there is an early period in which all players cooperate. The cooperative subgame-perfect equilibria that I describe in this paper will be such that (i) all players cooperate during all initial periods, (ii) then sequentially or simultaneously turn to defection, until (iii) all players defect during one or more final periods. As this proposition shows, if such an equilibrium is possible for a network dilemma game repeated  $T$ -times, then one exists also when the game is repeated more than  $T$ -times.

**Proposition 1** *If a cooperative subgame perfect equilibrium exists for  $\Gamma^{T'}(\mathbf{k})$  then there exists an integer  $\gamma \leq T'$  such that a cooperative subgame perfect equilibrium for  $\Gamma^T(\mathbf{k})$  exists if and only if  $T \geq \gamma$ . In any subgame perfect equilibrium, (i) at least one relation is defective in each of the final  $\gamma - 1$  periods, and (ii) all relations are defective in the final period.*

**Proof.** Assume that a cooperative subgame perfect equilibrium (CSPE) exists for  $\Gamma^{T'}(\mathbf{k})$ . Obviously, there exists a smallest  $\gamma$  such that a CSPE exists for  $\Gamma^\gamma(\mathbf{k})$ . In any one-shot dilemma game all relations are defective, hence  $\gamma \geq 2$ . For any  $T$ : if a CSPE  $\sigma$  exists for  $\Gamma^T(\mathbf{k})$  then one exists also for  $\Gamma^{T+1}(\mathbf{k})$ ; for example, "play  $\sigma$  in the first  $T$  periods and play a static equilibrium in period  $T + 1$ ".

A subgame perfect equilibrium (SPE) of  $\Gamma^T(\mathbf{k})$  must select a SPE for any subgame  $\Gamma^t(\mathbf{k}), t < T$  and any history. No CSPE exist for  $\Gamma^t(\mathbf{k})$  if  $t < \gamma$ . All relations are defective in any Nash equilibrium of  $\Gamma(\mathbf{k})$ . Hence, an equilibrium outcome path for the  $\Gamma^T(\mathbf{k})$  must be such that all relations are defective in the last period, and in none of the last  $\gamma - 1$  periods are all relations cooperative. ■

If all static equilibria are payoff-equivalent the subgame perfect equilibrium must select an equilibrium outcome in each period of the finitely repeated game. In contrast, Friedman (1985) and Benoit and Krishna (1985) show that if static equilibria are not payoff-equivalent then a subgame perfect equilibrium may be constructed whose equilibrium path is not a sequence of static equilibrium outcomes. One way to construct such

subgame-perfect equilibria is with trigger strategies. The following definition is due to Friedman (1985).<sup>1</sup>

**Definition 2** Let  $Q$  be the set of Nash equilibria of a stage game  $\Gamma(\mathbf{k}) = \langle N, J(\mathbf{k}), \pi \rangle$ . Take  $q^*, q^1, \dots, q^n \in Q$ , which possibly coincide, and a profile  $r \in J(\mathbf{k})$ . A **trigger strategy profile** for  $\Gamma^T(\mathbf{k})$ , based upon  $(r, q^*, \{q^i\}_{i \in N}, t^*)$ ,  $1 \leq t^* < T$ , is denoted by  $\sigma(r, q^*, \{q^i\}_{i \in N}, T, t^*)$  and is given by

*outcome path:* play  $r$  during the early periods  $\{1, \dots, T - t^*\}$ ; play  $q^*$  during the remaining periods  $\{T - t^* + 1, \dots, T\}$ ,

*threat:* if player  $i$  deviates early, i.e. in an early period  $t \in \{1, \dots, T - t^*\}$ , play  $q^i$  during the remaining periods  $\{t + 1, \dots, T\}$ ,

*simultaneous deviations:* if several players deviate in the same early period, exercise the threat for the deviating player with the lowest index.

If no player ever deviates from the trigger strategy, the (possibly non-equilibrium) outcome  $r$  is selected in periods  $\{1, \dots, T - t^*\}$ , and the static equilibrium  $q^*$  is selected in periods  $\{T - t^* + 1, \dots, T\}$ . Any deviation, on the other hand, triggers an immediate switch to the static equilibrium  $q^i$ , where  $i$  is the deviating player with the lowest index, selected ever after. A sufficient condition for the threat of punishment to be effective is that each player  $i$  strictly prefers  $q^*$  from  $q^i$ . The following theorem, which I use throughout the paper, is due to Friedman (1985).<sup>2</sup>

**Theorem 3** Let  $Q$  be the set of Nash equilibria of a stage game  $\Gamma(\mathbf{k}) = \langle N, J(\mathbf{k}), \pi \rangle$ . Take  $q^*, q^1, \dots, q^n \in Q$  and a profile  $r \in J(\mathbf{k})$  such that  $\pi_i(r) \geq \pi_i(q^i)$  for each  $i$ . If  $\pi_i(q^*) > \pi_i(q^i)$  for each player  $i$  then there exists a positive integer  $\gamma$  such that the trigger strategy profile  $\sigma(r, q^*, \{q^i\}_{i \in N}, T, t^*)$  is a subgame perfect equilibrium of  $\Gamma^T(\mathbf{k})$  for all  $T, t^*$  such that  $T > t^* \geq \gamma$ .

## 2.2 Some notation

The following are several terms from the mathematical theory of graphs that I use in this paper. A *path* of length  $k$  between  $i$  and  $j$  is the sequence of agents  $(i, i_1, \dots, i_{k-1}, j)$  such that  $g_{ii_1} = g_{i_1 i_2} = \dots = g_{i_{k-1} j} = 1$ . The *distance* between  $i$  and  $j$  is the length of the shortest path between them. Distance between  $i$  and  $j$  is infinite if there is no such path, and 1 if  $i$  and  $j$  are neighbors. If  $i$  and  $j$  are not neighbors but there is a path between them I say that they are *indirectly linked*. A network is *connected* if every pair of agents is (indirectly) linked.

Given a network  $g$  and a pair of distinct agents  $ij$  let  $g \oplus ij$  be the network established by adding link  $ij$  to network  $g$ , and let  $g \ominus ij$  be the network established when link  $ij$  is removed from network  $g$ .

Several prominent classes of networks, called network architectures, are illustrated in Figure 1. In an *empty network* no links are established:  $g_{ij} = 0$  for all  $i$  and  $j$ . In a

<sup>1</sup>Friedman (1985) makes a distinction between trigger strategies and discriminating trigger strategies. In a trigger strategy profile each deviation triggers the same collective punishment. In a discriminating trigger strategy profile the punishments can be player specific. I do not emphasize the distinction in this script and refer to all such profiles as trigger strategy profiles.

<sup>2</sup>The original theorem in Friedman (1985) allows for player-specific discount rates. Throughout this paper I assume, for simplicity, that players do not discount future. I therefore state a simplified version of the original theorem.

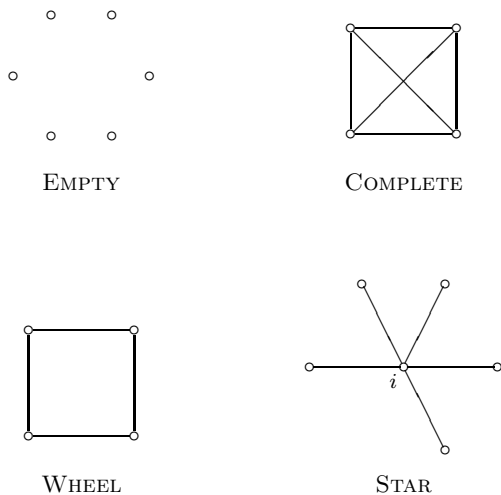


Figure 1: Common network architectures.

*complete network* all possible links are established:  $g_{ij} = 1$  for all  $i$  and  $j$ . Links in a *wheel network* constitute a cycle spanning all agents: there is an ordering of all agents  $(i_1, i_2, \dots, i_n)$  such that  $g_{i_1 i_n} = g_{i_n i_1} = 1$  and  $g_{i_j i_{j+1}} = g_{i_{j+1} i_j} = 1$  for all  $j \in N \setminus \{n\}$  and  $g_{k, k'} = 0$  otherwise. Finally, in a *star network* one central agent is linked to all other agents and there are no other links. If  $i$  is the central agent then  $g_{ik} = 1$  for all  $k \in N \setminus \{i\}$  and  $g_{jk} = 0$  for all  $j, k \in N \setminus \{i\}$ .

### 3 Mutual link formation

In this section I consider the mutual link formation model. For a profile of linking choices  $p$  the network of established links  $g(p)$  is defined by  $g_{ij}(p) = \min\{p_{ij}, p_{ji}\}$ .

For each network  $g$  and each player  $i$  let  $p_i(g)$  be the binary vector defined by  $p_{ij}(g) = g_{ij}$  for all  $j$ . I say that player  $i$  *supports network*  $g$  when her linking choice is  $p_i(g)$ . The profile  $p(g) = (p_1(g), \dots, p_n(g))$  is the minimal *support* for the network  $g$ , in the sense that each link proposal in  $p(g)$  is necessary to establish  $g$ .

To avoid trivialities I assume that  $c > 0$ , that is, the value of mutual cooperation is higher than the outside option. I also assume that  $1 \leq k_i \leq n - 1$  for each player  $i$ .<sup>3</sup> Let

$$\mathcal{G}(\mathbf{k}) = \{g \mid l_i(g) \leq k_i \text{ for each } i\} \quad (3)$$

be the set of feasible networks.

#### 3.1 Stage game equilibria and linking-proof networks

The complete characterization of Nash equilibria for dilemma games is possible but cumbersome. The following proposition characterizes the actions and the networks that are established in a Nash equilibrium of a one-shot dilemma game. The set of equilibrium networks depends only on whether the outside option is low or high.

<sup>3</sup>Obviously, in a group with  $n$  players each of them can establish at most  $n - 1$  links, hence it makes sense to assume that  $k_i \leq n - 1$  for all  $i$ . On the other hand, if a player cannot make any links ( $k_i = 0$ ) she will be isolated regardless of the linking behavior of other players. An isolated player does not affect the dynamics of play. I therefore assume  $k_i \geq 1$  for all  $i$ .

**Proposition 4** Consider the dilemma game  $\Gamma(\mathbf{k})$ .

1. A player cooperates in a Nash equilibrium only if no links to her are proposed. Hence, in a Nash equilibrium all cooperative players are isolated.
2. If  $d \geq 0$  then  $(\mathbf{D}, p(g))$  is a Nash equilibrium for any network  $g \in \mathcal{G}(\mathbf{k})$ .
3. If  $d < 0$  then the empty network is the unique equilibrium network.

**Proof.** (1) Let  $(a^*, p^*)$  be a Nash equilibrium (NE). There cannot be a pair of players  $i, j$  such that  $a_i^* = C$  and  $p_{ji}^* = 1$  as in this case  $i$  could strictly increase her payoff by switching to  $a_i = D$  and  $p_{ij} = 1$ . There also cannot be a pair of players  $i, j$  such that  $a_i^* = C$  and  $p_{ij}^* = 1$  and  $p_{ji}^* = 0$  as in this case  $j$  could strictly increase her payoff choosing some  $p_j$  such that  $p_{ji} = 1$ .

(2) For any  $g \in \mathcal{G}(\mathbf{k})$  the  $p(g)$  is the minimal support for  $g$  in the sense that all proposed links are reciprocated. Hence, no player can increase her payoff by unilaterally proposing additional links and can only (weakly) decrease her payoff if she removes some links. Obviously, no player can increase her payoff by switching to cooperation. The profile  $(\mathbf{D}, p(g))$  is therefore a NE.

(3) According to (1), if in NE players  $i$  and  $j$  are neighbors they should both defect. However, each could then increase her payoff by removing the link. Hence, in a NE there are no neighbors. ■

Statement (1) asserts that in a Nash equilibrium of a dilemma game all relations are defective. That is, in a Nash equilibrium players with at least one established link defect but the isolated players may cooperate. Consequently and as stated in (3), if the mutual defection payoff  $d$  is negative no links are established in a Nash equilibrium. For non-negative  $d$ , however, statement (2) asserts that any feasible network is an equilibrium network. The dilemma game with  $d = 0$  is rather trivial. In the rest of the section I consider only games with  $d \neq 0$ .

Consider a dilemma game with  $d > 0$ . If all players defect each of them maximizes her payoff by establishing as many links as possible. It may thus be surprising that networks with relatively little or no links can be established in a Nash equilibrium. The multiplicity of equilibrium networks is a consequence of the mutual link formation assumption. A link between two players is established only if both propose it. If one of the players does not propose the link the other is indifferent between proposing the link or not. It may therefore happen that two players prefer to establish a mutual link but none proposes it because each knows that the other will not propose the link. Hence, in a Nash equilibrium there may exist a pair of players such that (i) each could beneficially establish at least one more link but (ii) none proposes a link to the other player. This appears especially unintuitive given that proposing links is costless (see e.g. the discussion in Dutta et al., 1998).

Several resolutions have been discussed in the related literature on network formation (see Goyal and Joshi, 2003, Calvó-Armengol, 2004, and Gilles and Sarangi, 2004). I follow the common approach in this literature and supplement the idea of the Nash equilibrium with a requirement of network stability. Roughly speaking, an equilibrium network is said to be stable if no pair of separated players exists such that, by adding the mutual link, each could strictly increase her payoff.

My definition of network stability is inspired by the concept of pairwise-stability, introduced by Jackson and Wolinsky (1996). It is defined for network formation games with

mutual linking, but with exogenously fixed cost and benefit rules. While it retains some flavor of the non-cooperative equilibrium, pairwise-stability is analyzed with the tools of cooperative game theory.<sup>4</sup> It is not immediately obvious how to appropriately generalize pairwise-stability to network formation games with endogenous benefit structure, and how to analyze such games with the tools of non-cooperative game theory. My definition of linking-proofness below is chosen because it eliminates the unintuitive Nash equilibria in the dilemma games.

In a dilemma game the value of a link depends on the actions taken by the linked players. The dilemma game in this section is then a network formation game with mutual linking, no linking costs, and an endogenous benefit structure. The players are free to deviate by simultaneously changing their action, removing links, and adding a new link.

A profile of moves is a Nash equilibrium if no player wants to deviate given the moves of the other players. I say that an equilibrium profile of moves is linking-proof if no player wants to deviate even if there was a possibility to establish a new link. In other words, the only multilateral deviation considered is that of adding a new link. However, a player is free to deviate by adding a new link in parallel to any other unilateral changes to her move.

For a profile of linking choices  $p$  let  $p \oplus ij$  be another profile defined as

$$(p \oplus ij)_{i'j'} = \begin{cases} 1 & \text{if } i'j' = ij \\ p_{i'j'} & \text{otherwise.} \end{cases}$$

In words,  $p \oplus ij$  is a profile of linking choices obtained from  $p$  by assuming that player  $i$  proposes a link to  $j$  in addition to all the links proposed according to  $p$ . If  $p_{ij} = 1$  then  $p \oplus ij = p$ .

**Definition 5** *The profile of moves  $(a^*, p^*) \in J(\mathbf{k})$  is a **linking-proof equilibrium (LP equilibrium)** of game  $\Gamma(\mathbf{k})$  if (i) for each player  $i$  her move  $(a_i^*, p_i^*)$  is a best response to  $(a^*, p^*)$ , and (ii) for each pair of players  $i, j$  either  $(a_i^*, p_i^*)$  is a best response to  $(a^*, p^* \oplus ji)$  or  $(a_j^*, p_j^*)$  is a best response to  $(a^*, p^* \oplus ij)$ . Network  $g^* \in \mathcal{G}(\mathbf{k})$  is **linking-proof** if it is established in some linking-proof equilibrium.*

Any linking-proof equilibrium is Nash equilibrium, due to (i). Furthermore, in a linking-proof equilibrium there is no pair of separated players such that each of them strictly prefers to change her move and establish the mutual link. In other words, in each pair of

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<sup>4</sup>Below I give a slightly simplified definition of pairwise-stability (for the general definition and discussion see Jackson, 2003). The network formation game in the cooperative form is characterized by the set of feasible networks  $\mathcal{G}$  and by the allocation rule  $Y : \mathcal{G} \rightarrow \mathbb{R}^n$  which describes how the value generated by the network is shared among the players. The network  $g \in \mathcal{G}$  is said to be *pairwise stable* with respect to the allocation rule  $Y$  if

- (i) for all  $ij \in g$ ,  $Y_i(g) \geq Y_i(g \ominus ij)$  and  $Y_j(g) \geq Y_j(g \ominus ij)$ , and
- (ii) for all  $ij \notin g$  such that  $(g \oplus ij) \in \mathcal{G}$ ,  $Y_i(g \oplus ij) > Y_i(g)$  implies  $Y_j(g \oplus ij) < Y_j(g)$ .

It is implicit in the definition of pairwise stability that the termination of a link can be done unilaterally but that the addition of a link requires mutual consent of both involved players. A network is pairwise-stable if no player can profit by unilaterally removing a link and no pair of players can simultaneously profitably deviate by adding a mutual link.

A few extensions of the original definition of pairwise-stability exist. For example, one may assume that adding a link is plausible if it makes both linked players strictly better off, or alternatively, if it makes both linked players weakly better off, or yet some intermediate concept (see Dutta and Mutuswami, 1997). The original definition does not consider deviations of one player by simultaneous removal of several links or by simultaneous removal of one link and addition of another link, which would bring the concept closer to the spirit of a non-cooperative equilibrium (see Calvó-Armengol, 2004, and Gilles and Sarangi, 2004).

separated players at least one of them has no move that strictly improves her payoff and establishes the mutual link.

Supplementing an equilibrium concept with that of network stability is not the only route to study strategic form games of network formation with mutual linking. For example, a stronger equilibrium concept, such as coalition-proof Nash equilibrium (Bernheim et al., 1987) or Strong Nash equilibrium (Aumann, 1959), may also eliminate unintuitive Nash equilibria, as shown in Dutta and Mutuswami (1997), Dutta et al. (1998), Slikker and van den Nouweland (2001) and Jackson and van der Nouweland (2002). The problem with these equilibrium refinements is that they eliminate too many networks because they require stability against deviations by variously sized coalitions of players. My concept of linking-proof equilibrium is much weaker: it supplements the Nash equilibrium only with the requirement that a pair of players is linked whenever it is possible and in their mutual interest, but does not permit any other coordinated actions.

I denote the set of linking-proof networks of the game  $\Gamma(\mathbf{k})$  by  $\mathcal{S}(\Gamma(\mathbf{k}))$ . The following proposition asserts that, when  $d > 0$ , the set  $\mathcal{S}(\Gamma(\mathbf{k}))$  contains all networks in which only the linking constraints prohibit any pair of separated players from adding a mutual link.

**Proposition 6** *Consider dilemma game  $\Gamma(\mathbf{k})$ .*

1. *Let  $d > 0$ . Network  $g^* \in \mathcal{G}(\mathbf{k})$  is a linking-proof network if and only if there is no pair of separated players  $i, j$  such that  $l_i(g^*) < k_i$  and  $l_j(g^*) < k_j$ .*
2. *If  $d < 0$  the empty network is the unique linking-proof network.*

**Proof.** (1.a) Let  $d > 0$ . Consider  $g^* \in \mathcal{S}(\Gamma(\mathbf{k}))$  and let  $(a^*, p^*)$  be the LP equilibrium such that  $g(p^*) = g^*$ . Assume (A1): there is a pair of distinct players  $i$  and  $j$  such that  $l_i(g^*) < k_i$  and  $l_j(g^*) < k_j$ .

Let  $p_{ij}^* = 0$ . Define  $p'_i$  as follows: (a) if there is  $j'$  such that  $p_{ij'}^* = 1$  and  $g_{ij'}^* = 0$  then let  $p'_i$  coincide with  $p_i^*$  in all values except for setting  $p'_{ij} = 1$  and  $p'_{ij'} = 0$  (if  $i$  proposed a link which was not reciprocated propose instead the link to  $j$ )

(b) if there is no such  $j'$  then let  $p'_i$  coincide with  $p_i^*$  in all values except for setting  $p'_{ij} = 1$  ( $i$  did not propose the maximal number of links, hence propose also the link to  $j$ ). Define  $p'_j$  in a symmetric manner. As  $p^* \in P(\mathbf{k})$  then  $p'_i \in P_i(k_i)$  and  $p'_j \in P_j(k_j)$ .

Because  $g_{ij}^* = 0$  it must be that either  $p_{ij}^* = 0$  or  $p_{ji}^* = 0$  or both. If  $p_{ji}^* = 1$  then for player  $i$ ,  $(D, p'_i)$  is a better response to  $(a^*, p^*)$  than is  $(a_i^*, p_i^*)$ , as thus the link  $ij$  is established in addition to all other links of player  $i$  and this increases the payoff to player  $i$  for at least  $d > 0$ . But this should not be possible in a LP equilibrium, hence  $p_{ji}^* = 0$ . In this case, however,  $(D, p'_i)$  is a better response to  $(a^*, p^* \oplus ji)$  than is  $(a_i^*, p_i^*)$ .

Similarly it can be shown that  $p_{ij}^* = 0$ , in which case  $(D, p'_j)$  is a better response to  $(a^*, p^* \oplus ij)$  than is  $(a_j^*, p_j^*)$ . This, however, is again not possible in a LP equilibrium. This proves that (A1) cannot hold.

(1.b) Let  $d > 0$ . Consider network  $g \in \mathcal{G}(\mathbf{k})$  such that  $g_{ij} = 1$  for each pair of distinct players  $i, j$  such that  $l_i(g) < k_i$  and  $l_j(g) < k_j$ . I argue that  $(\mathbf{D}, p(g))$  must be a LP equilibrium. By Proposition 4 it is a Nash equilibrium which proves part (i) of the definition of LP equilibrium. I show next that part (ii) is also fulfilled.

Take a pair of distinct players  $i$  and  $j$ . If  $g_{ij} = 1$  then (ii) follows from (i). Assume therefore  $g_{ij} = 0$ , implying that either  $l_i(g) = k_i$  or  $l_j(g) = k_j$ . W.l.o.g. let  $l_i(g) = k_i$ . Player  $i$  cannot increase her payoff by removing or by moving some of her links. She also cannot add any new links. Hence  $(D, p_i)$  is a best response to  $(\mathbf{D}, p \oplus ji)$ , and (ii) is satisfied.

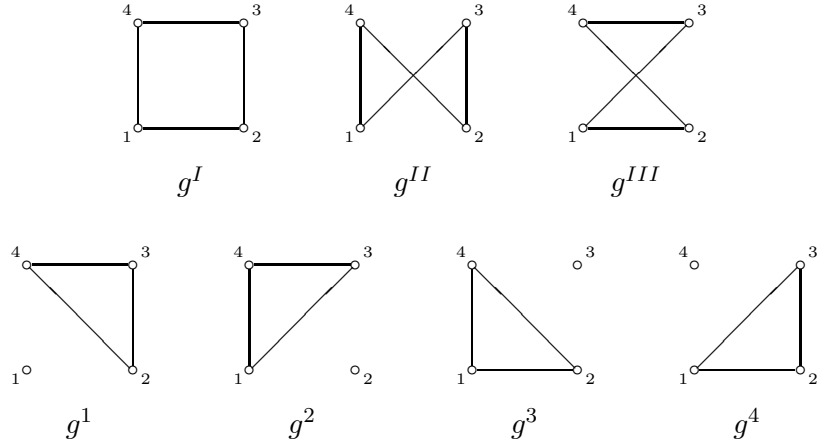


Figure 2: Linking-proof networks of the dilemma game with  $n = 4$  players,  $\mathbf{k} = (2, 2, 2, 2)$ , and  $d > 0$ . Only established links are shown.

(2) Let  $d < 0$ . By Proposition 4 the empty network is the only equilibrium network and thus the only candidate to be linking-proof. Let  $0_i$  be the vector denoting that player  $i$  proposes no links, and let  $\mathbf{0} = (0_1, \dots, 0_n)$  be the corresponding profile. To see that  $(\mathbf{D}, \mathbf{0})$  is a LP equilibrium, note that for each  $i$ ,  $(D, 0_i)$  is best response both to  $(\mathbf{D}, \mathbf{0})$  and to  $(\mathbf{D}, \mathbf{0} \oplus ij)$  for any  $j \neq i$ . ■

Let  $d > 0$ . If a pair of players in a linking-proof network are separated it must be that at least one of them has established her maximal number of links. The restriction to linking-proof equilibria may considerably reduce the set of networks established by an equilibrium profile and lead to existence problems. However, proposition 7 below states that a linking-proof network always exists. When only the empty network is established in a Nash equilibrium (i.e. when  $d < 0$ ) this network is the unique linking-proof network. Several linking-proof networks may exist when  $d > 0$ . I demonstrate this in the following examples.

**Example 1 (no linking constraints)** Let  $d > 0$  and let  $k_i = n - 1$  for all  $i$ . In this game the linking is not constrained and players may establish any number of links. Hence, if  $g_{ij} = 0$  then  $l_i < k_i$  and  $l_j < k_j$  for any pair of distinct players  $i$  and  $j$  and  $g$  is not linking-proof. The complete network is therefore the unique linking-proof network.

**Example 2 (uniform linking constraint)** Let  $d > 0$  and let  $n = 4$ . Let  $\mathbf{k} = (2, 2, 2, 2)$ . Any of the 64 possible networks can be established in a Nash equilibrium. However, only seven of them, illustrated in Figure 2, are linking-proof. Networks  $g^I, g^{II}$  and  $g^{III}$  constitute the three possible wheel networks in which each player links to two neighbors. In networks  $g^1, g^2, g^3$  and  $g^4$  one player is isolated and each of the other three players has two links. For  $i = 1, 2, 3, 4$  the network  $g^i$  forms when players  $N \setminus \{i\}$  form a clique, thus leaving player  $i$  without any links.

The following Proposition asserts that every dilemma game has a linking-proof equilibrium, and consequently, a linking-proof network.

**Proposition 7** *There always exists a linking-proof equilibrium of the game  $\Gamma(\mathbf{k})$ .*

**Proof.** Let  $0_i$  be the vector denoting that player  $i$  proposes no links, and let  $\mathbf{0} = (0_1, \dots, 0_n)$  be the corresponding profile. The profile  $(\mathbf{D}, \mathbf{0})$  is LP equilibrium for dilemma

games with  $d \leq 0$ . For  $d < 0$  this is shown in Proposition 6. For  $d = 0$  this is because if all players defect no player can increase her payoff either by switching to cooperation, or by removing, moving or adding links.

For  $d > 0$  a LP network can be constructed with the following iterative procedure. Let  $g^0$  be an empty network. For  $x = 1, 2, \dots$  let  $g^x$  be the network obtained from  $g^{x-1}$  by the addition of one link: take a pair of distinct players  $i, j$  such that  $g_{ij}^{x-1} = 0$ ,  $l_i(g^{x-1}) < k_i$  and  $l_j(g^{x-1}) < k_j$ , and let  $g_{ij}^x = 1$ , and otherwise let  $g_{i'j'}^x = g_{i'j'}^{x-1}$ . Stop the procedure if there is no such pair of players.

This procedure stops after finite number of steps, because a new link is added in each step and there is a finite number of possible links. It follows from Proposition 6 that the resulting network is an LP equilibrium. ■

### 3.2 Subgame perfect equilibrium of the repeated game

In the repeated game the players can condition their linking choices on the behavior of players in previous periods. More specifically, players may punish a deviation from the agreed outcome path by removing links to any player that deviated. For example, players may agree to cooperate and punish defectors by exclusion from the neighborhood of cooperative players.

In a repeated game I define exclusion as follows. Let  $t \geq 2$ . I say that player  $i$  *excludes* player  $j$  in period  $t$  if  $i$  and  $j$  were neighbors at  $t - 1$  and  $i$  removes the link with  $j$  in period  $t$ .

Two players may exclude each other simultaneously. For example, player  $i$  may remove her link with player  $j$  if she knows  $j$  will also remove it. Recall that each player is indifferent between proposing a link or not if she knows that it will not be reciprocated. Two neighbors could therefore exclude each other even if the resulting network is such that each would prefer to keep the link established. I call an exclusion *mutual* if two players exclude each other but both miss at least one link in the resulting network.<sup>5</sup>

On the other hand, a single player may be willing to exclude another regardless of the other player's linking decision. It is possible, for example, to exclude a player and yet establish the maximal number of links. This can be done, for example, by removing the link with one player and establish a new one with another player, thus excluding the first and including the latter.<sup>6</sup> I say that player  $i$  *unilaterally* excludes player  $j$  if  $i$  still establishes her maximal number of links in the resulting network. I call an exclusion *unilateral* if each *excluding* player establishes her maximal number of links in the ensuing network. There is no condition on the number of links that the excluded player establishes in the ensuing network. Unilateral exclusion is defined only for games with mutual link formation and is not related to unilateral link formation. See Figure 3 for examples of unilateral and mutual exclusion.

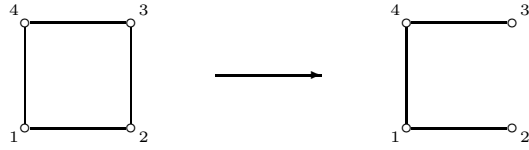
I begin with a few examples of the equilibria of repeated dilemma games. The first example illustrates that not every Nash equilibrium of the repeated dilemma game is subgame perfect. Recall that in order to distinguish between the Nash equilibria of the repeated game and those of the stage game I refer to the latter as the static equilibria.

**Example 3** Consider the dilemma game  $\Gamma$  with two players and no linking constraints,<sup>7</sup> repeated twice. Let the outside option be low,  $d > 0$ . Consider the following strategy  $\sigma_i$  for

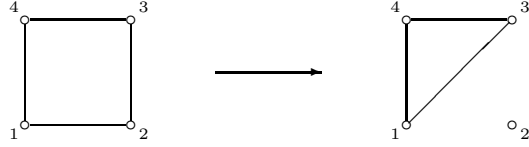
<sup>5</sup>I say that player  $i$  is missing one or more links in network  $g$  if she establishes less than her maximal number of links, that is, if  $l_i(g) < k_i$ .

<sup>6</sup>If a player  $i$  removes a link with player  $j$  to establish a link with player  $j'$  I say that  $i$  *relocates* a link.

<sup>7</sup>This game is a variant of the usual two-player prisoner's dilemma game with outside option.



(a) mutual exclusion



(b) unilateral exclusion

Figure 3: Two types of exclusion under mutual link formation. Exclusion in the repeated dilemma game with  $n = 4$  players,  $\mathbf{k} = (2, 2, 2, 2)$ , and  $d > 0$ . (a) Players 2 and 3 simultaneously exclude each other, each missing one link in the resulting network. (b) Players 1 and 3 both exclude player 2 and establish a mutual link, thus missing no links in the resulting network.

player  $i = 1, 2$ : "Propose the link and cooperate in the first period. In the second period defect, and propose the link if and only if the opponent cooperated in the first period."

The pair  $(\sigma_1, \sigma_2)$  constitutes a Nash equilibrium of  $\Gamma^2$  if  $f < c + d$ : given that player  $i$  follows  $\sigma_i$ , the best response of player  $j$  entails always proposing the link and defection in the last period; this given, defection in the first period earns her a total payoff of  $f$ , which is less than  $c + d$  earned if she cooperates in the first period.

Assume now that player 2 defects in the first period nevertheless. In response, the player's strategies require both players to defect, and that only player 2 proposes the link which, consequently, is not established. However, in the absence of commitment it is not obvious that in the second period player 1 will persist in playing  $\sigma_1$ . In fact, rather than to exercise the threat of removing the link, player 1 does better in the second period by renegeing on her threat and propose the link anyway. If player 1 is rational she never excludes player 2. If player 2 is rational she anticipates this and defects in both periods. Realizing this, rational players would not even agree on playing  $(\sigma_1, \sigma_2)$ . The threat of unilateral exclusion, implicit in the strategy  $\sigma_1$ , is in this sense empty and the equilibrium  $(\sigma_1, \sigma_2)$  is not subgame perfect.

**Example 4 (Exogenous network)** The  $n$ -player prisoner's dilemma game can be seen as a dilemma game without the linking choice. Rather, the network is fixed exogenously to be a complete network. Each player chooses an action and must play the game with all other players. The payoffs are given by (1), with  $g$  being the complete network.

For each player defection strictly dominates cooperation. The stage game thus has a unique Nash equilibrium in which all players defect. Consequently, the finitely repeated  $n$ -player prisoner's dilemma game has a unique subgame perfect equilibrium in which all players defect in each of the periods.

**Example 5 (Endogenous network, high outside option)** Consider any dilemma game and let  $d < 0$ . Proposition 4 states that the empty network is established in any static Nash equilibrium of this game. All its static equilibria are therefore payoff-equivalent because the payoff of each player in the empty network is 0, regardless of the profile of actions. By implication, each subgame perfect equilibrium of the repeated dilemma game selects a se-

quence of static equilibria. To summarize, whenever  $d < 0$  the empty network is established along the outcome path of any subgame perfect equilibrium of the repeated dilemma game.

Example 3 motivates the focus on subgame perfect equilibria in analysis of repeated games. All the subgame-perfect equilibria that were constructed in the above examples have a common feature: they select a static equilibrium in each period. In each static equilibrium all relations are defective. Hence, all subgame perfect equilibria constructed from sequences of static equilibria are defective. No other subgame perfect equilibrium exist for finitely repeated dilemma games with high outside option, which is shown in the example above. In the following section I show that cooperative subgame-perfect equilibria may exist for dilemma games with low outside option.

### 3.3 Cooperation in subgame perfect equilibria of the repeated game

In section 3.3.1 I show that, for any repeated dilemma game with  $d > 0$ , cooperative relations may be sustained in a subgame perfect equilibrium via the threat of mutual exclusion. Mutual exclusion requires that both players simultaneously remove the link with each other. Punishment with mutual exclusion thus requires the participation of a punished player in her own punishment. Furthermore, the resulting network is not linking-proof. This may motivate the players, especially the punished one, to renege on their participation in the punishment. In section 3.3.2 I follow up by discussing the possibility to sustain cooperation via threats of unilateral exclusion. I show that this is possible for most vectors of linking constraints.

#### 3.3.1 Cooperation through threats of mutual exclusion

Consider a dilemma game  $\Gamma(\mathbf{k})$  and let there be a network  $g^* \in \mathcal{G}(\mathbf{k})$  with no isolated players:  $l_i(g^*) \geq 1$  for each player  $i$ . For each  $i$  let  $g^i = g \ominus 1i \ominus \dots \ominus ni$  be the network obtained from  $g^*$  by removing all established links with player  $i$ :  $l_i(g^i) = 0$ . Obviously,  $g^i \in \mathcal{G}(\mathbf{k})$  for each  $i$ . Note that  $q^i$  is a Nash equilibrium only if (i) player  $i$  proposes no links and (ii) no player proposes a link to  $i$ .

Let  $d > 0$ . It follows from Proposition 4 that  $g^*$  and all  $g^i$  can be established in the Nash equilibria  $q^* = (\mathbf{D}, p(g^*))$  and  $q^i = (\mathbf{D}, p(g^i))$ . The payoff of player  $i$  in each of these equilibria is proportional to the number of her neighbors. In particular,

$$\pi_i(q^*) = d \cdot l_i(g^*) > 0 \text{ and } \pi_i(q^i) = d \cdot l_i(g^i) = 0.$$

Consider now the profile of moves  $r^* = (\mathbf{C}, p(g^*))$  where all players cooperate and establish the network  $g^*$ . The payoff of player  $i$  in this profile is

$$\pi_i(r^*) = c \cdot l_i(g^*) > 0 = \pi_i(q^i).$$

Recall Definition 2, of a trigger strategy profile. Take two integers  $T > t^* > 0$ . Consider the trigger strategy profile  $\sigma(r^*, q^*, \{q^i\}_{i \in N}, T, t^*)$ , which can be described in words as follows:

”Cooperate in the early periods  $1, \dots, T - t^*$  and defect in the remaining periods. Establish network  $g^*$  in each period. If in an early period some player  $i$  defects, establish network  $g^i$  and defect forever.”

Each player  $i$  earns strictly more in the equilibrium  $q^*$  compared to equilibrium  $q^i$ . If player  $i$  defects early, she earns  $t^* \pi_i(q^i) = 0$  in the last  $t^*$  periods. If there are no early

defections she earns  $t^*\pi_i(q^*)$ . Hence, if she defects early she loses  $t^*\pi_i(q^*)$  in the last  $t^*$  periods. There exists a sufficiently large  $t^*$  such that for each player this loss is larger than the benefit from any early deviation. If  $t^*$  is such, then no player wants to defect in an early period and cooperation is sustained.

Proposition 8 confirms this conclusion: there exist  $T, t^*$ , such that  $\sigma(r^*, q^*, \{q^i\}_{i \in N}, T, t^*)$  is a subgame perfect equilibrium of  $\Gamma^T(\mathbf{k})$ . By definition,  $\sigma(r^*, q^*, \{q^i\}_{i \in N}, T, t^*)$  is cooperative as it induces the cooperative outcome  $r^*$  in the early periods of the repeated game.

In the following I focus on the trigger strategy profiles where, similar to the profile outlined above, an early defection triggers a change of the network. For reference I use the notation  $(a, g) = (a, p(g))$  and define, for networks  $g, g^*, g^1, \dots, g^n \in \mathcal{G}(\mathbf{k})$ , the following trigger strategy profile

$$\rho(g, g^*, \{g^i\}_{i \in N}, T, t^*) \equiv \sigma((\mathbf{C}, g), (\mathbf{D}, g^*), \{(\mathbf{D}, g^i)\}_{i \in N}, T, t^*). \quad (4)$$

**Proposition 8** *Consider the dilemma game  $\Gamma^T(\mathbf{k})$  with  $d > 0$  such that there exists a network  $g^* \in \mathcal{G}(\mathbf{k})$  with no isolated players. For each  $i$  let  $g^i$  be the network obtained from  $g^*$  by removing all links with player  $i$ . For large enough  $T$  there exists  $t^*$  such that the trigger strategy profile  $\rho(g^*, g^*, \{g^i\}_{i \in N}, T, t^*)$  for  $\Gamma^T(\mathbf{k})$  is fully cooperative and subgame perfect.*

**Proof.** I have outlined the proof in the discussion above. Profiles of moves  $(\mathbf{D}, p(g^*))$  and  $(\mathbf{D}, p(g^i))$  are Nash equilibria. Furthermore,  $\pi_i(\mathbf{C}, p(g^*)) > \pi_i(\mathbf{D}, p(g^*)) > \pi_i(\mathbf{D}, p(g^i))$ . The rest of the proof follows from Theorem 3. ■

**Corollary 9** *A cooperative trigger strategy profile for  $\Gamma^T(\mathbf{k})$  with  $d > 0$  exists for sufficiently large  $T$  if  $k_i \geq 1$  for each  $i$  and, if  $n$  is odd,  $k_j \geq 2$  for some  $j$ .*

**Proof.** If  $n$  is even, a network  $g^* \in \mathcal{G}(\mathbf{k})$  with no isolated players may be established by linking pairs of players: for example, for each  $x = 1, \dots, n/2$ , players with indices  $2x - 1$  and  $2x$  are linked. If  $n$  is odd a network  $g^* \in \mathcal{G}(\mathbf{k})$  with no isolated players may be established by linking two players to player  $j$  and link pairs of the remaining players: for example, if  $k_1 \geq 2$  players 1 and 2, players 1 and 3, and for each  $x = 2, \dots, n/2$ , players with indices  $2x$  and  $2x + 1$  are linked. ■

The trigger strategies of proposition 8 threaten to punish deviations in the early periods with mutual exclusion: after a player deviates from the equilibrium path all links with that player are mutually removed and she remains (mutually) isolated from the network throughout the remaining periods of the game.

**Example 6 (cooperation via mutual exclusion)** *Consider again the dilemma game  $\Gamma$  of Example 3, repeated twice. Let  $f < c + d$  so that, for each player, mutual cooperation in the first and defection in the second period is better than defection in the first and exclusion in the second period. Inspired by proposition 8 I consider the following strategy: "Propose the link and cooperate in the first period. In the second period defect, and propose the link if and only if both players cooperated in the first period."*

*This strategy differs from the strategy  $\sigma_i$  of Example 3 in that it requires second period link removal after deviation of any player, including own deviation. A deviation in the first period is punished by mutual, rather than unilateral exclusion of strategy  $\sigma_i$ . The threat of exclusion is effective. Mutual exclusion is credible as no player can profit by unilateral abstention from excluding the other player. A pair of strategies described above is thus subgame perfect. It is important to note that punishment by mutual exclusion requires participation of both players.*

The finitely repeated prisoner’s dilemma game without an outside option has a unique subgame perfect equilibrium in which both players defect in all periods. Example 6 demonstrates that the addition of a low outside option to the prisoner’s dilemma game is sufficient to obtain cooperative subgame perfect equilibria. Cooperation in these equilibria is sustained by the threat of mutual exclusion.

Mutual exclusion may not be the most intuitive form of punishment, because it requires participation of a punished player in her own punishment. Following her deviation the player is expected to remove all of her links and isolate herself throughout the remaining periods. Her isolation is an equilibrium because other players never again propose the link to her so that she is indifferent between proposing any links or not. However, there are several reasons why it may not be sensible to expect a player to contribute to her own punishment.

A player may be expected to participate in her own punishment only if it is in her own interest to do so, that is, if doing so constitutes the subgame perfect equilibrium across the remaining periods of the game. To make a threat credible it is sufficient that each player *weakly* prefers to participate in the punishment. This is the case with the threats in the trigger strategies of Proposition 8. Namely, knowing that she is being excluded by all other players the punished player is indifferent between participating in the punishment or not, hence she does participate in equilibrium. Similarly, knowing that the punished player will participate in the punishment all other players are indifferent between punishing or not, hence they punish in equilibrium.

However, the punished player never strictly prefers to remove a link in order to support her punishment. She will keep her links if even a smallest chance exists that the other players will not exclude her. Given that after the deviation all players defect, each player strictly prefers to have more links from having less. Proposing a maximal number of links thus never hurts. Yet, punishments with mutual exclusion, as described in Proposition 8, always requires that punishing players propose less than their maximal number of links and that the punished player proposes no links. If there is even a slight doubt about whether one of the parties will participate in the punishment, or about whether mutual participation is common knowledge, none of the parties will punish.

In the following section I discuss strategies with threats of unilateral exclusion. Such threats may not always be credible, as I demonstrated in Example 3. Nevertheless, I conclude that for almost all dilemma games with linking constraints it is possible to sustain cooperation in the subgame perfect equilibrium with threats of unilateral exclusion only. In such equilibria the punishing players are willing to exclude the punished player regardless of her linking behavior.

### 3.3.2 Cooperation through threats of unilateral exclusion

The ideas in this section may be outlined as follows. Consider an  $n$ -player dilemma game  $\Gamma(\mathbf{k})$  and let  $\mathbf{k}$  be such that linking is strictly constrained, that is,  $k_i < n - 1$  for each player  $i$ . Each player must thus choose at least one other player to whom she does *not* propose a link. If the dilemma game is repeated the choice of which player to exclude may be made contingent on player’s past behavior. For example, players may unilaterally exclude those other players who defected in the previous period. This in turn may be sufficient to discourage early defections.

The following example demonstrates that unilateral exclusion can indeed form a credible threat when linking is constrained. The example also gives the sketch of the general analysis.

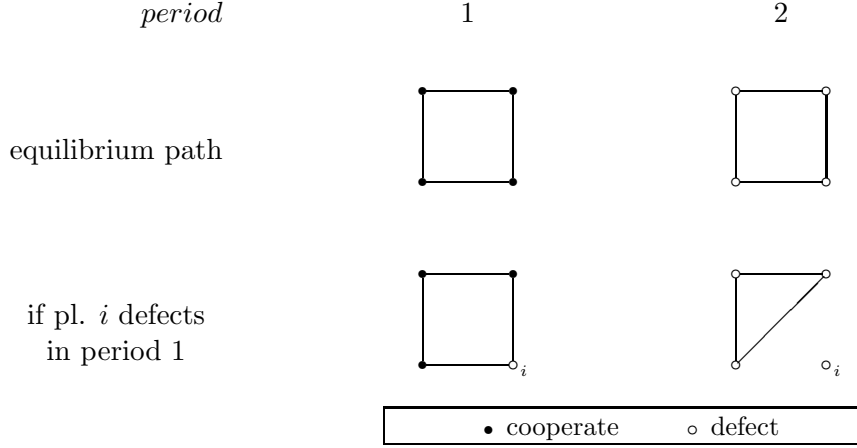


Figure 4: An illustration of a subgame perfect, cooperative and linking-proof strategy profile for the repeated game of example 7, with  $n = 4$ ,  $\mathbf{k} = (2, 2, 2, 2)$ ,  $d > 0$  and  $f < c + d$ .

**Example 7 (cooperation via unilateral exclusion)** Consider the dilemma game of example 2 with  $d > 0$ ,  $n = 4$  and  $\mathbf{k} = (2, 2, 2, 2)$  for each  $i$ . Let the game be repeated twice and let  $f < c + d$ . Consider the following strategy for player  $i$ : "Cooperate in the first and defect in the second period. Establish the network  $g^I$  in the first period. In the second period: establish  $g^I$  if in the first period (i) no player defected, or (ii) two or more players defected; establish  $g^j$  if another player  $j \neq i$  was the only player who has defected; make any linking choice otherwise (i.e. if  $i$  was the only player to have defected)."

If all players follow this strategy the wheel network  $g^I$  forms in both periods, players cooperate in the first period and defect in the second period. If in the first period player  $i$  is the only to defect, she is unilaterally excluded by her neighbors and network  $g^i$  is established in the second period. See Figure 4 for an illustration.

Network  $g^i$  is linking-proof. The opponents of player  $i$  are willing to establish  $g^i$  independently of  $i$ 's linking choice. The threat of unilateral exclusion is both credible and effective and the ensuing strategy profile is subgame perfect.

In the example above all threats with exclusion implement unilateral exclusion. A linking-proof network is established in each period along the equilibrium path, as well as in each period along any punishment path. The following proposition asserts that sequential formation of linking-proof networks implies that any exclusion is unilateral.

**Proposition 10** Consider a repeated dilemma game  $\Gamma^T(\mathbf{k})$  with  $d > 0$ , and an arbitrary  $t \leq T$ . If all networks which form along the history  $h^t$  are linking-proof, then each exclusion during  $h^t$  was unilateral.

**Proof.** Assume that, for some  $\tau \leq t$ , player  $i$  excludes player  $j$  between periods  $\tau - 1$  and  $\tau$  but none of them establish their maximal number of links in the ensuing network  $g^\tau$ . Then,  $l_i(g^\tau) < k_i$  and  $l_j(g^\tau) < k_j$ , while  $g_{ij}^\tau = 0$ . Following Proposition 6  $g^\tau$  is not a LP network. Hence,  $g^\tau$  is a LP network only if all exclusions between periods  $\tau - 1$  and  $\tau$  are unilateral. ■

To assure that each exclusion is unilateral I thus concentrate on strategies such that, after any possible history, a linking-proof network is established in each period along the resulting outcome path.<sup>8</sup>

<sup>8</sup>I do not assume that along the outcome paths a linking-proof outcome is chosen but only that a

**Definition 11** Let  $\sigma$  be a profile of strategies in the repeated dilemma game with linking constraints  $\Gamma^T(\mathbf{k})$ . Profile  $\sigma$  is a **linking-proof strategy profile** if, for each period  $t < T$  and each possible history  $h^t \in H^t$ ,  $g(p(\sigma^{t+1}(h^t)))$  is a linking-proof network.

In what follows I restrict my attention to a subset of subgame perfect equilibria, by focusing on linking-proof subgame perfect profiles. Example 7 demonstrates that simple linking-proof subgame perfect equilibria can be constructed using trigger strategies. When trigger strategies fail to sustain cooperation, non-trigger strategies may be used.

I first characterize in Propositions 12 and 13 the games for which a linking-proof subgame perfect equilibrium can be constructed using simple trigger strategies. I then show in Theorem 16 that cooperative and linking-proof subgame perfect equilibria can be constructed for most dilemma games with  $d > 0$ , using *recursive trigger* strategies.

### Trigger strategies

Consider a trigger strategy profile  $\rho(g^*, g^*, \{g^i\}_{i \in N}, T, t^*)$ , defined by (4). Along the equilibrium path of  $\rho(g^*, g^*, \{g^i\}_{i \in N}, T, t^*)$  network  $g^*$  is established in each period, all players cooperate during the early periods  $1, \dots, T - t^*$  and defect during the remaining periods. Any deviation during the early periods triggers a change of the network: during the remaining periods all players defect and establish network  $g^i$ , where  $i$  is one of the players which deviated. Profile  $\rho(g^*, g^*, \{g^i\}_{i \in N}, T, t^*)$  is linking-proof whenever each of the networks  $g^*, g^1, \dots, g^n$  is linking-proof. In this case all threats are credible because in each period of each threat the players play a linking-proof equilibrium.

The following proposition asserts that a subgame-perfect and linking-proof trigger strategy profile exists if and only if there is a linking-proof network from which each player can be unilaterally excluded.

**Proposition 12** Consider an  $n$ -player dilemma game  $\Gamma(\mathbf{k})$  with  $d > 0$ . Let  $g^*, g^1, \dots, g^n$  be linking-proof networks. There exist  $T, t^*$ , such that  $\rho(g^*, g^*, \{g^i\}_{i \in N}, T, t^*)$  is subgame-perfect for  $\Gamma^T(\mathbf{k})$ , if and only if  $l_i(g^i) < l_i(g^*)$  for each  $i$ . In this case, for any  $T' \geq T$ ,  $\rho(g^*, g^*, \{g^i\}_{i \in N}, T', t^*)$  is subgame perfect for  $\Gamma^{T'}(\mathbf{k})$ .

**Proof.** Let  $d > 0$ . Assume that  $l_i(g^*) > l_i(g^i)$  for some  $i$ . If player  $i$  defects in one of the early periods she thereby loses some of her neighbors. This decreases all her future per-period earnings,

$$\begin{aligned} \pi_i(\mathbf{D}, p(g^i)) &= d \cdot l_i(g^i) < d \cdot l_i(g^*) = \pi_i(\mathbf{D}, p(g^*)) \\ &< c \cdot l_i(g^*) = \pi_i(\mathbf{C}, p(g^*)), \end{aligned} \tag{5}$$

which makes this threat of unilateral exclusion effective for  $t^*$  sufficiently small. If  $l_i(g^*) > l_i(g^i)$  holds for each player  $i$  then (5) holds for each  $i$ . The profile  $\rho(g^*, g^*, \{g^i\}_{i \in N}, T, t^*)$  then satisfies conditions of Theorem 3 to be subgame-perfect for all sufficiently high  $T$  and  $t^*$  such that  $T > t^*$ .

Assume now that  $l_i(g^*) \leq l_i(g^i)$  for some  $i$ . Following  $\rho(g^*, g^*, \{g^i\}_{i \in N}, T, t^*)$  all players cooperate during periods  $1, \dots, T - t^*$  and defect in the remaining periods. In this case player  $i$  earns  $l_i(g^*)((T - t^*)c + t^*d)$ . If, however, player  $i$  defects already in period  $T - t^*$ , and follows  $\rho$  otherwise, she earns

$$\begin{aligned} l_i(g^*)((T - t^* - 1)c + f) + l_i(g^i)t^*d &> l_i(g^*)((T - t^*)c) + l_i(g^i)t^*d \\ &\geq l_i(g^*)((T - t^*)c) + l_i(g^*)t^*d \end{aligned}$$

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linking-proof network is established. Obviously, whenever a pairwise equilibrium is chosen all relations are defective.

thus strictly increasing her earning. The threat against her defection in period  $T - t^*$  is not effective and  $\rho(g^*, g^*, \{g^i\}_{i \in N}, T, t^*)$  is not subgame-perfect. ■

When  $d > 0$  the vector of linking constraints  $\mathbf{k}$  determines the set of linking-proof networks  $\mathcal{S}(\Gamma(\mathbf{k}))$ . It would thus be of interest to know which vectors  $\mathbf{k}$  imply the conditions of Proposition 12. Providing a full characterization appears to be a difficult combinatorial task and is beyond the scope of this paper. Instead, I give below a few partial characterizations and an interpretation of my results.

**Proposition 13** *Let  $d > 0$ . Given a sufficient number of periods, trigger strategies can be used to construct (i) cooperative, (ii) linking-proof, and (iii) subgame perfect equilibrium for a repeated dilemma game with linking constraints  $\mathbf{k}$ , in any of the following cases:*

1.  $k_i = k$  for each  $i$ , where  $2 \leq k \leq n - 2$ ,
2.  $2 \leq k_i < \sqrt{2n - 9}$  for each  $i$ .

In words, cooperation and linking proofness can be sustained (1) if linking constraints are uniform, or (2) if the set of all players is large relative to the maximal possible number of individual links. The proof of Proposition 13 follows a sequence of lemmas and is given in the appendix.

The conditions derived in Proposition 13 exclude some interesting dilemma games. Consider, for example, the original network dilemma game with unconstrained linking,  $k = n - 1$ . In this game the complete network is the unique linking-proof network, as I demonstrated in Example 1. Using backwards induction I prove below that the unique subgame-perfect selects this equilibrium in each period. This implies that the complete network is established in each period and all players always defect.

All linking-proof subgame perfect equilibria are defective also when  $k_i = 1$  for each  $i$  and  $n$  is even, because all linking-proof equilibria are payoff-equivalent. In contrast, if  $k_i = 1$  for each player  $i$  but  $n$  is odd, linking-proof subgame perfect equilibrium can be constructed in which all relations are cooperative in early periods.

**Proposition 14** *Consider an  $n$ -player dilemma game  $\Gamma(\mathbf{k})$  with  $d > 0$  and  $k_i = k$  for each  $i$ .*

1. *If  $k = n - 1$ , or if  $k = 1$  and  $n$  is even, then each linking-proof subgame perfect equilibrium is defective.*
2. *If  $k = 1$  and  $n$  is odd, there is a linking-proof subgame perfect equilibrium of  $\Gamma^T(\mathbf{k})$  with sufficiently large  $T$ , such that one player is isolated and all players cooperate in the early periods.*

**Proof.** (1) Consider the dilemma game without the linking constraints, that is,  $k_i = n - 1$  for each player  $i$ . A complete network  $g^c$  is the unique linking-proof equilibrium of this game, and the profile  $(\mathbf{D}, p(g^c))$  is the unique static equilibrium establishing  $g^c$ . Any linking-proof and subgame perfect profile thus selects  $(\mathbf{D}, p(g^c))$  in the last period regardless of the history. By backwards induction, there is a unique such profile and it selects  $(\mathbf{D}, p(g^c))$  in each period.

A similar conclusion holds for the dilemma game  $\Gamma(\mathbf{k})$  with an even number of players  $n$  and  $k_i = 1$  for each player  $i$ . Each linking-proof network consists of isolated pairs, where each player is linked to one other player. In a linking-proof equilibrium all players defect.

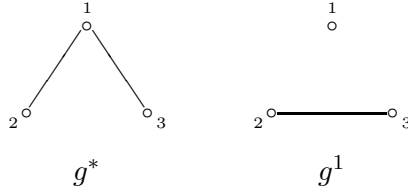


Figure 5: Linking-proof networks of the dilemma game with  $n = 3$ ,  $\mathbf{k} = (2, 1, 1)$ , and  $d > 0$ .

This implies that each player earns  $d$  in each linking-proof equilibrium profile. All pairwise-equilibria are thus payoff-equivalent. Any linking-proof and subgame perfect profile selects a linking-proof equilibrium in the last period. However, as these are payoff-equivalent, the penultimate period is treated just as the last one and a linking-proof equilibrium is again selected. Hence, by backwards induction a static linking-proof equilibrium must be selected in each period along the outcome path of any such strategy profile. Players defect in all periods along the equilibrium path of any linking-proof and subgame perfect profile.

(2) Construct a linking-proof network  $g$  as follows: link each odd  $i$  to  $i + 1$  and leave  $n$  unlinked. The profile of the following strategies is linking-proof: "Establish  $g$  as long as there have been no deviations or if more than one player simultaneously deviated. Cooperate in periods  $1, \dots, T - \gamma$  and defect in the remaining periods. If own neighbor is the only player to deviate then unilaterally exclude her and link to the previously isolated player. If isolated, propose link to any player whose neighbor defected."

Take a player  $i$  with a neighbor and consider any period  $\tau \leq T - \gamma$ . Assume that all players  $N \setminus \{i\}$  cooperate. If player  $i$  defects, she gains  $f$  immediately and 0 ever after. In contrast, if she cooperates she earns at least  $c + \gamma d$ . Punishment with exclusion is effective if  $f < c + \gamma d$ . The strategy profile is subgame perfect and cooperative if  $T > \gamma > (f - c)/d$ .

■

### Non-trigger strategies

The trigger strategies above threaten to punish any early defection with unilateral exclusion. If, however, some player cannot be unilaterally excluded the trigger strategies fail to achieve complete cooperation. Take, for example, a player who has the same number of neighbors in all possible linking-proof networks. This player must have the same number of neighbors in each period along the outcome path of any linking-proof profile and cannot be made to cooperate using the trigger strategies defined by (4).

**Example 8** Consider the dilemma game  $\Gamma(2, 1, 1)$  with  $n = 3$  players and vector of linking constraints  $\mathbf{k} = (2, 1, 1)$ . Let  $d > 0$ . There exist only two linking-proof networks,  $g^*$  and  $g^1$ , illustrated in Figure 5. Players 2 and 3 establish one link in each of these networks and earn the same per-period payoff in the two corresponding stable-equilibria. Since  $l_2(g) = 1$  for each linking-proof network  $g \in \{g^*, g^1\} \equiv \mathcal{S}(\Gamma(2, 1, 1))$ , conditions of Proposition 12 are not satisfied. Only player 1 can be punished effectively with unilateral exclusion. Therefore, there exists no cooperative linking-proof equilibrium trigger strategy (4) that is subgame-perfect.

It is interesting that it may nevertheless be possible to design strategy profiles that are linking-proof, subgame perfect, and cooperative, albeit not of the form (4). I describe the construction of such strategies below.

Trigger strategies threaten to retaliate any deviations with the repetition of a punishment static equilibrium. While such threats are most intuitive, and thus implemented in simple behavioral strategies of the Tit-for-tat or Grim type, they may not be the most effective ones. Trigger strategies can not sustain outcomes which yield payoffs that are below the worst equilibrium payoffs. In contrast, Benoit and Krishna (1985) demonstrated that, if the so-called three phase punishment paths are used, any outcome that yields payoffs above the minimax levels may be sustained in early periods of a subgame perfect equilibrium. They proved a limit folk theorem for subgame perfect equilibria of finitely repeated games<sup>9</sup>, under the sufficient condition that each player has several distinct equilibrium payoffs and that the dimension of the set of feasible payoffs is  $n$ .

The game is said to have *distinct equilibrium payoffs* if every player has two or more different equilibrium payoffs. This implies that every player has a strictly preferred equilibrium and can be punished by playing her non-preferred one. Conversely, if only one player has distinct equilibrium payoffs then only she can be punished in the last period of the repeated game. Nevertheless, other players may still be induced to play any of their actions, not by threats of punishment but by promises of *rewards*.

An informal outline of the idea can be given as follows. Consider a generic game  $\Gamma = \langle N, A, \pi \rangle$  in which only player  $i$  has distinct equilibrium payoffs. Because she has distinct equilibrium payoffs player  $i$  can be made to play repeatedly any action: only if she complies her preferred equilibrium is played in the last periods. Let  $a_i, b_i \in A_i$  be two possible actions of player  $i$  and let  $\Gamma_{a_i}$  and  $\Gamma_{b_i}$  be games obtained from  $\Gamma$  by fixing the action of player  $i$  to either  $a_i$  or  $b_i$ . Let  $j$  be a player who prefers if player  $i$  chooses  $a_i$  rather than  $b_i$ , in the sense that  $j$  earns more in his worst equilibrium of  $\Gamma_{a_i}$  than in his worst equilibrium of  $\Gamma_{b_i}$ . Player  $j$  may now be induced to play any of her actions if doing so is rewarded by player  $i$  playing  $a_i$ . Player  $j$  may thus also be made to play any action repeatedly. Hence, both players may be induced to play any of their actions, given a sufficiently large number of periods. A third player, whose payoff crucially depends on the actions of player  $j$ , may now in the same fashion be induced to play any of her actions, expecting reward from  $j$ . Indeed, iterative rewarding may induce any feasible outcome in the early periods of the repeated game if the utilities of *all* players are appropriately interrelated.

See Smith (1995) for precise definitions and a thorough elaboration of this idea. Formally, the game is said to have *recursively distinct equilibrium payoffs* if there exists an ordering of the players  $1, \dots, n$  such that

- (i) player 1 has at least two distinct equilibrium payoffs, and
- (ii) for all  $i < n$ , there exist strategy profiles  $a(i), b(i) \in A$  such that
  - each player  $i + 1, \dots, n$  plays her best response in both  $a(i)$  and  $b(i)$ ,<sup>10</sup> and
  - the payoff to player  $i + 1$  in  $a(i)$  is distinct from her payoff in  $b(i)$ .

Smith (1995) shows that, if the stage game has recursively distinct equilibrium payoffs, any feasible and individually rational outcome may be approximated as an average payoff of the repeated game with sufficiently long horizon. Recursively distinct equilibrium payoffs are thus the necessary and sufficient condition for the limit folk theorem.

The limit folk theorem of Smith cannot be straightforwardly applied to dilemma games because of the additional restriction of linking-proofness. For instance, the strategy profiles

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<sup>9</sup>The folk theorem was initially proven for infinitely repeated games. It states that any feasible and individually rational payoff vector can be obtained by a long-run undiscounted average of some subgame perfect equilibrium. See Friedman (1971) and Aumann and Shapley (1994) for its early formalizations.

<sup>10</sup>In other words, for each player  $j \in \{i + 1, \dots, n\}$ ,  $a(i)_j$  is a best response to  $a(i)_{-j}$  and  $b(i)_j$  is a best response to  $b(i)_{-j}$ .

designed in Smith (1995) punish an early deviation by selecting the outcome in which the deviating player earns her minimax payoff. In the dilemma game with low outside option the player attains her minimax payoff when she has no neighbors. A network in which player has no links may not be linking-proof, though. Indeed, there exist linking constraints such that some players establish a positive number of links in each linking-proof network.<sup>11</sup>

Nevertheless, iterative rewarding can be used to design strategy profiles which are cooperative, subgame-perfect and linking-proof, in dilemma games with linking constraints that do not satisfy the conditions of Proposition 12. This is possible under two, albeit weak, conditions: there should exist a player  $i$  and two linking-proof networks  $g^*$  and  $g^i$  such that (i) player  $i$  has more neighbors in  $g^*$  than in  $g^i$ , and (ii)  $g^*$  is connected.

The parallel between these conditions and that of the recursively distinct equilibrium payoffs is apparent: condition (i) implies that player  $i$  has distinct linking-proof equilibrium payoffs, while condition (ii) implies that payoffs of all players in some linking-proof network are interrelated. The proof of Theorem 16, below, is inspired by this parallel. To give the flavor of the proof I construct in the following example an instance of cooperative, subgame-perfect, and linking-proof strategy profile for the game  $\Gamma(2, 1, 1)$ .

**Example 9 (8 continued)** *Consider again the game  $\Gamma(2, 1, 1)$  with  $d > 0$ , and linking-proof networks  $g^*$  and  $g^1$ , shown by Figure 5. Let the game be repeated  $T$ -times and let  $t^0$  and  $t^1$  be integers such that  $0 < t^0 < t^1 < T$ . See Figure 6 for the illustration of the following strategy profile:*

- *On the outcome path:*
  - *network  $g^*$  is established in all periods,*
  - *player 1 cooperates during periods  $\{1, \dots, T - t^0\}$ , and*
  - *players 2 and 3 cooperate during periods  $\{1, \dots, T - t^1\}$ .*
- *If player 1 defects early, network  $g^1$  is established and all players defect during the remaining periods.*
- *If player 2 or 3 defects early, network  $g^*$  is kept and all players defect during the remaining periods.*

*In words, the threatened loss of links during  $\{T - t^0 + 1, \dots, T\}$  constitutes an incentive to player 1 to cooperate during  $\{1, \dots, T - t^0\}$ . The incentive to players 2 and 3 to cooperate during  $\{1, \dots, T - t^1\}$  is the possibility to free ride on player 1 during  $\{T - t^1 + 1, \dots, T - t^0\}$ . Players will conform to the strategy profile if one-period profit of any early defection is offset by the loss of profit in the resulting path. All threats are credible as they consist of a repetition of a static equilibrium.*

*More precisely, let  $\Delta_0 = t^0$  and let  $\Delta_1 = t^1 - t^0$ . If players 2 and 3 follow the strategy profile they are rewarded in  $\Delta_1$  periods by free riding on player 1, thus earning  $\Delta_1 f$  instead of  $\Delta_1 d$ . The reward increases with its length and there certainly exists a positive integer  $\Delta_1$  such that early deviation does not pay. Similarly, if player 1 deviates early she is punished by exclusion for at least  $\Delta_0$  periods, earning 0 instead of earning at least  $\Delta_0 2d$ . The punishment increases with its length and there exists a positive integer  $\Delta_0$  such that early deviation does not pay. Find such  $\Delta_0$  and  $\Delta_1$ , and set  $t^0 = \Delta_0$ ,  $t^1 = t^0 + \Delta_1$  and  $T > t^1$ . The resulting strategy profile is subgame perfect, linking-proof, and cooperative.*

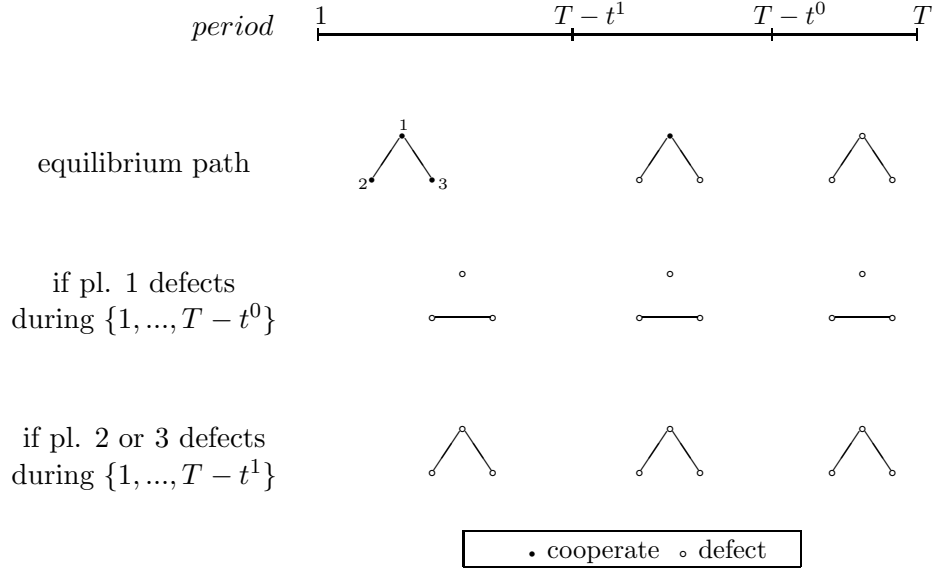


Figure 6: An illustration of a subgame perfect, cooperative and linking-proof strategy profile for the repeated game of example 8, with  $n = 3$ ,  $\mathbf{k} = (2, 1, 1)$ , and  $d > 0$ .

In the example above only one iteration of rewarding is needed to sustain complete cooperation during early periods of the repeated game. More than one iteration may be necessary for dilemma games with general linking constraints. The definition of the recursive trigger profile below suggests that the number of necessary iterations is related to the structure of the initial network structure.<sup>12</sup>

Let  $d > 0$  and let  $g^*$  be a connected linking-proof network for  $\Gamma(\mathbf{k})$ . Define

$$N^0 = \{i \in N \mid l_i(g^i) < l_i(g^*) \text{ for some } g^i \in \mathcal{G}(\Gamma(\mathbf{k}))\}$$

to be the set of players who can be punished (for an early defection) by unilateral exclusion from  $g^*$ . Assume that  $N^0$  is non-empty. Consider now the set  $N^1$  of their neighbors,

$$N^1 = \left( \bigcup_{i \in N^0} L_i(g^*) \right) \setminus N^0.$$

Players in  $N^1$  can be rewarded for cooperation with the opportunity to free ride on players in  $N^0$ . Now define recursively the sets  $N^2, \dots, N^m$  by

$$N^\eta = \left( \bigcup_{i \in N^{\eta-1}} L_i(g^*) \right) \setminus (N^{\eta-1} \cup N^{\eta-2})$$

and let  $N^m$  be the last nonempty set in the sequence.<sup>13</sup> By definition, each set  $N^\eta$  consists of players whose shortest distance to a player from the set  $N^0$  is  $\eta$ . Given that  $g^*$  is connected, any player is at a finite distance from any other player. Each player thus belongs to some  $N^\eta$ . Hence, the family  $\{N^\eta\}_{\eta=0}^m$  is a partition of the set of players  $N$ . For each player  $i$  define  $\eta(i)$  to be such that  $i \in N^{\eta(i)}$ .

<sup>11</sup>Take, for example, player 2 in the game  $\Gamma(2, 1, 1)$  of example 8.

<sup>12</sup>More precisely, the number of necessary iterations coincides with the maximal distance between a player who can be excluded from the network and a player who cannot be excluded.

<sup>13</sup>Such set exists because the number of players is finite and all sets  $N^\eta$  with  $\eta < m$  are nonempty.

**Definition 15** Consider an  $n$ -player dilemma game  $\Gamma(\mathbf{k})$  with  $d > 0$ . Let  $g^*$  be a connected linking-proof network and let  $\{N^\eta\}_{\eta=0}^m$  be the corresponding partition of  $N$ . Assume that  $N^0$  is non-empty. For each  $i \in N^0$  let  $g^i$  be a linking-proof network such that  $l_i(g^i) < l_i(g^*)$ . A **recursive trigger strategy profile** for  $\Gamma^T(\mathbf{k})$ , based upon  $(g^*, \{g^i\}_{i \in N^0}, (t^\eta)_{\eta=0}^m)$ ,  $0 < t^0 < \dots < t^m < T$ , is a strategy profile denoted by  $\rho(g^*, g^*, \{g^i\}_{i \in N^0}, T, (t^\eta)_{\eta=1}^m)$  and given by

*outcome path: establish  $g^*$  in all periods, player  $i$  cooperates during  $\{1, \dots, T - t^{\eta(i)}\}$  and defects otherwise,*

*threat for  $N^0$ : if a player  $i \in N^0$  defects early, i.e. during  $\{1, \dots, T - t^0\}$ , all players defect and establish  $g^i$  during the remaining periods,*

*threat for  $N^\eta$ : if a player  $i \notin N^0$  defects early, i.e. during  $\{1, \dots, T - t^{\eta(i)}\}$ , all players defect and establish  $g^*$  during the remaining periods,*

*simultaneous deviations: if several players simultaneously defect early exercise the threat for the deviating player with the lowest index.*

The recursive trigger profile is clearly linking-proof. It is also cooperative because all players cooperate in a connected network during  $\{1, \dots, T - t^m\}$ . The following theorem characterizes sufficient conditions for existence of a subgame perfect recursive trigger profile.

**Theorem 16** Consider a dilemma game  $\Gamma(\mathbf{k})$  with  $d > 0$ . Let  $g^*$  be a connected linking-proof network. If  $l_i(g^i) < l_i(g^*)$  for some player  $i$  and some linking-proof network  $g^i$  then there exists a positive number  $T^*$  such that for any integer  $T > T^*$  a subgame perfect recursive trigger profile for  $\Gamma^T(\mathbf{k})$  can be constructed that is (i) subgame perfect, (ii) linking-proof, and (iii) cooperative, selecting the outcome  $(\mathbf{C}, g^*)$  during the periods  $1, \dots, T - T^*$ .

**Proof.** The complete proof is given in the appendix. However, I provide here an outline of the proof.

All threats of the recursive trigger profile are credible, because they consist of a repetition of a static equilibrium. I thus need to verify that there exist positive integers  $t^0, \dots, t^m$  such that all threats are effective.

From the perspective of a player  $i$ , such that  $0 < \eta(i) < m$ , the outcome path of a recursive trigger strategy profile  $\rho(g^*, g^*, \{g^i\}_{i \in N^0}, T, (t^\eta)_{\eta=0}^m)$  can be divided into four parts as follows: (p1) during periods  $\{1, \dots, T - t^{\eta(i)+1}\}$  player  $i$  and all her neighbors cooperate; (p2) during periods  $\{T - t^{\eta(i)+1} + 1, \dots, T - t^{\eta(i)}\}$  her neighbors in  $N^{\eta(i)+1}$  defect, but player  $i$  and her other neighbors continue to cooperate; (p3) during periods  $\{T - t^{\eta(i)} + 1, \dots, T - t^{\eta(i)-1}\}$  player  $i$  defects and free-rides on her neighbors in  $N^{\eta(i)-1}$  who still cooperate; and finally (p4) during periods  $\{T - t^{\eta(i)-1} + 1, \dots, T\}$  player  $i$  and all her neighbors defect.

If player  $i$  defects during (p1) or (p2) then all her neighbors (and all other players) defect in all subsequent periods, and  $i$  thus loses the payoff she would otherwise have earned by free-riding on some of her neighbors during (p3). This loss increases with the length of part (p3),

$$\Delta_{\eta(i)} = (T - t^{\eta(i)-1}) - (T - t^{\eta(i)}) = t^{\eta(i)} - t^{\eta(i)-1}, \quad (6)$$

in a linear manner. Hence, player  $i$  will not defect during (p1) or (p2) if the length of part (p3) is so large that no unilateral deviation of player  $i$  in part (p1) or (p2) exceeds

the potential loss of payoff during part (p3). I show in the appendix that, given a finite length of part (p2), a *finite* minimal length of period (p3),  $\Delta^*(i)$ , exists for each  $i$  such that the threat of punishment for any her unilateral deviation is effective. No player in  $N^\eta$  can profit from deviating during her part (p1) if

$$\Delta_\eta \geq \max_{i \in N^\eta} \Delta^*(i). \quad (7)$$

A player  $j \in N^m$  faces only the parts (p1), (p3) and (p4) but not part (p2). Therefore, there exists the *finite* minimal length of period (p3),  $\Delta^*(j)$ , such that the threat of punishment for any her unilateral deviation is effective, independently of  $T$  and all  $t^\eta$ . No player in  $N^m$  can profit from deviating during her part (p1) if (7) is satisfied for  $\eta = m$ .

Given that  $\Delta^*(j)$  for each  $j \in N^m$  is finite, there exists a finite  $\Delta_m$  that satisfies 7 for  $\eta = m$ . Given a finite  $\Delta_m$  there exists a finite  $\Delta^*(i)$  for each  $i \in N^{m-1}$ , and thus a finite  $\Delta_{m-1}$  that satisfies 7 for  $\eta = m - 1$ . Using this argument recursively, I prove in the appendix that a sequence  $(\Delta_\eta)_{\eta=1}^m$  of finite integers exists such 7 is satisfied for each  $\eta \geq 1$ .

A player  $i \in N^0$  faces only the parts (p1), (p2) and (p4) but not part (p3). If she deviates during (p1) or (p2) she is subsequently punished by exclusion during the remaining periods. This threat is effective if the number of periods during her part (p4),  $\Delta_0 = t^0$  is sufficiently long. I prove in the appendix that, given a finite  $\Delta_1$  a finite  $\Delta_0$  exists such that no player  $i \in N^0$  can profit from deviating during her parts (p1) or (p2).

Given this  $\Delta_0 = t^0$  and the finite  $(\Delta_\eta)_{\eta=1}^m$  that satisfy (7), the sequence  $(t^\eta)_{\eta=0}^m$  can now be obtained by recursive application of (6), such that  $\rho(g^*, g^*, \{g^i\}_{i \in N^0}, T, (t^\eta)_{\eta=0}^m)$  is subgame perfect for any  $T > t^m$ . ■

Conditions of Theorem 16 are much weaker than those of Proposition 13. Those of Proposition 13 require that a network is constructed such that each player can be punished by exclusion. In contrast, conditions of Theorem 16 require only a connected network such that at least one player can be punished by exclusion. Proposition 17 below shows that for a vast majority of linking constraints *each* connected linking-proof network satisfies conditions of Theorem 16.

**Proposition 17** *Consider an  $n$ -player dilemma game  $\Gamma(\mathbf{k})$  with  $d > 0$ . If (i)  $k_i \geq 2$  for each  $i$  and (ii)  $k_j \leq n - 2$  for some  $j$  then connected linking-proof networks exist, and each satisfies conditions of Theorem 16.*

**Proof.** Given in the appendix. ■

The condition that network  $g^*$  be connected is not necessary for the conclusions of Theorem 16. If  $g^*$  is disconnected then the sufficient condition for existence of a subgame perfect recursive trigger profile is that at least one player from each connected component of  $g^*$  belongs to  $N^0$ . That is, in each connected component of  $g^*$  it must be possible to punish at least one player by exclusion. To construct a cooperative, linking-proof and subgame perfect profile one may then apply the construction of a strategy profile, outlined in the proof above, to each of the connected components.

## 4 Unilateral link formation

In this section I consider the unilateral link formation model. For a profile of linking choices  $p$  the network of established links  $g(p)$  is defined by  $g_{ij}(p) = \max\{p_{ij}, p_{ji}\}$ . Let

$$m_i(p) = \sum_{j \in N} p_{ij}$$

be the number of links proposed by player  $i$ . By the definition of the model, it is assumed that a player accepts any number of links proposed by other players, but can herself propose only a limited number of links. In particular, a player can establish more links than she can herself propose,  $l_i(g(p)) \geq m_i(p)$ , and may have any number of neighbors. Let

$$\mathcal{H}(\mathbf{k}) = \{g(p) \mid m_i(p) \leq k_i \text{ for each } i\} \quad (8)$$

be the set of feasible networks.

In this section I use directed graphs in illustrations of networks. Links are illustrated by directed arrows instead of undirected lines. The direction of an arrow describes which of the linked players proposed the link. It is important to remember that, in spite of this illustration, the interaction in the network is two-way. A proposal of only one player is needed to establish a link. However, once a link is established, both linked players earn their payoffs according to their actions in the prisoner's dilemma game.

To avoid trivialities I assume that  $c > 0$ , that is, the value of cooperation is higher than the outside option. I also assume that  $k_i \geq 1$  for at least one player, and for at least two players if the outside option is high.<sup>14</sup>

#### 4.1 Stage game equilibria and equilibrium networks

I say that a linking profile  $p \in P(\mathbf{k})$  is *maximal* if, for each player  $i$  either  $l_i(g(p)) = n - 1$ , or

$$m_i(p) = k_i \text{ and } p_{ij}p_{ji} = 0 \text{ for all } j.$$

If a linking profile is maximal no player can unilaterally increase the number of her established links.

I say that linking profile  $p \in P(\mathbf{k})$  is *redundant* if  $p_{ij} = p_{ji}$  for all  $i$  and  $j$ , that is, if each link is proposed by both players. The following proposition gives a complete characterization of Nash equilibria of game  $\Gamma(\mathbf{k})$ . Again, whether the outside option is low or high crucially determines the set of equilibrium networks.

**Proposition 18** *In each Nash equilibrium  $(a^*, p^*)$  of a game  $\Gamma(\mathbf{k})$  all players defect, i.e.  $a^* = \mathbf{D}$ .*

1. *Let  $d < 0$ . The profile  $(\mathbf{D}, p) \in J(\mathbf{k})$  is a Nash equilibrium of  $\Gamma(\mathbf{k})$  if and only if  $p$  is redundant.*
2. *Let  $d > 0$ . The profile  $(\mathbf{D}, p) \in J(\mathbf{k})$  is a Nash equilibrium of  $\Gamma(\mathbf{k})$  if and only if  $p$  is maximal.*
3. *If  $d = 0$  then any profile  $(\mathbf{D}, p) \in J(\mathbf{k})$  is a Nash equilibrium of  $\Gamma(\mathbf{k})$ .*

**Proof.** Let  $(a^*, p^*)$  be a Nash equilibrium of  $\Gamma(\mathbf{k})$  and let  $N^C = \{i \mid a_i^* = C\}$  be the set of cooperative players. Each player  $i \in N^C$  is isolated as otherwise defection would strictly increase her payoff. Let  $d > 0$  and let  $k_i > 0$ . If  $i \in N^C$  then this player could strictly increase the payoff by defecting and proposing the link to any other player. In equilibrium this should not be possible, hence  $i \notin N^C$ . Now,  $i$  can strictly increase her payoff by proposing the link to any player in  $N^C$ , hence  $N^C$  must be empty. Consider now  $d < 0$  and let  $i \in N^C$  and  $j \neq i$  such that  $k_j > 0$ . Player  $j$  could strictly increase her

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<sup>14</sup>The following are equilibria of a dilemma game with  $d < 0$  and  $k_j = 0$  for all but one player  $i$ . Two Nash equilibria exist; in both no links are proposed and all players  $j \neq i$  defect but player  $i$  can either cooperate or defect. The two equilibrium profiles are payoff-equivalent and the empty network is established in all periods of any subgame-perfect equilibrium of the repeated dilemma game.

payoff by defecting, removing all her proposed links and proposing the link to  $i$ . Again, this implies that  $N^C$  is empty.

(1) Let  $d < 0$ . Consider  $(\mathbf{D}, p)$  with redundant  $p$ . If all links are proposed by both players then no player can change her payoff by removing some of her links, while players decrease their payoff by adding links. Hence,  $(\mathbf{D}, p)$  is a Nash equilibrium. On the other hand, if some link is proposed only by one of the two players, this player could increase her payoff by removing the link. If  $(\mathbf{D}, p)$  is a Nash equilibrium,  $p$  must be redundant.

(2) Let  $d > 0$ . Let  $(\mathbf{D}, p)$  be a Nash equilibrium and let  $i$  be such that  $l_i(g(p)) < n - 1$ . It must be that  $m_i = k_i$  and  $p_{ij}p_{ji} = 0$  for all  $j$ , as otherwise  $i$  could increase her payoff by proposing more links or moving some of the links already proposed by another player. Hence,  $p$  is maximal. Consider now  $(\mathbf{D}, p)$  and let  $p$  be maximal. If all players defect then a player can increase her payoff only by adding links. If  $p$  is maximal then no player can unilaterally increase the number of her links. Hence,  $(\mathbf{D}, p)$  is Nash equilibrium.

(3) If  $d = 0$  then players earn the same payoff in each  $(\mathbf{D}, p) \in J(\mathbf{k})$ . ■

If  $(\mathbf{D}, p^*) \in J(\mathbf{k})$  is a Nash equilibrium of  $\Gamma(\mathbf{k})$  I say that  $g(p^*)$  is an equilibrium network for  $d$ . There are many redundant linking profiles and many maximal ones. Hence, for any value of  $d$  several equilibrium networks can exist.<sup>15</sup>

Assume  $d < 0$ . Under the mutual link formation model only the empty network is established in a Nash equilibrium. The reason for existence of nonempty equilibrium networks under unilateral link formation is that unilateral exclusion is not possible. If two players propose the link to each other each of them is indifferent between proposing the link or not. Two players separate only if both mutually exclude each other. However, the equilibrium in which all players defect and no links are proposed is the unique *strict* Nash equilibrium.

**Example 10** Consider dilemma game  $\Gamma(\mathbf{k})$  with  $n = 4$  and  $k = (1, 1, 1, 1)$ . Selected equilibrium networks for the game  $\Gamma(\mathbf{k})$  are illustrated in Figure 7. The star network  $g^s$ , the wheel network  $g^w$ , and the flower network  $g^{f:ij}$  are equilibrium networks when  $d > 0$ . The empty network  $g^e$  and the pairs networks  $g^{p:ij}$  and  $g^p$  are equilibrium networks when  $d < 0$ . Note that each link in  $g^{p:ij}$  and  $g^p$  is proposed by both linked players. Other equilibrium networks exist.

## 4.2 Cooperation in subgame perfect equilibria of the repeated game

Just as in section 3 above it is possible to construct cooperative subgame perfect equilibria of the repeated dilemma game with  $d > 0$ , using threats with exclusion of early defectors. Such threats are effective if there exists an equilibrium network  $g^*$  in which each player has more links than she has in her specific punishment equilibrium network  $g^i$ . In proposition 19 below I give sufficient conditions on the vector of linking constraints  $\mathbf{k}$  for the existence of networks  $g^*$  and  $\{g^i\}_{i \in N}$  that satisfy this requirement.

Furthermore, cooperative subgame perfect equilibria can be constructed also for dilemma games with  $d < 0$ . This is possible because non-empty equilibrium networks exist.

Recall Definition 2 of the trigger strategy profile  $\sigma(r, q^*, \{q^i\}_{i \in N}, T, t^*)$  and define

$$\phi(p, p^*, \{p^i\}_{i \in N}, T, t^*) \equiv \sigma((\mathbf{C}, p), (\mathbf{D}, p^*), \{(\mathbf{D}, p^i)\}_{i \in N}, T, t^*). \quad (9)$$

Along the equilibrium path of  $\phi(p, p^*, \{p^i\}_{i \in N}, T, t^*)$ : all players cooperate and establish network  $g(p)$  during the early periods  $1, \dots, T - t^*$ ; and establish network  $g(p^*)$  and defect

<sup>15</sup>In fact, for  $d < 0$  the set of equilibrium networks coincides with  $\mathcal{G}(\mathbf{k})$ , defined by (3).

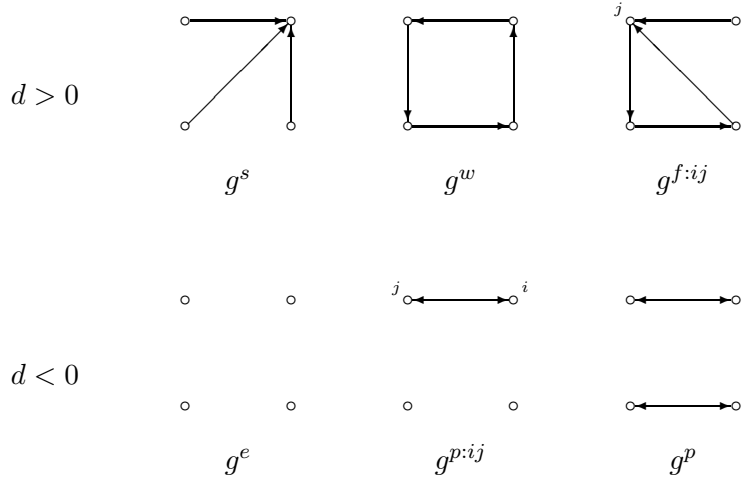


Figure 7: Selected equilibrium networks for the dilemma game with  $n = 4$  players and  $\mathbf{k} = (1, 1, 1, 1)$ , for positive and negative  $d$ . Direction of arrows: each arrow is directed away from the player who initiates the link. If both players initiate the mutual link then the line has two arrows. Note that both players interact even if only one of them initiates the mutual link.

during the remaining periods. Any deviation during the early periods triggers a change of the network: all players defect and establish  $g(p^i)$  forever, where  $i$  is one of the players which deviated. Profile  $\phi(p, p^*, \{p^i\}_{i \in N}, T, t^*)$  is cooperative by definition, and can be subgame perfect only if  $g(p^*)$  and all  $g(p^i)$  are equilibrium networks.

**Proposition 19** Consider dilemma game  $\Gamma(\mathbf{k})$  with  $d > 0$  and let  $1 \leq k_i \leq \frac{n}{2} - 1$  for each player  $i$ . There exist maximal profiles  $p^*, \{p^i\}_{i \in N} \in P(\mathbf{k})$  such that (i)  $l_i(g(p^*)) > k_i$ , and (ii)  $p_{ji}^i = 0$  for all  $i$  and  $j$ . Furthermore, for any maximal profile  $p \in P(\mathbf{k})$  there exists  $\gamma$  such that the cooperative strategy profile  $\phi(p, p^*, \{p^i\}_{i \in N}, T, t^*)$  is subgame perfect for  $\Gamma^T(\mathbf{k})$  for all  $T, t^*$  such that  $T > t^* \geq \gamma$ .

**Proof.** Given in the appendix. ■

Let  $d > 0$ . Proposition 19 gives sufficient conditions for the existence of equilibrium networks  $g(p^*), \{g(p^{f:i})\}_{i \in N}$  such that (i) in  $g(p^*)$  each player  $i$  establishes more than  $k_i$  links, and (ii) in  $g(p^{f:i})$  player  $i$  establishes only the  $k_i$  links proposed by herself. If any player  $j$  deviates from the equilibrium path of  $\phi(p, p^*, \{p^{f:i}\}_{i \in N}, T, t^*)$  she is punished when other players remove their links with her. The following example demonstrates a construction of such strategy profile. Let  $\overleftarrow{i} = i$  for  $i \in \{1, \dots, n\}$  and let  $\overleftarrow{n+1} = 1$ ,  $\overleftarrow{n+2} = 2$ , and  $\overleftarrow{0} = n$ .<sup>16</sup>

**Example 11** Consider dilemma game  $\Gamma(\mathbf{k})$  of example 10, with  $n = 4$  and  $\mathbf{k} = (1, 1, 1, 1)$ , and let outside option be low,  $d > 0$ . Let the game be repeated twice and let  $f < c + d/2$ . Consider the following strategy for player  $i$ : "Cooperate in the first and defect in the second period. In both periods propose a link to player  $\overleftarrow{i+1}$ , unless  $\overleftarrow{i+1}$  was the only defector in the first period, in which case propose the link to player  $\overleftarrow{i+2}$  in the second period." If all players follow this strategy, or if more than one player defects in the first period, the wheel network  $g^w$  is established in both periods. If in the first period player  $i$  is the only to defect, player  $\overleftarrow{i-1}$  relocates her link and the flower network  $g^{f:i, \overleftarrow{i+1}}$  is established. See Figure 8 for an illustration.

<sup>16</sup>This characterizes a version of the indexing function  $\overleftarrow{(\cdot)}$ , defined by (10) in the appendix.

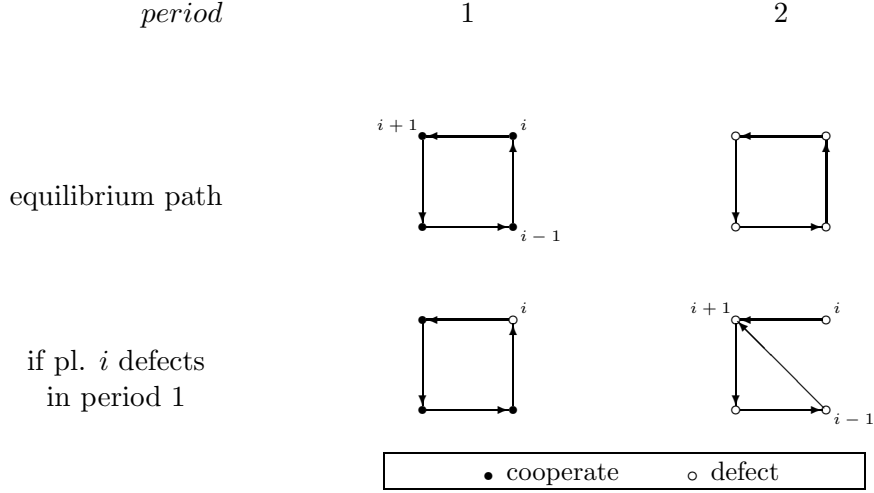


Figure 8: An illustration of a cooperative and subgame perfect strategy profile for the repeated game of example 10, with  $n = 4$ ,  $\mathbf{k} = (1, 1, 1, 1)$ ,  $d > 0$  and  $f < c + d/2$ .

Conditions of proposition 19 are not necessary for existence of a cooperative and subgame perfect equilibrium for a dilemma game with  $d > 0$ . Just as in section 3, recursive trigger strategies may be used to construct cooperative subgame perfect equilibria even if this is not possible with the trigger strategies (9). The following proposition shows that such construction is possible for almost all dilemma games.

**Theorem 20** *Consider dilemma game  $\Gamma(\mathbf{k})$  with  $d > 0$ . If (i)  $1 \leq k_j$  for all  $j$  and (ii)  $k_i, k_{i'} < n - 1$  for some distinct  $i$  and  $i'$ , then there exists a positive number  $T^*$  such that for any integer  $T > T^*$  a cooperative subgame perfect profile for  $\Gamma^T(\mathbf{k})$  can be constructed.*

**Proof.** It is straightforward to define sets  $N^0, N^1, \dots, N^m$  and rewrite definition 15 of recursive trigger strategy profiles for the set of equilibrium profiles of linking choices  $\mathcal{F}(\mathbf{k}, d)$ . The proof of Theorem 16 can then be applied to show that a subgame perfect recursive trigger profile for  $\Gamma^T(\mathbf{k})$  with sufficiently large  $T$  exists if  $l_i(g(p^i)) < l_i(g(p^*))$  for some  $i$  and some equilibrium profiles  $p^*$  and  $p^i$  such that  $g(p^*)$  is connected. I show that there exist such  $p^*$  and  $p^i$  in the continuation of this proof, given in the appendix. ■

Finally, trigger strategies (9) can be used to construct cooperative subgame perfect equilibria for dilemma games with  $d < 0$ . Let  $p^e$  be the profile in which no links are proposed and an empty network is established, that is,  $p_{ij}^e = 0$  for all  $i, j$ . Let  $p^{p:i}$  be the redundant profile in which the link between players  $i$  and  $i+1$  is mutually proposed and no other links are proposed, that is,  $p_{i,i+1}^{p:i} = p_{i+1,i}^{p:i} = 1$  and  $p_{ij}^{p:i} = 0$  otherwise.

**Proposition 21** *Consider dilemma game  $\Gamma(\mathbf{k})$  with  $d < 0$ . If  $k_i \geq 1$  for each player  $i$ , then there exists  $p \in P(\mathbf{k})$  and  $\gamma$  such that cooperative trigger profile  $\phi(p, p^e, \{p^{p:i}\}_{i \in N}, T, t^*)$  is subgame perfect for  $\Gamma^T(\mathbf{k})$  for all  $T, t^*$  such that  $T > t^* \geq \gamma$ .*

**Proof.** If  $k_i \geq 1$  for each player  $i$  there exists a profile  $p \in P(\mathbf{k})$  such that the network  $g(p)$  is connected. Consider, for example, any profile establishing a star network  $g^s$ . Clearly  $\pi_i(\mathbf{C}, p) > 0 = \pi_i(\mathbf{D}, p^e) > \pi_i(\mathbf{D}, p^{p:i})$  for each  $i$ . The proposition then follows from Theorem 3. ■

If linking is unilateral, then exclusion has to be mutual. By consequence non-empty equilibrium networks exist even if  $d < 0$ . Hence, cooperative subgame perfect equilibria

may be constructed where any early defection is *punished by inclusion* into one of the non-empty equilibrium networks.<sup>17</sup>

**Proposition 22** *Consider dilemma game  $\Gamma(\mathbf{k})$  with  $d > 0$  and no linking constraints, i.e.  $k_i = n - 1$  for each  $i$ . All subgame perfect equilibria of  $\Gamma^T(\mathbf{k})$ , for any  $T$ , are defective.*

**Proof.** If  $k = n - 1$  and  $d > 0$  then a profile is maximal only when  $l_i(g(p)) = n - 1$  for each  $i$ . Hence, following Proposition 18, the complete network is the unique equilibrium network. All players defect in a static equilibrium. Hence, all static equilibria are payoff-equivalent, which implies that in each subgame perfect equilibrium a static equilibrium outcome is selected in each period. ■

## 5 Network dilemma game with linking costs

In the sections above I assume that linking is exogenously constrained. I argue in the introduction that such an assumption is not too artificial. Social relations, for example, have to be nurtured frequently, which requires time. The amount of time which can be spent on relations is limited and people cannot support any number of relations. In a sense, I have modeled a world in which each player has a limited amount of available time to be spent on time-consuming relations.

In this section I explicitly model the relation between the number of links and the associated costs. Throughout the section one can think of these costs as the opportunity costs of devoting a part of available time to exchange relations, rather than to some other potentially profitable activity. In particular, I assume that players are not constrained in the number of links, but that each link is costly.

A cost of a link can be incurred by both linked players or only by one of them. I say that a player *sponsors* a link if she bears its costs. In particular, I assume that the player sponsors a link if she proposes and establishes the link. The cost of a new link increases with the number of links already sponsored but is otherwise independent of the identities of the players it links. The benefit of having a new link, however, depends on the behavior of the new neighbors, captured here by their actions in the prisoner's dilemma game.

In terms of opportunity costs, imagine that by sponsoring a new link the player forgoes the value of some alternative activity. When deciding whether to add a link the player compares its expected benefit with the value of the least profitable activity among those she would undertake if she does not establish any new links. The larger the number of established links, the smaller the set of activities pursued in the remaining time, and the more valuable is the cheapest of them. In this sense, the unit of available time becomes more valuable when available time is scarce. The opportunity cost of sponsoring a new link is therefore independent of who the link is established with, but increases with the number of links already sponsored.

In general, sponsoring is represented by a function  $x_i : P \rightarrow \{1, \dots, n - 1\}$ , which counts the number of links sponsored by player  $i$  given the profile of proposed links. Assuming that a player sponsors only links which she both proposed and established, sponsoring for the two models of link formation is defined as follows:

**MUTUAL LINK FORMATION:** Player must have proposed each link that she established. Hence, she sponsors each of her established links:  $x_i(p) = l_i(g(p))$ .

**UNILATERAL LINK FORMATION:** Player established each link she proposed. Hence, she sponsors each of her proposed links:  $x_i(p) = m_i(p)$ .

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<sup>17</sup>This, however, crucially relies on the active participation of a punished player in her own punishment.

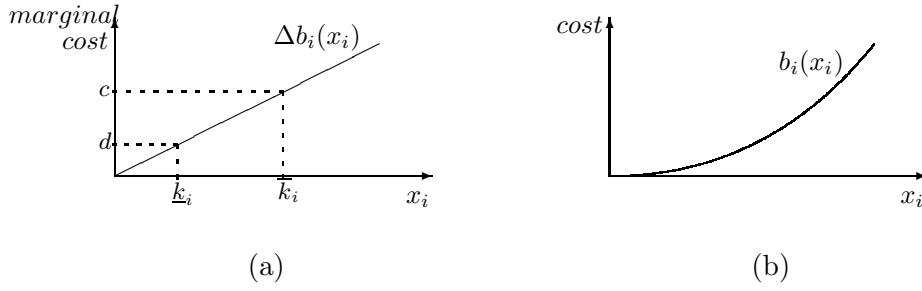


Figure 9: Illustration of a cost function  $b_i$  with an increasing marginal cost  $\Delta b_i$ . (a) If all players defect, player  $i$  earns  $d$  from each sponsored link and is willing to sponsor up to  $\underline{k}_i$  links. If, however, all players cooperate, player  $i$  earns  $c$  from each sponsored link and is willing to sponsor up to  $\bar{k}_i \geq \underline{k}_i$  links. (b) The cost function  $b_i$  is convex because the marginal cost  $\Delta b_i$  is increasing.

Let  $b_i(x_i)$  be the cost that player  $i$  incurs if she sponsors  $x_i$  links. I assume that for each player  $i$  her cost function  $b_i : \{1, \dots, n-1\} \rightarrow \mathbb{R}$  is non-decreasing and that  $b_i(0) = 0$ . I also assume that for each  $i$  the marginal cost of establishing the  $x_i$ -th link,  $\Delta b_i(x_i) = b_i(x_i) - b_i(x_i - 1)$ , is not decreasing with  $x_i$ , which implies that  $b_i$  is a convex function. For convenience I assume that there is no  $i$  and  $x_i$  such that  $\Delta b_i(x_i) \in \{c, d, e, f\}$ .

Given the link formation model  $g(\cdot)$  and the sponsoring model  $x(\cdot)$  the payoff function for player  $i$  is defined by

$$\varphi_i(a, p) = \sum_{j \in L_i(p)} v(a_i, a_j) - b_i(x_i(p)).$$

I refer to the stage game  $\Omega = \langle N, J, \varphi \rangle$  as the *dilemma game with linking costs*.

## 5.1 Stage game equilibria

The theory developed in the previous sections for dilemma games with linking constraints is very useful and instrumental in the analysis of the dilemma game with linking costs. I first characterize the close relation between the Nash equilibria of dilemma game with linking costs and the Nash equilibria of an associated dilemma game with linking constraints. Then I show that this relation extends also to subgame-perfect equilibria of the repeated dilemma games.

Let

$$\underline{k}_i = \max\{x_i \mid \Delta b_i(x_i) < d\}$$

be the maximal number of links player  $i$  is willing to support if all players defect. I refer to the vector  $\underline{\mathbf{k}} = (\underline{k}_1, \dots, \underline{k}_n)$  as the *minimal linking support*. In a Nash equilibrium of the dilemma game with linking costs each non-isolated player defects. Hence, no player  $i$  is willing to support more than  $\underline{k}_i$  links. The following Proposition shows that, in a Nash equilibrium, players behave as if their linking was constrained by  $\underline{\mathbf{k}}$ .

**Proposition 23** *Fix the prisoner's dilemma game payoffs  $v$ . Consider a dilemma game with linking costs  $\Omega = \langle N, J, \varphi \rangle$ , with the minimal linking support  $\underline{\mathbf{k}}$ . Let  $\Gamma(\underline{\mathbf{k}}) = \langle N, J(\underline{\mathbf{k}}), \pi \rangle$  be the dilemma game with linking constraints  $\underline{\mathbf{k}}$ .*

1. *If  $d < 0$  then, for both mutual and unilateral link formation models, only the empty network is established in Nash equilibria of  $\Omega$ .*

2. If  $d > 0$  then, for both mutual and unilateral link formation models, the set of networks established in Nash equilibria of  $\Omega$  coincides with the set of networks established in Nash equilibria of  $\Gamma(\underline{\mathbf{k}})$ . In particular,

- a. for the mutual link formation model: the profile  $(a, p)$  is a Nash equilibrium of  $\Omega$  if and only if  $(a, p')$  is a Nash equilibrium of  $\Gamma(\underline{\mathbf{k}})$  for some  $p' \in J(\underline{\mathbf{k}})$  such that  $g(p) = g(p')$ ,
- b. for the unilateral link formation model: the profile  $(a, p)$  is a Nash equilibrium of  $\Omega$  if and only if it is a Nash equilibrium of  $\Gamma(\underline{\mathbf{k}})$  and  $p_{ij}p_{ji} = 0$  for each  $i, j$ .

**Proof.** In a Nash equilibrium each player with at least one established link defects. Furthermore, if link formation is unilateral then proposing a link is always costly, and thus no player is willing to propose a link to another player if the other player already proposed that link. In the following I use results of Propositions 4 and 18.

(1) Let  $d < 0$ . In a Nash equilibrium a player may have proposed a link only if it is not established. Hence, no links are established.

(2.a) Consider mutual link formation and let  $d > 0$ . Let  $(a^*, p^*)$  be a Nash equilibrium of  $\Omega$  and let  $g^* = g(p^*)$  be the corresponding network. All linked players defect, hence no player  $i$  has more than  $\underline{k}_i$  links. Therefore,  $g^* \in \mathcal{G}(\underline{\mathbf{k}})$ . Then,  $(a^*, p(g^*))$  is a Nash equilibrium of  $\Gamma(\underline{\mathbf{k}})$ :  $g^*$  is feasible and if  $a_i^* = C$  for some  $i$  then  $i$  is isolated in  $g^*$ . This proves the “only if” part of the claim.

To prove the “if” part of the claim, let  $(a^*, p^*)$  be a Nash equilibrium of  $\Gamma(\underline{\mathbf{k}})$  and let  $g^* = g(p^*)$ . Because this is a Nash equilibrium no player wants to remove any links. If  $a_i^* = C$  then  $p_{ij}^* = p_{ji}^* = 0$  for all  $j$ . For each player  $i$  such that  $l_i(g^*) < \underline{k}_i$ , it must be that  $p_{ji} = 0$  or for all  $j$  with whom  $i$  has no link, as otherwise  $j$  could add a link to  $i$ . If  $l_i(g^*) = \underline{k}_i$  then  $i$  does not want to establish more links with defective players. Hence, no player can or wants to establish more links. The  $(a^*, p^*)$  is then also a Nash equilibrium of  $\Omega$ .

It follows from the above that the sets of networks established in Nash equilibria of  $\Omega$  and, respectively, of  $\Gamma(\underline{\mathbf{k}})$ , coincide.

(2.b) Consider unilateral link formation and let  $d > 0$ . Let  $(a^*, p^*)$  be a Nash equilibrium of  $\Omega$  and let  $g^* = g(p^*)$ . If  $a_i^* = C$  for some  $i$  then she must be isolated, but then other players can profitably deviate by proposing a link to  $i$ . Hence,  $a^* = \mathbf{D}$ . Consequently, no player proposes more than  $\underline{k}_i$  links. No link is proposed by two players as otherwise each could profitably deviate by not proposing and still keeping that link. Hence,  $p_{ij}p_{ji} = 0$  for each  $i, j$ . If  $l_i(g^*) < n - 1$  for some  $i$  then it must be that  $i$  proposed exactly  $\underline{k}_i$  links: if she proposed less she could profitably add another. This implies that, in relation to  $\Gamma(\underline{\mathbf{k}})$ ,  $p$  is maximal. The profile  $(a^*, p^*) = (\mathbf{D}, p^*)$  is therefore a Nash equilibrium of  $\Gamma(\underline{\mathbf{k}})$ . By implication, any  $g^*$  established in a Nash equilibrium of  $\Omega$  is established in a Nash equilibrium of  $\Gamma(\underline{\mathbf{k}})$ . This proves the “only if” part of the claim.

To prove the “if” part of the claim, let  $(a^*, p^*)$  be a Nash equilibrium of  $\Gamma(\underline{\mathbf{k}})$  such that  $p_{ij}p_{ji} = 0$  for each  $i, j$  and let  $g^* = g(p^*)$ . All players defect. No player  $i$  proposes more than  $\underline{k}_i$  links. Player  $i$  proposes less than  $\underline{k}_i$  links only if  $l_i(g^*) = n - 1$ . Hence, in relation to  $\Omega$ , no player can profitably deviate by adding, moving or removing links, thus  $(a^*, p^*)$  is a Nash equilibrium of  $\Omega$ .

Finally, I prove now that for any  $g^*$  established in a Nash equilibrium  $(\mathbf{D}, p^*)$  of  $\Gamma(\underline{\mathbf{k}})$  it is possible to construct a Nash equilibrium  $(\mathbf{D}, p^{**})$  of  $\Omega$  supporting  $g^*$ . Take an arbitrary Nash equilibrium  $(\mathbf{D}, p^*)$  of  $\Gamma(\underline{\mathbf{k}})$  and let  $g^* = g(p^*)$ . If  $p_{ij}^*p_{ji}^* = 1$  for some  $i, j$  then it must be that  $l_i(g^*) = l_j(g^*) = n - 1$ . Let  $p^{**}$  be obtained from  $p^*$  by setting  $p_{ij}^{**} = 0$  for

each  $i < j$  such that  $p_{ij}^* p_{ji}^* = 1$ , and  $p_{ij}^{**} = p_{ij}^*$  otherwise. The linking profile  $p^{**}$  satisfies (i)  $l_i(g^*) = l_i(g(p^{**}))$  for each player  $i$ , (ii)  $p_{ij}^* p_{ji}^* = 0$  for all  $i, j$ , and (iii)  $g(p^{**}) = g^*$ .

If  $m_i(p^{**}) < m_i(p^*)$  for some  $i$  then it must be that she is one of players who double-proposed a link in  $p^*$ , and hence  $l_i(g^{**}) = l_i(g^*) = n - 1$ . If  $m_i(p^{**}) = m_i(p^*) < \underline{k}_i$  it must also be that  $l_i(g^*) = n - 1$ , because  $(\mathbf{D}, p^*)$  is a Nash equilibrium of  $\Gamma(\underline{\mathbf{k}})$ . Hence,  $l_i(g^{**}) = l_i(g^*) = n - 1$  for all  $i$  such that  $m_i(p^{**}) < \underline{k}_i$ . This proves that  $(\mathbf{D}, p^{**})$  is a Nash equilibrium of  $\Gamma(\underline{\mathbf{k}})$ , and therefore also of  $\Omega$ , such that  $p_{ij} p_{ji} = 0$  for each  $i, j$ . ■

For the mutual link formation model there is a similar relation, between the dilemma games with linking costs and with linking constraints, with regard to the linking-proof networks. I define linking-proofness for dilemma games with linking costs in line with Definition 5.

**Definition 24** Consider a mutual link formation model. A profile of moves  $(a^*, p^*) \in J$  is a **linking-proof equilibrium (LP equilibrium)** of the game  $\Omega = \langle N, J, \varphi \rangle$  if (i) for each player  $i$  the move  $(a_i^*, p_i^*)$  is a best response to  $(a^*, p^*)$ , and (ii) for each pair of players  $i, j$  either  $(a_i^*, p_i^*)$  is a best response to  $(a^*, p^* \oplus ji)$  or  $(a_j^*, p_j^*)$  is a best response to  $(a^*, p^* \oplus ij)$ . Network  $g^*$  is **linking-proof** if it is established in a linking-proof equilibrium.

**Proposition 25** Consider a mutual link formation model. Fix the prisoner's dilemma game payoffs  $v$ . The set of linking-proof networks of a dilemma game with linking costs  $\Omega = \langle N, J, \varphi \rangle$ , with the minimal linking support  $\underline{\mathbf{k}}$ , coincides with the set of linking-proof networks of the dilemma game with linking constraints  $\Gamma(\underline{\mathbf{k}}) = \langle N, J(\underline{\mathbf{k}}), \pi \rangle$ .

**Proof.** In the following I use results of Proposition 6. Let  $d < 0$ . The Nash equilibrium  $(\mathbf{D}, \mathbf{0})$  of  $\Omega$  is linking-proof as no player wants to reciprocate a link proposed by a defector. Hence the empty network is the unique LPN of  $\Omega$ . It is also the unique LPN of  $\Gamma(\underline{\mathbf{k}})$ .

Consider now  $d > 0$ . Let  $g^*$  be a LPN for  $\Omega$ . As it is established in a Nash equilibrium of  $\Omega$ , it is also established in a Nash equilibrium of  $\Gamma(\underline{\mathbf{k}})$ , and thus  $g^* \in \mathcal{G}(\underline{\mathbf{k}})$ . Take a pair of players  $i \neq j$  such that  $l_i(g^*) < \underline{k}_i$  and  $l_j(g^*) < \underline{k}_j$ . They must have an established link: if not, each would strictly prefer to add the link given that it is reciprocated, and  $g^*$  would not be LPN for  $\Omega$ . Hence, there is no pair of such separated players, which implies that  $g^*$  is LPN for  $\Gamma(\underline{\mathbf{k}})$ .

Let now  $g^*$  be a LPN for  $\Gamma(\underline{\mathbf{k}})$ . Consider the profile  $(\mathbf{D}, p(g^*))$ . This profile is a Nash equilibrium of  $\Gamma(\underline{\mathbf{k}})$  and, therefore, of  $\Omega$ . No player can profit from relocating a link because all players defect and only player  $i$  such that  $l_i(g^*) < \underline{k}_i$  wants to add a link. However, there are no separated players  $i$  and  $j$  such that  $l_i(g^*) < \underline{k}_i$  and  $l_j(g^*) < \underline{k}_j$  ( $g^*$  is LPN of  $\Gamma(\underline{\mathbf{k}})$ ), hence  $(\mathbf{D}, p(g^*))$  is a linking-proof equilibrium of  $\Omega$ . ■

## 5.2 Cooperation in subgame perfect equilibria of the repeated game

In sections 3 and 4 I have shown that, given the sufficient variety of equilibrium networks, it is possible to construct cooperative and subgame perfect equilibria for finitely repeated dilemma games with linking constraints. Propositions 23 and 25 assert that the variety of equilibrium networks in dilemma games with linking costs is related to that in dilemma games with linking constraints. Hence, there should also be a relation between the sets of subgame perfect equilibria of different dilemma games. I characterize this relation next.

**Proposition 26** Fix the prisoner's dilemma game payoffs  $v$ . Consider a dilemma game with linking costs  $\Omega = \langle N, J, \varphi \rangle$ , with the minimal linking support  $\underline{\mathbf{k}}$ . Let  $\Gamma(\underline{\mathbf{k}}) = \langle N, J(\underline{\mathbf{k}}), \pi \rangle$  be the dilemma game with linking constraints  $\underline{\mathbf{k}}$ .

1. If  $d \leq 0$  then, for both mutual and unilateral link formation models and for any  $T$ , the empty network is established in each period along the equilibrium path of any subgame perfect equilibrium of  $\Omega^T$ .

2. Let  $d > 0$ .

(i) Consider the mutual link formation model. If the cooperative trigger strategy profile  $\rho(g^*, g^*, \{g^i\}_{i \in N}, T', t')$  is subgame perfect for  $\Gamma^{T'}(\underline{\mathbf{k}})$  for some  $T' > t'$ , then there exists a finite  $\gamma$  such that a cooperative trigger strategy profile  $\rho(g^*, g^*, \{g^i\}_{i \in N}, T, t^*)$  for  $\Omega^T$  is subgame perfect for all  $T > t^* \geq \gamma$ .

(ii) Consider the mutual link formation model. If the cooperative trigger strategy profile  $\rho(g^*, g^*, \{g^i\}_{i \in N}, T', t')$  is subgame perfect and linking-proof for  $\Gamma^{T'}(\underline{\mathbf{k}})$  for some  $T' > t'$ , then there exists a finite  $\gamma$  such that a cooperative, linking-proof, trigger strategy profile  $\rho(g^*, g^*, \{g^i\}_{i \in N}, T, t^*)$  for  $\Omega^T$  is subgame perfect for all  $T > t^* \geq \gamma$ .

(iii) Consider the unilateral link formation model. If for some  $T' > t'$  there exists a subgame perfect and cooperative trigger strategy profile  $\phi(p^*, p^*, \{p^i\}_{i \in N}, T', t')$  for  $\Gamma^{T'}(\underline{\mathbf{k}})$ , then there exists a finite  $\gamma$  such that a cooperative trigger strategy profile  $\phi(p^*, p^*, \{p^i\}_{i \in N}, T, t^*)$  for  $\Omega^T$  is subgame perfect for all  $T > t^* \geq \gamma$ .

**Proof.** (1) Let  $d \leq 0$ . All Nash equilibria involve the empty network and are payoff-equivalent, hence one must be selected in each period along the equilibrium path of any subgame perfect equilibrium.

(2.i) Let  $d > 0$ . If  $\rho(g^*, g^*, \{g^i\}_{i \in N}, T', t')$  is subgame perfect for  $\Gamma^{T'}(\underline{\mathbf{k}})$ , then  $(\mathbf{D}, p(g^*))$  and all  $(\mathbf{D}, p(g^i))$  are Nash equilibria of  $\Gamma^{T'}(\underline{\mathbf{k}})$  and, consequently, of  $\Omega$ . Furthermore, if threats are effective, then for each  $i$ ,  $\pi_i(\mathbf{D}, p(g^*)) > \pi_i(\mathbf{D}, p(g^i))$ , implying  $l_i(g^*) > l_i(g^i)$ . As  $g^* \in \mathcal{G}(\underline{\mathbf{k}})$  it must be that  $l_i(g^i) < \underline{k}_i$  for each  $i$ . Consider now the payoff function with linking costs,  $\varphi_i$ . By definition of  $\underline{k}_i$ , given that all players defect, player  $i$  strictly prefers having  $x_i$  links from having  $x_i - 1$  as long as  $x_i \leq \underline{k}_i$ . Hence,  $\varphi_i(\mathbf{D}, p(g^*)) > \varphi_i(\mathbf{D}, p(g^i))$  for each  $i$ .

Following Theorem 3, any profile  $(a, p)$  such that  $\varphi_i(a, p) \geq \varphi_i(\mathbf{D}, p(g^i))$  can be sustained in the early periods of the game  $\Omega^T$  if  $T$  is sufficiently large. Profile  $(\mathbf{C}, p(g^*))$  is one such profile. Hence, there exists a  $\gamma$  such that  $\rho(g^*, g^*, \{g^i\}_{i \in N}, T, t^*)$  is subgame perfect for  $\Omega^T$  for all  $T > t^* \geq \gamma$ .

(2.ii) and (2.iii) are proven following the same steps as above. ■

Proposition 26 can be summarized as follows: a cooperative and subgame perfect trigger strategy for a dilemma game with linking costs, with the minimal linking support  $\underline{\mathbf{k}}$ , repeated sufficiently many times, exists if it exists for a finitely repeated dilemma game with linking constraints  $\underline{\mathbf{k}}$ . I can now use results of Propositions 13 and 19 to describe several classes of cost functions which permit construction of cooperative subgame perfect equilibria for finitely repeated dilemma games with linking costs.

**Proposition 27** Let  $\Omega = \langle N, J, \varphi \rangle$  be an  $n$ -player dilemma game with linking costs and  $d > 0$ .

1. Consider the mutual link formation model. A (i) cooperative, (ii) linking-proof, and (iii) subgame perfect equilibrium for  $\Omega^T$  with sufficiently large  $T$  exists if  $\Delta b_i(2) < d$  for each  $i$  and  $d < \Delta b_j(n - 2)$  for some  $j$ . If, in addition, any of the following two conditions holds then such an equilibrium can be constructed using trigger strategies:

a.  $b_i = b$  for each  $i$  and  $d < \Delta b(n - 1)$ , or

b.  $d < \Delta b_i(\sqrt{2n-9})$  for each  $i$ .

2. Consider the unilateral link formation model. A cooperative and subgame perfect equilibrium for  $\Omega^T$  with sufficiently large  $T$  exists if  $\Delta b_i(1) < d$  for each  $i$  and  $d < \min\{\Delta b_j(n-2), \Delta b_{j'}(n-2)\}$  for some distinct  $j$  and  $j'$ . If, furthermore,  $d < \Delta b_i(\frac{n}{2}-1)$  for each  $i$  then such equilibrium can be constructed using trigger strategies.

**Proof.** Conditions in Propositions 13, 17 and 19 and in Theorem 20 are given in terms of  $\underline{k}$ . Condition  $\underline{k}_i < y$  can be rewritten as  $\Delta b_i(y) > d$  and condition  $\underline{k}_i > y$  as  $\Delta b_i(y) < d$ . Now apply assertions of propositions 13, 19 and 26 to prove the statements about the trigger strategies. Next I prove the statements about general (no-trigger) strategy profiles.

Combining Proposition 26 with either Proposition 17 or Theorem 20 it can be concluded that for some player  $i$  there exists (linking-proof) equilibrium profiles  $(D, p^*)$  and  $(D, p^i)$  such that  $l_i(g(p^i)) < l_i(g(p^*))$ . Now, sets  $N^0, \dots, N^m$  can be defined given  $g(p^*)$ , in the same way as in section 3.3.2, and construct recursive trigger strategy profiles in line with constructions in the proofs of Theorems 16 and 20. ■

Cooperation in a finitely repeated dilemma game with linking costs can therefore be sustained whenever the linking costs are such that players are willing to establish a first few links even with defectors, but want to add more links only if other players begin to cooperate. I conclude this section with a couple of examples.

**Example 12** Let  $b^k$  be the linking cost function such that  $b^k(x) = 0$  for  $x = 0, 1, \dots, k$  and  $b^k(x) = \infty$  for  $x > k$ . It is an extreme example of a cost function, as the first  $k$  links are costless, but all subsequent links are costlier than any potential benefit. The  $n$ -player dilemma game with linking constraints  $\mathbf{k}$  is similar to the  $n$ -player dilemma game with linking costs  $b_i = b^{k_i}$ : in the latter no rational player  $i$ , optimizing her total payoff, would ever establish more than  $k_i$  links. In fact, both the one-shot and the repeated game equilibrium payoffs coincide between the two games.

Consider an arbitrary dilemma game with linking costs. If all players cooperate they may be willing to establish more than  $\underline{k}$  links. Namely, by the definition of the prisoner's dilemma game, the benefit of mutual cooperation  $c$  is higher than the benefit of mutual defection  $d$ . Hence, given that all players cooperate, some player  $i$  may find that the benefit of cooperation exceeds the cost of the  $(\underline{k}_i + 1)$ -st link. Consequently, *networks among cooperative players may have more links than the networks among defective players*. Figure 9, discussed earlier, illustrates an instance of a cost function of player  $i$  such that when all players cooperate she is willing to support more than  $\underline{k}_i$  links.

**Example 13** In this example I demonstrate that there exist subgame perfect equilibria of the repeated dilemma game with linking costs such that in the early periods all players cooperate and establish a network with more links than in any equilibrium network. I consider  $n = 4$  and the prisoner's dilemma payoffs  $(f, c, d, e) = (7, 5, 3, 1)$ .

(a) Let  $\Omega$  be the dilemma game with mutual link formation and the following cost function for each player  $i$ :  $b_i(0) = 0$ ;  $b_i(1) = 1$ ;  $b_i(2) = 3$ ;  $b_i(3) = 7$ . The minimal linking support is  $\underline{k} = (2, 2, 2, 2)$ . The marginal cost of supporting the third link is 4 and a player is willing to support it if all other players cooperate. The linking-proof networks for  $\Omega$  are the same as given in Figure 2 for the game  $\Gamma(2, 2, 2, 2)$ . However, if all players cooperate a complete network could be established. Consider the twice repeated game  $\Omega$  and take the following strategy: "Cooperate in the first and defect in the second period. Support the complete network in the first period. If in the first period there was no defection, support

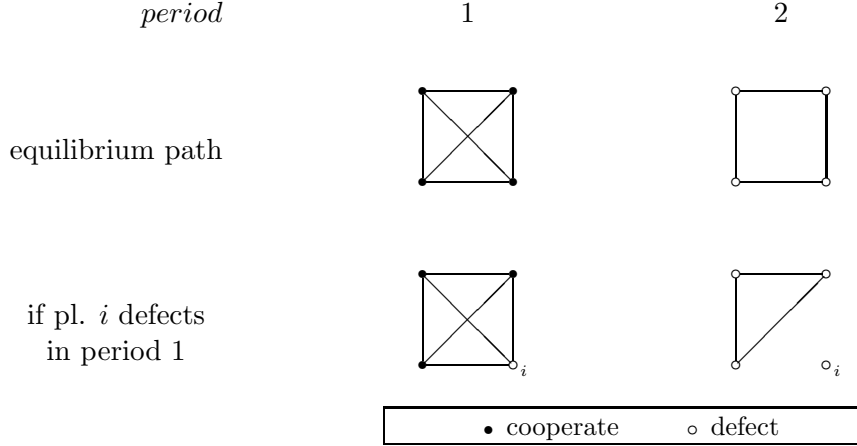


Figure 10: An illustration of a cooperative and subgame perfect strategy profile for the dilemma game with linking costs and mutual linking formation of example 13a, with  $n = 4$ , cost functions  $b_i(0) = 0$ ;  $b_i(1) = 1$ ;  $b_i(2) = 3$ ;  $b_i(3) = 7$ , and  $(f, c, d, e) = (7, 5, 3, 1)$ , repeated twice.

network  $g^I$  in the second period; otherwise support network  $g^i$ , where  $i$  is the defector with the lowest index.” See Figure 10 for an illustration. The profile of these strategies is subgame perfect for  $\Omega^2$ . In each period, no pair of separated players is willing to establish a new link, if taking the profile of actions as fixed.<sup>18</sup> In the first period all players cooperate and establish the complete network.

(b) Consider now the dilemma game  $\tilde{\Omega}$  with unilateral link formation and the following cost function for each player  $i$ :  $b_i(0) = 0$ ;  $b_i(1) = 2$ ;  $b_i(2) = 6$ ;  $b_i(3) = 10$ . The minimal linking support is  $\underline{k} = (1, 1, 1, 1)$ , thus the equilibrium networks for  $\tilde{\Omega}$  coincide with those for the game  $\Gamma(1, 1, 1, 1)$ . Some equilibrium networks are shown in the upper row of Figure 7. If all players cooperate the complete network  $g^c$ , shown in Figure 11, can also be supported,. Let the game  $\tilde{\Omega}$  be repeated three times and take the following strategy: ”Cooperate in the first and defect in the remaining periods. Support the network  $g^c$  in the first period. If in the first period there was no defection, support network  $g^w$  in the remaining periods; otherwise support network  $g^{f:i,j}$ , where  $i$  is the defector with the lowest index.” See Figure 11 for an illustration. The profile of these strategies is cooperative and subgame perfect.

## 6 Conclusions

It is well known that a finitely repeated prisoner’s dilemma game has a unique subgame perfect equilibrium: players defect in each period. The same holds for  $n$ -player prisoner’s dilemma games played in fixed groups or on a fixed network. In this paper, however, I prove that a different result holds if the network is endogenously generated by the players. In particular, I show that cooperation can be sustained in a subgame perfect equilibrium of a finitely repeated prisoner’s dilemma game played on an endogenous network. The sufficient conditions for the existence of such equilibria depend on the game length, the outside option value, the linking constraints and the linking costs. It is interesting that introducing endogenous network formation itself is not sufficient for cooperation, but that assuming, in addition, very weak constraints on the number of links or linking costs may be sufficient.

<sup>18</sup>One could say that in each period the network is linking-proof given the profile of actions. An elaboration of this concept is a scope for further research.

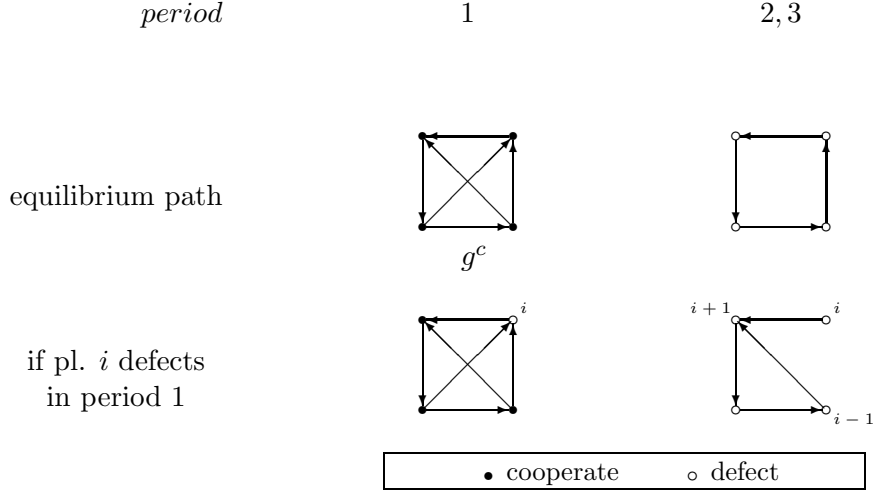


Figure 11: An illustration of a cooperative and subgame perfect strategy profile for the dilemma game with linking costs and unilateral linking formation of example 13b, with  $n = 4$ , cost functions  $b_i(0) = 0$ ;  $b_i(1) = 2$ ;  $b_i(2) = 6$ ;  $b_i(3) = 10$ , and  $(f, c, d, e) = (7, 5, 3, 1)$ , repeated three times.

My results hold under the traditional assumptions of common knowledge of rationality, complete information and selfishness. The following are my main conclusions:

- cooperation can be part of a subgame perfect equilibrium of a finitely repeated prisoner's dilemma game if it is played on an endogenous network,
- to achieve cooperation it may be necessary that there is some competition for partners: either players are strictly constrained in the number of links, or linking is costly and the cost function is convex,
- cooperation can be sustained solely via exclusion of defectors if the number of all players is substantially larger than the number of links that players can or are willing to support.

In the paper I assume that players cannot discriminate in their action between different neighbors. However, the results of the paper can be generalized to situations where players are free to choose different actions for different neighbors, if information about past moves, including the actions of each player in interactions with each of her neighbors, is complete. Defection of any player on any of her neighbors is then observed by everyone and can trigger exclusion, just as in games without discrimination in actions. The only addition to strategies described in this paper is that defection in any relation counts as deviation. This implies that, given complete information, the set of network dilemma games that support cooperation is the same whether or not discrimination across neighbors in respect to actions is permitted.

## 7 Appendix

For convenience I introduce the indexing function  $\overleftarrow{(\cdot)} : \{-n + 1, \dots, 2n\} \rightarrow \{1, 2, \dots, n\}$ , defined by

$$\overleftarrow{i} = \begin{cases} i - n & \text{if } i \in \{n + 1, \dots, 2n\} \\ i & \text{if } i \in \{1, \dots, n\} \\ i + n & \text{if } i \in \{-n + 1, \dots, 0\} \end{cases} . \quad (10)$$

The application of this function is as follows. Place players on the circle such that player  $i$  follows player  $i - 1$  and that player 1 follows player  $n$ , clockwise. For any  $i$  the indices of her  $m$  immediate neighbors, going in one direction along the circle, are given by  $\overleftarrow{i-1}, \dots, \overleftarrow{i-m}$ , and by  $\overrightarrow{i+1}, \dots, \overrightarrow{i+m}$ , going in the other direction. For even  $n$  the players  $i$  and  $i + n/2$  are directly opposite on the circle.

The proof of Proposition 13 relies on the following lemmas.

**Lemma 28** *Take  $k$  such that  $2 \leq k < n$ . Consider  $\Gamma(\mathbf{k})$  with  $d > 0$  and  $k_i = k$  for each  $i$ .*

- a. *If  $k$  and  $n$  are odd, there exists a linking-proof network  $g$  such that  $l_j(g) = k - 1$  for some  $j$  and  $l_i(g) = k$  for all  $i \neq j$ .*
- b. *Otherwise, there exists a linking-proof network  $g$  such that  $l_i(g) = k$  for all players  $i$ .*

**Proof.** (b.1) If  $k$  is even then  $g$  is constructed by linking each player  $i$  to players  $\overleftarrow{i-1}, \dots, \overleftarrow{i-k/2}$  and  $\overrightarrow{i+1}, \dots, \overrightarrow{i+k/2}$ . All players thus establish  $k$  links, hence network is linking-proof.

(b.2) If  $k$  is odd but  $n$  is even then  $g$  is constructed by linking each player  $i$  to players  $\overleftarrow{i-1}, \dots, \overleftarrow{i-(k-1)/2}$ , to players  $\overrightarrow{i+1}, \dots, \overrightarrow{i+(k-1)/2}$ , and to the player  $\overrightarrow{i+n/2}$ . All players thus establish  $k$  links, hence network is linking-proof.

(a) If  $k$  and  $n$  are both odd then a network  $g'$  is constructed by linking each player  $i$  to players  $\overleftarrow{i-1}, \dots, \overleftarrow{i-(k-1)/2}$  and  $\overrightarrow{i+1}, \dots, \overrightarrow{i+(k-1)/2}$ . All players thus establish  $k - 1$  links. Network  $g$  is constructed from  $g'$  by linking each of the  $(n - 1)/2$  disjoint pairs of separated players  $\{(i, (n - 1)/2 + i)\}_{i=1}^{(n-1)/2}$ . Player  $n$  was not assigned to any pair and thus establishes  $k - 1$  links in  $g$ , while all other players establish  $k$  links, hence network  $g$  is linking-proof. ■

**Lemma 29** *Consider  $\Gamma(\mathbf{k})$  with  $d > 0$  and  $2 \leq k_i < \sqrt{2n - 7}$  for each  $i$ . Take any stable-equilibrium network  $g \in \mathcal{S}(\Gamma(\mathbf{k}))$ . For any pair of players  $i$  and  $j$  there exists another pair of players  $i'$  and  $j'$  such that  $g_{ii'} = 0, g_{jj'} = 0$ , and  $g_{i'j'} = 1$ .*

**Proof.** The proof proceeds as follows. Let  $k = \max_{i \in N} k_i$ . Fix  $i$  and  $j$ . I characterize the set of players  $\overline{M}_{ij}$  that cannot be in the role of  $i'$  or  $j'$ . I show that the size of this set depends on  $k$ . I characterize this dependence and prove that the size of  $\overline{M}_{ij}$  is less or equal to  $n - 2$  if  $k < \sqrt{2n - 7}$ . If the size of  $\overline{M}_{ij}$  is less or equal to  $n - 2$  then there must be two players  $i'$  and  $j'$  satisfying the conditions of the Lemma.

I say that a pair of linked players  $i'$  and  $j'$  complement  $ij$  if  $g_{ii'} = 0$  and  $g_{jj'} = 0$ . If  $xy$  is not separated from  $ij$  it must be that either (a)  $g_{ix} = g_{iy} = 1$ , or (b)  $g_{jx} = g_{jy} = 1$ , or (c)  $g_{ix} = g_{jx} = 1$ , or (d)  $g_{iy} = g_{jy} = 1$ , that is, either one of  $i, j$  is linked to both  $x, y$ , or both  $i, j$  are linked to one of  $x, y$ . Define sets  $O_{ij}, N_{ij}, N_i$ , and  $N_j$  as follows:  $N_{ij} = L_i(g) \cap L_j(g)$ ,  $N_i = L_i(g) \setminus N_{ij}$ ,  $N_j = L_j(g) \setminus N_{ij}$ , and  $O_{ij} = N \setminus (L_i(g) \cup L_j(g))$ .  $N_{ij}$  is the set of players linked to both  $i$  and  $j$ ,  $N_i$  and  $N_j$  are sets of players linked to one of  $i, j$ , and  $O_{ij}$  is the set of remaining players, separated from both  $i$  and  $j$ . Let  $M_{ij} = \{i, j\} \cup L_i(g) \cup L_j(g)$ .

If a pair of linked players  $x, y$  does not complement  $ij$ , then either (i) both of them belong to  $N_i$  or both to  $N_j$ , or (ii) at least one of them belongs to  $N_{ij}$ . Let

$$\overline{N}_{ij} = \{x \mid y \in N_{ij} \text{ for each } y \text{ s.t. } g_{xy} = 1\} \setminus M_{ij}$$

be the set of players, separated from  $i$  and  $j$ , but whose neighbors all belong to  $N_{ij}$ . Let  $\overline{M}_{ij} = M_{ij} \cup \overline{N}_{ij}$  be the set of players whose neighbors are either  $i$  or  $j$  or belong all to  $N_{ij}$ , including players  $i$  and  $j$ . If a pair of neighbors  $x, y$ ,  $g_{xy} = 1$  does not complement  $ij$ , both  $x$  and  $y$  belong to  $\overline{M}_{ij}$ .

All but at most one player in  $\overline{N}_{ij}$  establish their maximal number of links in  $g$ . To see this assume  $x, y \in \overline{N}_{ij}$  such that  $l_x(g) < k_x$  and  $l_y(g) < k_y$ . Because  $g$  is a linking-proof network, Proposition 6 implies that  $g_{xy} = 1$ . Then, by definition of  $\overline{N}_{ij}$ , both  $x, y$  should belong to  $N_{ij}$ . This, however, is not possible, since they both belong to  $\overline{N}_{ij}$ .

Since  $k_x \geq 2$  for all  $x \in \overline{N}_{ij}$  and since at most one of them does not establish all her links, all but at most one of them is linked to at least two players in  $N_{ij}$ . This restricts the maximal possible number of

players in  $N_{ij}$ . Let  $n_{ij} = |N_{ij}|$ ,  $n_i = |N_i|$ , and  $n_j = |N_j|$ . Each player in  $N_{ij}$  is already linked to two players,  $i$  and  $j$ , and can have at most  $k - 2$  more links. Number  $n_{ij}$  is maximized if each player in  $N_{ij}$  makes  $k - 2$  links with players in  $\overline{N_{ij}}$ , each of whom makes two links, apart from one who makes one link. The joint number of links made by players in  $N_{ij}$  is thus  $n_{ij}(k - 2)$  and each player in  $\overline{N_{ij}}$  shares two of these, aside from at most one who shares only one link. The number of players in  $\overline{N_{ij}}$  is therefore bounded above by

$$|\overline{N_{ij}}| \leq (n_{ij}(k - 2) - 1)/2 + 1.$$

Note that  $\overline{M_{ij}} = \overline{N_{ij}} \cup N_{ij} \cup N_i \cup N_j \cup \{i, j\}$  with no overlap between pairs of sets. This implies

$$|\overline{M_{ij}}| \leq (n_{ij}(k - 2) - 1)/2 + 1 + n_{ij} + n_i + n_j + 2 \leq (n_{ij}(k - 2) - 1)/2 + 3 + k,$$

since  $n_{ij} + n_i + n_j \leq k$ . This bound is maximized when  $n_{ij} = k$ , in which case it becomes

$$|\overline{M_{ij}}| \leq (k^2 + 5)/2$$

By assumption,  $k < \sqrt{2n - 7}$ , which implies that  $|\overline{M_{ij}}| \leq n - 2$ . At least two players do not belong to  $\overline{M_{ij}}$ . Following Proposition 6 at least one of them makes at least one link. There must then be a pair of neighbors which complement  $ij$ . ■

**Lemma 30** Consider  $\Gamma(\mathbf{k})$  with  $d > 0$  and  $2 \leq k_i < \sqrt{2n - 7}$  for each  $i$ . There exists a linking-proof network  $g$  such that  $2 \leq l_j(g) \leq k_j$  for some player  $j$  and  $l_i(g) = k_i$  for all other players  $i \neq j$ .

**Proof.** The proof proceeds constructively as follows. I create, by an iterative procedure, an initial linking-proof network (LPN)  $g^0$  in which each player establishes at least two links. In this network there may be several players that miss one or more links. I then use Lemma 29 iteratively to create a finite sequence of LPN  $g^1, \dots, g^\Phi$  such that the total number of links strictly increases. At most one player is missing links in  $g^\Phi$ .

Let  $g^0$  be the network generated by the following procedure:

1. establish links between each pair  $\{i, i + 1\}$  and between the pair  $\{n, 1\}$ .
2. repeat: if there exists a pair of separated players  $i$  and  $j$  such that  $l_i < k_i$ ,  $l_j < k_j$ , establish the link  $ij$ ; until no such pair exists.

Because the number of established links in the above procedure strictly increases, but the maximal possible number of links is finite, the procedure stops in a finite number of steps. By Proposition 6, the network  $g^0$  is LPN as there exists no pair of separated players  $i$  and  $j$  such that  $l_i(g^0) < k_i$ ,  $l_j(g^0) < k_j$ .

Let networks  $g^1, g^2, \dots$  be generated by the following procedure for  $\phi = 0, 1, \dots$ :

As long as in  $g^\phi$  there exist two players  $i$  and  $j$  such that  $l_i(g^\phi) < k_i$ ,  $l_j(g^\phi) < k_j$ , then

1. take a pair of neighbors  $i'j'$ ,  $g_{i'j'}^\phi = 1$  which complement  $ij$ , that is,  $g_{ii'}^\phi = 0$  and  $g_{jj'}^\phi = 0$  (I show in Lemma 29 that such pair exists),
2. let  $g^{\phi+1}$  coincide in all links with  $g^\phi$ , aside from  $g_{ii'}^{\phi+1} = 1$ ,  $g_{jj'}^{\phi+1} = 1$ , and  $g_{i'j'}^{\phi+1} = 0$ .

The procedure ends when at most one player is still missing links. Again, the number of established links strictly increases with steps and the procedure stops in finite number  $\Phi$  of steps. In  $g^\Phi$  all players establish their maximal number of links, aside from at most one player who has at least two links.

To see that each  $g^{\phi+1}$  is LPN, proceed again iteratively. Let  $g^\phi$  be LPN and satisfy the linking constraints. Let  $ij$  and  $i'j'$  be the two pairs of players chosen by the above procedure in the corresponding step. Then,  $g^{\phi+1}$  also satisfies linking constraints. Furthermore, by Proposition 6,  $g_{ij}^\phi = 1$ , and thus  $g_{ij}^{\phi+1} = 1$ . Also by Proposition 6, because  $g^\phi$  is LPN and  $l_i(g^\phi) < k_i$  and  $g_{ii'}^\phi = 0$ , then  $l_{i'}(g^\phi) = k_{i'}$ . Similarly,  $l_{j'}(g^\phi) = k_{j'}$ . The only link that is removed is  $i'j'$ , but as players  $i'$  and  $j'$  establish the same number of links in both  $g^\phi$  and  $g^{\phi+1}$ , the  $g^{\phi+1}$  is a LPN. Hence, network  $g^\Phi$  is also LPN. ■

**Proof of Proposition 13.** (1) Assume that  $k_i = k$  for each  $i$ . Let  $2 \leq k \leq n - 2$ . In the following I apply Lemma 28.

(a) Let  $k$  be even. For every  $i$  the remaining players  $N \setminus \{i\}$  can form a linking-proof network (LPN)  $g^i$  such that  $l_j(g^i) = k$  for each  $j \neq i$  and  $l_i(g^i) = 0$ . Furthermore, a LPN  $g$  can be established such that  $l_i(g) = k$  for each  $i$ , see Lemma 28 (b). (b) Let  $k$  be odd and  $n$  even. For every  $i$  the remaining  $n - 1$  players  $N \setminus \{i\}$  can form a LPN  $g^i$  such that  $l_j(g^i) = k$  for each  $j \neq i$  and  $l_i(g^i) = 1$ , see Lemma 28 (a). A LPN  $g$  can also be established such that  $l_i(g) = k$  for each  $i$ . (c) Let  $k$  and  $n$  both be odd. For every  $i$  the remaining  $n - 1$  players  $N \setminus \{i\}$  can form a LPN  $g^i$  such that  $l_j(g^i) = k$  for each  $j \neq i$  and  $l_i(g^i) = 0$ . A LPN  $g$  can also be established such that  $l_i(g) \geq k - 1$  for each  $i$ .

In all three cases (a), (b), and (c),  $l_i(g^i) < l_i(g)$  for each  $i$ . This fulfills the conditions of Proposition 12.

(2) Let  $2 \leq k_i < \sqrt{2n-9} = \sqrt{2(n-1)-7}$  for each  $i$ . According to Lemma 30, for any subgroup of players  $N \setminus \{i\}$  of size  $(n-1)$  there exists a network  $g^{N \setminus \{i\}}$  such that  $l_j(g^{N \setminus \{i\}}) \leq k_j$  for some  $j \in N \setminus \{i\}$  and  $l_x(g^{N \setminus \{i\}}) = k_x$  for all other  $x \in N \setminus \{i, j\}$ . Let  $g^i$  be the network among players  $N$  which is obtained from  $g^{N \setminus \{i\}}$  by adding player  $i$  and (i) adding the link  $ij$  if  $l_j(g^{N \setminus \{i\}}) < k_j$  or (ii) adding no links if  $l_j(g^{N \setminus \{i\}}) = k_j$ . Aside from player  $i$  who establishes at most one link, all other players establish their maximal number of links in  $g^i$ , hence, following Proposition 6,  $g^i$  is a linking-proof network (LPN).

I have shown that for each player  $i$  there exists a LPN  $g^i$  such that  $l_i(g^i) \leq 1$ . Furthermore, according to Lemma 30, there also exists a network  $g$  such that  $l_i(g) \geq 2$  for each  $i$ . The conditions of Proposition 12 are thus satisfied. ■

**Proof of Theorem 16.** All threats of the recursive trigger profile are credible, because they consist of a repetition of a static equilibrium. I thus need to verify that there exist positive integers  $t^0, \dots, t^m$  such that all threats are effective.

A threat against an early defection of player  $i \in N^0$  is effective if the one-period profit from the defection is offset by the loss incurred through subsequent exclusion. A threat against an early deviation of player  $i \notin N^0$  in period  $t \in \{1, \dots, T - t^{\eta(i)}\}$  is effective if the profit from the deviation collected during  $\{t, \dots, T - t^{\eta(i)}\}$  is offset by the loss of reward during  $\{T - t^{\eta(i)} + 1, \dots, T - t^{\eta(i)-1}\}$ . By an early defection a player may avoid that other players free-ride on her, and may thus gain for more than one period. Namely, if some player defects early then all players defect in all subsequent periods. Player  $i \in N^{\eta(i)}$  may thus avoid being free-riden upon by her neighbors from  $N^{\eta(i)+1}$  during  $\{T - t^{\eta(i)+1} + 1, \dots, T - t^{\eta(i)}\}$ . I need to take this potential profit into account to determine the effectiveness of threats.

Let  $\gamma_i$  be the per-period difference in payoff to player  $i$  for avoiding being free-riden upon during  $\{T - t^{\eta(i)+1} + 1, \dots, T - t^{\eta(i)}\}$ . This value depends on the number of neighbors of  $i$  in sets  $\underline{L}_i = L_i \cap (N^{\eta(i)} \cup N^{\eta(i)-1})$  and  $\overline{L}_i = L_i \cap N^{\eta(i)+1}$ . If there were no deviations then all players in  $\underline{L}_i$  cooperate and all players in  $\overline{L}_i$  defect during the above mentioned periods. However, if  $i$  deviated early then all players defect during these periods. Player  $i$  thus loses because her neighbors in  $\underline{L}_i$  do not cooperate, and gains because her neighbors in  $\overline{L}_i$  do not free-ride on her. Hence,  $\gamma_i$  can be positive, negative or 0. Let  $\overline{\gamma}_i = \max\{0, \gamma_i\}$ .

Let  $\alpha_i$  be the maximal potential one-period profit to player  $i$  from an early defection. Let  $\beta_i$  be the per-period loss to player  $i$  from an exercised threat in any of the periods  $\{2, \dots, T - t^{\eta(i)}\}$  (the first deviation can take place in period 1 and the first threat is then exercised in period 2). Finally, let  $\delta_i$  be the per-period loss to player  $i$  when foregoing the reward of free-riding during  $\{T - t^{\eta(i)} + 1, \dots, T - t^{\eta(i)-1}\}$ , or when  $i \in N^0$  is punished by exclusion during  $\{T - t^0 + 1, \dots, T\}$ . The following holds for each  $i$ :  $\alpha_i, \beta_i, \delta_i > 0$ , while  $\overline{\gamma}_i \geq 0$ .

Define  $\Delta_0 = t^0$  and  $\Delta_\eta = t^\eta - t^{\eta-1}$  for  $\eta = 1, \dots, m$ . Let  $\Lambda(i, t)$  be the difference in the total payoff to player  $i$  for an early defection in period  $t \in \{1, \dots, T - t^{\eta(i)}\}$ . Then,

$$\begin{aligned} \Lambda(i, t) &\leq \alpha_i - (T - t^{\eta(i)+1} - 1)\beta_i + \Delta_{\eta+1}\overline{\gamma}_i - \Delta_\eta\delta_i \\ &\leq \alpha_i + \Delta_{\eta+1}\overline{\gamma}_i - \Delta_\eta\delta_i. \end{aligned}$$

All threats are surely effective if  $\alpha_i + \Delta_{\eta+1}\overline{\gamma}_i - \Delta_\eta\delta_i < 0$  for each  $i$ .

Players in  $N^m$  do not award any player by letting her free ride. Hence,  $\overline{\gamma}_i = 0$  for  $i \in N^m$ . The threats for these players are thus effective if  $\alpha_i - \Delta_m\delta_i < 0$ , which rewrites as

$$\Delta_m > \max_{i \in N^m} \frac{\alpha_i}{\delta_i}. \quad (11)$$

There exists a finite positive integer  $\Delta_m$  which satisfies (11). Similarly, for  $\eta \in \{0, \dots, m-1\}$ , the threats for players in  $N^\eta$  are effective if

$$\Delta_\eta > \max_{i \in N^\eta} \frac{\alpha_i + \Delta_{\eta+1} \bar{\gamma}_i}{\delta_i}. \quad (12)$$

Given a finite  $\Delta_{\eta+1}$ , there exists a finite positive integer  $\Delta_\eta$  which satisfies (12). Starting with  $\Delta_m$  it is now possible to recursively determine the minimal  $\Delta_\eta$  such that (11) and (12) are satisfied for all  $\eta$ . Setting  $t^\eta = \sum_{\zeta=0}^{\eta} \Delta_\zeta$  I get positive integers  $t^0, \dots, t^m$  such that all threats are effective. Setting  $T^* = t^m$  I conclude that  $\rho(g^*, g^*, \{g^i\}_{i \in N^0}, T, (t^\eta)_{\eta=0}^m)$  is subgame perfect for any  $T \geq T^* + 1$ . ■

**Proof of Proposition 17.** Consider the following construction of a connected LPN. Begin with a wheel network connecting all players. Now recursively add links between pairs of separated players who can still add links. By Proposition 6 the network is LPN when there is no such pair of players. This construction stops in finite time as there is a finite number of possible links.

The complete network is not feasible because  $k_j \leq n-2$ . Let  $g^*$  be a connected LPN. There exist separated players  $i'$  and  $i''$ . There also exists a shortest path  $(i' = i^0, i^1, \dots, i^\kappa = i'')$  between each such pair. Define a partition of  $N$  into players  $M^1$  who establish all their links and players  $M^0$  who do not,

$$\begin{aligned} M^0 &= \{i \in N \mid l_i(g^*) < k_i\} \text{ and} \\ M^1 &= \{i \in N \mid l_i(g^*) = k_i\}. \end{aligned}$$

By Proposition 6 all players in  $M^0$  are linked. Set  $M^1$  cannot be empty as otherwise all players would be linked and the network complete. In the rest of the proof I consider all possible cases of how pairs of separated players are distributed between  $M^0$  and  $M^1$ . For each case I construct another LPN in which one player has less neighbors than in  $g^*$ .

a) Assume that  $M^0$  is empty. Take separated players  $i'$  and  $i''$  and a shortest path  $(i' = i^0, i^1, \dots, i^\kappa = i'')$ . A network  $g^{i^1}$  can be constructed from  $g^*$  by removing links  $i^0 i^1$  and  $i^1 i^2$  and adding the link  $i^0 i^2$ . By Proposition 6  $g^{i^1}$  is LPN because  $i^1$  is the only player who does not establish all her links.

b) Assume that both  $M^0$  and  $M^1$  are non-empty. Assume also that  $g_{i',i''}^* = 1$  for all  $i \in M^0$  and  $i' \in M^1$ . Then there exist separated players  $i^0, i^2 \in M^1$  and a shortest path  $(i^0, i^1, i^2)$  with  $i^1 \in M^0$ . A network  $g^{i^1}$  can be constructed from  $g^*$  by removing links  $i^0 i^1$  and  $i^1 i^2$  and adding the link  $i^0 i^2$ . The sets  $M^0$  and  $M^1$  thus remain the same and no links between players in  $M^0$  change. In  $g^{i^1}$  all players in  $M^0$  are still linked. By Proposition 6  $g^{i^1}$  is LPN.

c) Assume now that both  $M^0$  and  $M^1$  are non-empty and take separated players  $i \in M^0$  and  $i' \in M^1$  with a shortest path  $(i = i^0, i^1, \dots, i^\kappa = i')$ . Because players  $i$  and  $i^2$  are not linked, but all players in  $M^0$  must be linked, it must be that  $i^2 \in M^1$ . W.l.o.g. let  $i^2 = i'$ .

c.1) Assume that  $i^1 \in M^0$ . Player  $i^0$  has no link to  $i^2$  and can add links to those she has in  $g^*$ . A network  $g^{i^1}$  can be constructed from  $g^*$  by removing link  $i^1 i^2$  and adding the link  $i^0 i^2$ . The new set  $M^0(g^{i^1})$  is a subset of  $M^0$  and no links between players in  $M^0$  change. All players in  $M^0(g^{i^1})$  are still linked. By Proposition 6  $g^{i^1}$  is LPN.

c.2) Assume that  $i^1 \in M^1$  and that  $g_{i'',i^1}^* = 1$  for all  $i'' \in M^0$ . Hence, all players in set  $M^0 \cup \{i^1\}$  are linked. Again, a network  $g^{i^1}$  can be constructed from  $g^*$  by removing the link  $i^1 i^2$  and adding the link  $i^0 i^2$ . The new set  $M^0(g^{i^1})$  is a subset of  $M^0 \cup \{i^1\}$  and no links between players in  $M^0 \cup \{i^1\}$  change. All players in  $M^0(g^{i^1})$  are linked. By Proposition 6  $g^{i^1}$  is LPN.

c.3) Finally, assume that  $i^1 \in M^1$  and let  $g_{i'',i^1}^* = 0$  for some  $i'' \in M^0$ . Set  $j^0 = i''$ ,  $j^1 = i$  and  $j^2 = i^1$  and construct a LPN  $g^{j^1}$  as in (c.1).

In cases a) - c.2) above I constructed a LPN  $g^{i^1}$  such that  $l_{i^1}(g^{i^1}) < l_{i^1}(g^*)$ . In (c.2) I constructed a LPN  $g^{j^1}$  such that  $l_{j^1}(g^{j^1}) < l_{i^1}(g^*)$ . In all cases above the conditions of Theorem 16 are thus satisfied. ■

**Proof of Proposition 19.** The construction of equilibrium profiles  $p^*, \{p^{f:i}\}_{i \in N}$  satisfying (i) and (ii) is as follows. Recall the indexing function  $\overleftarrow{(\cdot)}$  defined in (10). Place players on a circle such that

each player  $i$  follows player  $i - 1$  and player 1 follows player  $n$ , clockwise. Let  $p^*$  be the linking profile obtained when each player  $i$  proposes links with her immediate  $k_i$  neighbors clockwise. That is,  $p_{ij}^* = 1$  if and only if  $j \in \{\overleftarrow{i+1}, \dots, \overleftarrow{i+k_i}\}$ . Let  $p^{f:i}$  be the flower network obtained from  $p^*$  when all players that proposed a link to  $i$  remove it and propose a link to another player as follows: for each  $j$  such that  $p_{ji}^* = 1$  let  $p_{ji}^{f:i} = 0$  and  $p_{j, \overleftarrow{j+k_j+1}}^{f:i} = 1$ . Let  $p_{i'j'}^{f:i} = p_{i'j'}^*$  otherwise.

To see that  $p^*$  is an equilibrium profile note that  $p^*$  is maximal. Namely,  $m_i(p^*) = k_i$  for each  $i$  and no link is proposed mutually: if  $p_{ij}^* = p_{ji}^* = 1$  then  $i = \overleftarrow{j+x}$  for  $x \leq k_j$  and  $j = \overleftarrow{i+y}$  for  $y \leq k_i$ , and since  $i = \overleftarrow{i+x+y}$  it must be that  $n = x+y \leq k_j + k_i \leq n-2$ , which is impossible. Now consider  $p^{f:i}$  for some fixed  $i$  and note that  $m_j(p^{f:i}) = k_j$  for each  $j$ . In  $p^{f:i}$  no link is proposed mutually: if  $p_{j'j}^* = p_{jj'}^* = 1$  then each  $i' \neq i$  has a link proposed either by  $j$  or  $j'$ , which implies that  $j$  and  $j'$  together proposed at least  $n-1$  links, which is impossible. Hence,  $p^{f:i}$  is an equilibrium profile.

Each player  $i$  has at least  $k_i + 1$  neighbors in  $g(p^*)$ : she proposes links to players  $\{\overleftarrow{i+1}, \dots, \overleftarrow{i+k_i}\}$  and player  $\overleftarrow{i-1}$  proposes a link to  $i$ . On the other hand, under  $p^i$  no links to player  $i$  are proposed, hence players  $\{\overleftarrow{i+1}, \dots, \overleftarrow{i+k_i}\}$  are her only neighbors. Properties (i) and (ii) are therefore satisfied.

The payoff to each player  $i$  in a Nash equilibrium is proportional to the number of her neighbors. In particular,  $\pi_i(\mathbf{D}, p^*) \geq d(k_i + 1) > dk_i = \pi_i(\mathbf{D}, p^{f:i})$ . Furthermore,  $\pi_i(\mathbf{C}, p) \geq ck_i > dk_i = \pi_i(\mathbf{D}, p^{f:i})$ . The conditions of Theorem 3 are therefore satisfied and a cooperative trigger strategy profile  $\phi(p, p^*, \{p^{f:i}\}_{i \in N}, T, t^*)$  is subgame perfect for sufficiently large  $T$  and  $t^*$ . ■

**Proof of Theorem 20, continued.** For a profile  $p^0 \in P(\mathbf{k})$  with no mutually proposed links, i.e.  $p_{jj'}^0 p_{j'j}^0 = 0$  for all  $j, j'$ , let  $p^{0*}$  be the profile obtained from  $p^0$  via the following iterative procedure. Let  $p^{00} = p^0$ . For  $x \geq 1$  let  $p^{0,x}$  be obtained from  $p^{0,x-1}$  by an addition of one link: set  $p^{0,x} = p^{0,x-1}$ ; take the player with the smallest index  $j$  such that  $m(p^{0,x}) < k_j$  and  $l_j(g(p^{0,x})) < n-1$  and then find a player with the smallest index  $j' \neq j$  such that  $g(p^{0,x})_{jj'} = 0$  and set  $p_{jj'}^{0,x} = 1$ . Stop the procedure when no such  $j$  exists and let  $p^{0*}$  be the resulting profile.  $(\mathbf{D}, p^{0*})$  is an equilibrium profile: clearly  $p^{0*} \in P(\mathbf{k})$ , no link is proposed mutually, and for each  $j$  either  $m(p^{0,x}) = k_j$  or  $l_j(g(p^{0,x})) = n-1$ .

Now construct  $p^*$  and  $p^i$  as follows. Define  $p^0$  by setting  $p_{ji}^0 = 1$ ,  $p_{ij}^0 = 0$  and  $p_{j'j'}^0 = 0$  for each  $j, j' \in N \setminus \{i\}$  and  $p_{ii}^0 = 0$ . No link in  $p^0$  is proposed mutually. Let  $p^*$  be the profile obtained from  $p^0$  via the above procedure. Define  $p^{i0}$  by setting  $p_{i'j}^{i0} = p_{ij}^{i0} = 1$  for  $k_{i'}$  players with smallest index  $j \in N \setminus \{i, i'\}$  and  $p_{j'j'}^{i0} = 0$  otherwise. Let  $p^i$  be the profile obtained from  $p^{i0}$  via the above procedure.

Both  $(\mathbf{D}, p^*)$  and  $(\mathbf{D}, p^i)$  are equilibrium profiles. Players  $i$  and  $i'$  are separated in  $g(p^i)$ . In  $g(p^*)$ , however,  $i$  is linked to each other player and  $g(p^*)$  is connected. Hence,  $l_i(g(p^i)) < n-1 = l_i(g(p^*))$ . ■

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