Competition for Status Creates Superstars
An Experiment on Public Good Provision and Network Formation[*]

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This version: November 2016

ABSTRACT: We investigate a mechanism that facilitates the provision of public goods in a network formation game. We show how competition for status encourages a core player to realize efficiency gains for the entire group. In a laboratory experiment we systematically examine the effects of group size and exogenously monetarized status rents. The experimental results provide very clear support for the concept of challenge freeness, a refinement that predicts when a repeated game equilibrium is selected, and if so which one. Two control treatments allow us to reject the possibility that these observations are driven by social preferences, independently of the competition for status.

Keywords: Network formation, public goods, competition, status.

JEL codes: C91, D85, H41

1   Introduction

The provision of public goods often benefits from the exemplary performance of a small subset of the people involved. For example, a very small group is usually responsible for developing open source software (OSS; Lerner and Tirole 2002; Crowston et al. 2006) and a limited number of people make most contributions to Wikipedia (Voss 2005; Ortega et al. 2008; Algan et al. 2013). In a similar vein, people volunteering to help out at amateur sports teams, often show extraordinary dedication and spend a substantial part of their free time working at the club instead of being with their families. Academics spend much more time organizing workshops than can reasonably be expected in a one-shot game and editors dedicate a lot of their time to their journals without proper contingent reimbursement. In all these examples, many free-riders benefit from the contributions of a few highly active players with whom they are connected.

The model introduced by Galeotti and Goyal (2010) – GG hereafter – provides a fruitful theoretical structure to study situations in which people decide both about how much to contribute to a public good and about with whom they want to connect. In their network formation game, each player simultaneously chooses links to other players and their own investment to the public good. Players consume some public good, for instance OSS code, which they can do either by investing personally (writing code) or by making links to others who invest in the public good (using someone else's publicly available code).

In this paper, we explore the effects of the possibility that players gain 'status' from having a pivotal role in a network. Status may yield expectations of material returns, e.g., contributors like OSS-developers may recognize that their conspicuous contributions can serve as a stepping stone to a better job in the future (Lerner and Tirole 2002; 2005); or may lead to payments by a third party, e.g. through advertisements (Roberts et al. 2006). Alternatively, status may yield an internalized psychological reward; for example, contributors may be driven by the prestige or warm glow that their exemplary behavior generates (Lakhani and Wolf 2005; von Krogh and von Hippel 2006; Fershtman and Gandal 2011). In this paper, we will refer to all such benefits (material and psychological) as 'status rents.'

Our intuition is that in many network examples of successful public good provision, competition for status plays an essential role. Status rents will encourage players to compete in terms of 'good' behavior. The most important contribution of our paper is that we show how – if the rents are high enough – competition for status allows for the formation of stable star networks in which a single (core) player realizes efficiency gains for the entire group. With

sizable status rents, even overprovision by the core player is expected. Without status rents, stable networks do not form, and the public good is typically inefficiently provided.

In GG's baseline model there are no status rents. We introduce these in their model by awarding players a monetary payoff for each incoming link. GG's main result is that in every strict equilibrium of the game, the number of players who invest in the public good is limited. These players – 'the influencers' – form the core of the network. Other (periphery) players link to the core, without contributing. Together, the players form a core-periphery network. If the core consists of only one player, we say that a star has formed. Important for our purpose is that GG's main result is unaffected by the introduction of status rents.[1]

In the one-shot game that GG study, efficient cooperation is not supported in equilibrium. In the finitely repeated game that we are interested in, a plethora of equilibria can be supported in equilibrium, including one with efficient provision of the public good almost until the end. To shed light on which of these repeated game equilibria is to be expected, we introduce the concept of *challenge freeness*. An equilibrium is challenge free if no player has an incentive to challenge the position of the player who is best off and if this player cannot improve her position without being challenged. The concept predicts *whether* a repeated game equilibrium will be reached, and if so, *which* one. A simple behavioral model in which selfish players with limited foresight compete for attractive network positions supports the concept of challenge freeness. Challenge freeness is closely related to the concept of envy-free equilibrium which has been used to successfully predict the equilibrium that materializes in position auctions (Edelman et al., 2007; Varian 2007).

In situations without status rents, the periphery position is more attractive than the core position. In these circumstances, players prefer others to do the painful job of providing the public good. Even if a star is formed, the person in the core will prefer to challenge the position of any player in the periphery. Without explicit agreement on a rotation scheme, this will lead to continued instability. Without status rents, both the refinement and the behavioral model predict that star networks are unstable and inefficiency will result. With status rents, the core position can become more attractive than a periphery position. As a consequence, players will compete to be in the core. We show how the person willing to invest most in the public good attracts all links and becomes the core player in a star network. Competition for status forces

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[1] GG's model explains findings reported in early work by Lazarsfeld et al. (1944) and Katz and Lazarsfeld (1955). These suggest that individuals' roles in the network are distributed in a specific way, where a limited number of individuals influence the majority. This has been observed in applications as diverse as fashion, opinions and voting. These observations imply that information is typically acquired and shared in networks with a core-periphery structure, where a small core acquires information and a large periphery free rides.

the core player to invest up to the level where payoffs across network positions are roughly equalized, i.e. to the point where periphery players no longer have an incentive to challenge the core player by investing more. This process yields a repeated game equilibrium with a public good investment level that follows from the parameters of the game.

In the laboratory, we consider two network characteristics that the concept predicts to systematically affect public good provision and the structure and stability of the network. The first is the extent of status rents that a player derives from incoming links; these rents are absent, of medium value or of high value. The second characteristic is group size, which is either small (4 players) or large (8 players). In a full 3x2 design, we systematically vary status rents and group size in such a way that the (stage-game) equilibrium predictions of the GG model remain unaffected.

In contrast, challenge freeness predicts that behavior will vary systematically across our two treatment dimensions. Only with sufficiently large status rents, we predict convergence to a stable core-periphery network. The particular equilibrium selected depends on the two characteristics. Essentially, provision of the public good benefits from an increase in status rents per link as well as from an increase in group size. Finally, we add two control treatments to the design, in which the network structure is exogenously imposed and based on actual networks formed in the endogenous counterparts. This allows us to isolate the competition-for-status explanation from other possible explanations of contributions by the core (e.g., specific kinds of other-regarding preferences).

In our experiments, we implement the game in a straightforward manner. Subjects participate in only one of the eight (3x2+2) treatments. They are informed that they remain in the same group for 75 periods and they are informed of the relevant parameters (most importantly, group size, status rents, linking costs, the costs of investing in the public good and the benefits that they derive from having access to the public good). They know that they have access to their own public good investments and to the investments of the players to whom they have created links. In each period, subjects simultaneously make their links and investment decisions (except in the control treatments, where they only make investment decisions).

Our experimental results for the treatments with endogenous network formation provide clear evidence that participants compete for status rents. The existence of status rents is necessary for stable star networks to form and the extent of such rents and group size both boost the provision of the public good. Without status rents, star networks are only observed in only 10% of the cases even in the final 25 periods. This means that in almost all cases, public

good provision is decentralized and subjects access on average less of the public good than the stage-game Nash amount. As a result, outcomes are highly inefficient and average experimental earnings are even below what could be expected if there was no scope for networks to form. At the other extreme (with high status rents), in the final 25 periods subjects in the core of a star contribute close to the efficient amount (on average 97% of the efficient amount) when groups are small and they vastly overcontribute when groups are large (on average 173% of the efficient amount). In these cases a star network is formed in 53% and 86% of the cases, respectively. Our results also show a large positive effect of group size on contributions to the group. This is in sharp contrast to previous experiments on '*supergame effects*'.[2] Finally, in the treatments with high status rents, but also in the treatment with medium status rents and large groups, we observe that groups mostly converge to '*superstars*', in which the core player invests in more units of the public good than is expected in the stage game equilibrium.

The refinement of challenge freeness predicts the comparative statics that we observe. Groups tend to converge to the repeated game equilibria selected by the refinement. Further support comes from the process by which this occurs. In the first half of the treatments with high status rents, in most groups multiple subjects compete by investing heavily in the public good. They converge to a (challenge-free) superstar in the second half of the experiment. Finally, our results confirm a central prediction of the GG model, that is, that the maximum number of players who invest and form the core is independent of group size.

The results for the endogenous network formation treatments are consistent with the hypothesis that players compete for status. There are, however, other possible explanations for the results. Bloch and Jackson (2007) argue that an exchange of transfers can lead to efficiency gains in repeated network games. Alternatively, core players may feel that it is their duty to reciprocate by investing more in the public good if they receive high rents from incoming links. Or, altruism or inequity aversion may motivate them to share some of the windfall gains that high status rents bring. Notice that all these alternative mechanisms are fundamentally different

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[2] We use the term 'supergame effect' to describe an increase in the provision of the public good when the stage game is repeated across multiple rounds. Such supergame effects are rarely observed in laboratory experiments. In applications like ours where the efficient outcome can only be supported as an equilibrium of the repeated game, coordination on this efficient outcome is rarely observed in the laboratory. Experimental supergame results are by and large limited to games with two players, and even there efficient play tends to be fragile (see for instance the evidence reviewed in Huck et al. 2004, and Dal Bó, and Fréchette, 2011). An additional behavioral mechanism is usually needed to support the emergence of an efficient outcome. Examples include the possibility to punish defectors in public good games (Fehr and Gächter 2000) and the possibility to exclude members from consuming the public good (Cinyabuguma et al. 2005). These mechanisms cannot explain the efficient provision of a public good by only a few members as in the examples that motivate this paper.

from the mechanism that we propose in the sense that they do not assign importance to competition for status. According to the concept of challenge freeness, supergame effects are not expected when players participate in an exogenously determined network (because they cannot challenge other players). In contrast, the alternative mechanisms do not require that the network is endogenously formed. Our two control treatments with exogenous networks therefore allow us to isolate the predictions derived from challenge freeness from these alternatives.

The results for these controls provide strong support for our conjecture that supergame effects are primarily driven by competition for status. We observe many more superstars when networks are formed endogenously than when they are exogenously imposed. In comparison, the positive role of social motivations is negligible. With exogenous networks, only a handful of pro-socially motivated core players contribute more than would be expected on the basis of selfishness. We conclude that superstars need status rents; these trigger competition between the players, which has a substantial impact on the provision level of the public good, and on the shape and stability of the network.

The remainder of this paper is structured as follows. We continue with a brief discussion of previous studies in Section 2. We present the theoretical framework in Section 3. Section 4 describes the experimental design and procedures and in Section 5 we provide equilibrium and efficiency predictions for the game with the parameters of the experiment. The results of the experiment are described in Section 6 and Section 7 concludes. [3]

2   State of the Art

There is a relatively large theoretical literature on network formation and the provision of public goods in networks, either with endogenously formed networks or exogenously given networks.[4] Most relevant for our study is GG (Galeotti and Goyal 2010), who extend the network public goods game of Bramoullé and Kranton (2007) by adding endogenous network formation using the protocol designed by Bala and Goyal (2000). As mentioned above, we employ the GG framework in our experiment.

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[3] In the working paper that this paper supersedes (van Leeuwen et al. 2013), we considered four treatments that differed in many respects from the treatments reported here. For example, in the previous paper we had no treatments where subjects contributed more than the efficient amount. Based on the previous results, we formulated the predictions –how network stability and the core player's contribution are determined by the relative profitability of the core position– before we ran any session reported in this paper.

[4] For an overview of the theoretical literature on network formation, see for example Goyal (2007) or Jackson (2008). Other theoretical papers that study public good provision on endogenously formed networks include Cho (2010) and Cabrales et al. (2011). Galeotti et al. (2010), Boncinelli and Pin (2012) and Bramoullé et al. (2014) study public good provision on exogenous networks.

Closest to the current study are two other papers that use the GG-framework in laboratory experiments. Both papers focus on other treatment variables than we do. The first is Rong and Houser (2015), who use the best-shot version of the GG-model, i.e. players face a binary choice whether or not to invest. In their setup, the public good is provided if and only if at least one of the ex-ante homogeneous players invests. Between treatments, they investigate the effect of sequential decision making and they vary the strategy set of the players. With sequential decision making, each subject is informed of the all choices of her predecessors. Surprisingly, sequential decision making does not facilitate the emergence of efficient stable star networks. They vary the strategy set by, first, limiting subjects to either investing or making a link to one other subject; and second, allowing at most one player at a time to contribute to the public good. This restricted strategy set yields more equilibrium (star) networks.

The second related paper is by Goyal et al. (2016), who study the effects of varying the linking costs and of introducing individual heterogeneity. Some of their findings are in agreement with the predictions of the GG-model. E.g., they find that increased linking costs lead to fewer links and higher investments by subjects in the core. In the treatments where a single individual has lower linking costs than the others, this subject is more likely to end up in the core, as predicted. At the same time, aggregate investments are higher than predicted and, in contrast to the GG-model, increase with linking costs.[5]

The results of Goyal et al. (2016) and those of the baseline treatment in Rong and Houser (2015) line up well with the results in our treatments without status rents. In all cases, (equilibrium) core-periphery networks are rarely observed and social welfare is low due to the ineffective network structures. Our paper provides two novel insights compared to these papers. First, we show how stable star networks among ex ante symmetric players can result without restricting subjects' strategy sets. Second, we identify conditions under which supergame effects are expected.

In our setup, players decide both on their network connections and their investments in a (local) public good where investments are strategic substitutes. These two elements have also been studied in isolation. In experiments purely concerned with network formation (i.e. players only decide on their links) a typical result is that groups rarely converge to equilibrium (star) networks when equilibrium payoffs between different positions are asymmetric (Falk and Kosfeld 2012). Introducing heterogeneity in values can reduce payoff asymmetries; as a result

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[5] The authors attribute these latter results to differences between the GG-model and their laboratory implementation. In their experiment, subjects make repeated decisions, but only the decisions at a random termination moment matter for payment.

star networks form more often (Goeree et al. 2009). Other experimental studies consider public good games with strategic substitutes, but on fixed networks (Rosenkranz and Weitzel 2012; Charness et al. 2014).[6]

To the best of our knowledge, we are the first to study endogenous network formation in combination with public goods investment and status rents. Our introduction and analysis of status rents also sheds light on results observed in previous field and laboratory studies. In a natural field experiment, Zhang and Zhu (2011) investigate contributions to Chinese Wikipedia. They interpret the repeated blockings of Chinese Wikipedia in mainland China as an exogenous variation in group size and observe that contributions increase when groups are larger. Restivo and van de Rijt (2012) provide an example of how status rents may be operationalized in the field. They show that informal rewards ('barnstars') encourage contributors on Wikipedia to increase their contributions. Algan et al. (2013) run experiments using a large sample of active Wikipedia contributors. Combining experimental and observational data from Wikipedia, they find that high contributions are strongly correlated with social image concerns, but not with altruism. In laboratory experiments, providing rankings based on pro-social behavior can positively affect giving in dictator games (Duffy and Kornienko 2010). Finally, the positive effect that intergroup competition has on cooperation (e.g. Bornstein et al. 1990; Schram and Sonnemans 1996; Nalbantian and Schotter 1997; Reuben and Tyran 2010) may also be attributable to intragroup status.

Aside from status rents, one could interpret the benefits from an incoming link as a transfer between players. Transfers (or side payments) can be an effective way to sustain otherwise unstable networks (Jackson and Wolinsky 1996; Bloch and Jackson 2007). However, our focus is on the competition for links that arise when there are status rents. This turns out to be important. Our two control treatments show that supergame effects are not observed without such competition.

Finally, there is some related work that supports the approach of our behavioral model. Previous theoretical work has studied network formation with forward-looking players (Dutta et al. 2005; Herings et al. 2009). In our behavioral model, we assume that players are forward-looking with limited foresight. This assumption is supported by experimental work on network

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[6] Other papers that experimentally study public goods on exogenous networks include Fatas et al. (2010), Carpenter et al. (2012) and Leibbrandt et al. (2014). Eckel et al. (2010) study public good provision on fixed star networks and assign the core positions in some treatments to either 'high-status' or 'low-status' individuals. Status is determined by performance on a trivia quiz. High-status core players are more often mimicked by the periphery than low-status core players. Several other experimental papers that allow for endogenous network formation (e.g. Ule, 2005, Corbae and Duffy, 2008, Knigge and Buskens, 2010, Berninghaus et al., 2012, Wang et al., 2012) use games that differ substantially from ours.

formation (Callander and Plott 2005; Berninghaus et al. 2012; Kirchsteiger et al. 2013; Caldara and McBride 2014).

3 Theory

3.1 Stage game and static analysis

We study the one-way flow variant of the static game in GG and extend the model to allow players to enjoy status rents for each incoming link. Wherever possible, we follow the notation in GG.

Denote the set of players by $N = \{1, 2 \ldots, n\}$. Every player $i \in N$ simultaneously decides on her (public good) investment level x_i and the links $\boldsymbol{g_i}$ that she forms. Investments are non-negative integers, i.e. players select their investments from the set $X = \{0, 1, 2, \ldots, x_{max}\}$. The vector $\boldsymbol{g_i} = (g_{i,1}, g_{i,2}, \ldots, g_{i,n})$ specifies the links that i forms, where $g_{i,j} = 1$ if i forms a link to j and $g_{i,j} = 0$ if not. Hence, a strategy for player i consists of the combination of her public good investment and links and we denote this by $s_i = (\boldsymbol{g_i}, x_i)$, and i's strategy space is denoted by S_i. The linking decisions of all players jointly define the (directed) network architecture $\boldsymbol{g} = (\boldsymbol{g_1}, \boldsymbol{g_2}, \ldots, \boldsymbol{g_n})$ and $\boldsymbol{x} = (x_1, x_2, \ldots, x_n)$ denotes the vector of investments. A strategy profile is then denoted by $\boldsymbol{s} = (\boldsymbol{x}, \boldsymbol{g})$. The set of all possible strategy profiles is denoted by S.

Forming a link to another player j allows i to access j's investment. Let $N_i(\boldsymbol{g}) = \{j \in N : g_{i,j} = 1\}$ denote the set of players that i links to and $\eta_i(\boldsymbol{g}) = |N_i(\boldsymbol{g})|$ the number of links that i forms. Likewise, we denote the number of links that are formed to i by $\omega_i(\boldsymbol{g}) = |j \in N : g_{j,i} = 1|$. The total investment that i accesses is then given by $y_i = x_i + \sum_{j \in N_i(\boldsymbol{g})} x_j$. The benefits $f(y_i)$ of accessing units are increasing and concave in y_i. Note that the investments of i and of the players she has linked to are perfect substitutes: i values her own investment the same as any investments by any $j \in N_i(\boldsymbol{g})$.

Investing in units of the good comes at a constant marginal cost of $c > 0$ per unit and making a link comes at a cost $k > 0$. Players receive status rents $b \geq 0$ from each incoming link. We take $k > b$, which ensures that making links has a net cost to society. This results in the following payoff function:

$$\Pi_i(\boldsymbol{s}) = f(y_i) - cx_i - k\eta_i(\boldsymbol{g}) + b\omega_i(\boldsymbol{g}).$$

If we assume self-regarding preferences, a strategy profile $\boldsymbol{s^N}$ is a strict Nash equilibrium if for every player $i \in N$ it holds that

$$\Pi_i(s_i^N, s_{-i}^N) > \Pi_i(s_i, s_{-i}^N) \ \forall \ s_i \in S_i,$$

where $\Pi_i(s_i^N, s_{-i}^N)$ is the stage-game payoff of player i given that she chooses s_i^N and the other players choose s_{-i}^N.

In any strict Nash equilibrium, a core-periphery network is formed where the players in the core invest in the public good and players in the periphery do not invest. This is the main result in GG. The proof of this and subsequent results is relegated to Appendix A.[7] In a core-periphery network, any player forms links to all the core players but not to any of the periphery players. In equilibrium, the players in the core jointly invest in $\hat{y}$ units, defined as the optimal public good investment if players were to act in isolation. The maximal number of players that can be sustained in the core (and invest) is independent of group size and status rents. A special case is the *Nash star*. In this outcome, a single player forms the core and invests in $\hat{y}$ units. When we refer to 'stars', we always mean periphery-sponsored stars.

If $c\hat{y} > k$, the Nash star is always a strict Nash equilibrium.[8] The intuition is the following. The marginal benefits of the public good exceed the costs of investing in up to $\hat{y}$ units of the good. This implies that every player wants to access at least $\hat{y}$ units of the good. Suppose there exists some player i that invests in $\hat{y}$ units. When forming a link is strictly less costly than investing in $\hat{y}$ units, i.e. $c\hat{y} > k$, the best response of any other player than i would be to link to i and not invest, hence a star forms where the core invests and all others free-ride and link to the core.[9] Finally, for i, given that no other player is investing, it is optimal to invest in $\hat{y}$ units. There are n such equilibria: one for each player being in the core.

Note that the rents from incoming links play no role in this intuition. This is why the stage-game equilibria are independent of the level of status rents. More formally, given a collection of strategies s_{-i} of all players $j \neq i$, player i will prefer strategy s_i over s_i' if

(1) $\qquad f(y_i) - f(y_i') - c_i(x_i - x_i') - k(\eta_i(\mathbf{g}) - \eta_i(\mathbf{g}')) + b(\omega_i(\mathbf{g}) - \omega_i(\mathbf{g}')) \geq 0.$

As the strategies of all other players are fixed, it must be that $\omega_i(\mathbf{g}) = \omega_i(\mathbf{g}')$ and the final term on the left hand side of (1) cancels. Then, i's decision is independent of the status rents b and the set of Nash equilibria must be independent of b. Moreover, as we show in Appendix

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[7] This, and the following results carry over from GG. As we study a slightly modified game with discrete investments and one-way flow, we provide the proofs in Appendix A for completeness.
[8] As we will describe in section 5, the Nash star is the only type of stage-game Nash equilibrium in our experiments.
[9] From here onward, we only consider this (arguably most interesting) case where $c\hat{y} > k$. If the reverse holds, the unique Nash equilibrium is the empty network (i.e. no links are formed) where all players invest in $\hat{y}$ units.

A, the number of players in the core is independent of group size.

We define social welfare W resulting from a strategy profile **s** as the sum of all individual payoffs, i.e. $W(\mathbf{s}) = \sum_{i \in N} \Pi_i(\mathbf{s})$. A strategy profile **s** is called *efficient* if

$$W(\mathbf{s}) \geq W(\mathbf{s}') \; \forall \; \mathbf{s}' \in S.$$

Based on this definition, the efficient outcome is a star in which the core player invests in (weakly) more units than in the Nash star, while the periphery players do not invest. This is the case because all players – either in the periphery or the core – benefit from additional investments by the core. The efficient investment by the core is denoted by $\tilde{y} \geq \hat{y}$ (see Appendix A). Note that any investment by the core above $\tilde{y}$ units will lead to welfare losses. In our further analysis, we refer to *superstars*. We call an outcome a superstar if it is a star where the core invests in strictly more units than in the Nash star. Note that efficient outcomes are superstars if $\tilde{y} > \hat{y}$.

3.2   Subgame perfect equilibria

The finitely repeated game that we will study hosts a plethora of equilibria. Appendix D provides more details. In Proposition D.1 we show that efficient superstars can be sustained in a subgame perfect repeated game equilibrium. Both with and without status rents, efficient superstars can be sustained by rotating the core position. Such rotation requires tremendous coordination, however, and is unlikely to be observed in laboratory play (e.g. Goeree et al. 2009; Falk and Kosfeld 2012). Considering only subgame perfect equilibria with fixed positions, Proposition D.2 shows that efficient superstars can be sustained in equilibrium only when there are status rents.

Although status rents affect the set of repeated-game equilibria, subgame perfection in itself provides little guidance which equilibrium, if any, to expect. As argued before, we hypothesize that players will compete for attractive network positions. We capture this hypothesis with a simple concept, which we use to derive predictions for the experimental treatments.

3.3   Challenge-freeness

We now introduce the concept of a *challenge-free* outcome. This concept is closely related to the concept of *envy freeness* developed for position auctions (independently developed by Edelman et al. 2007 and Varian 2007). In these auctions, bidders agree on the desirability of distinct positions for their online ads. The *i-th* best position is awarded to the *i-th* highest ranked

bidder at a price equal to the *(i+1)-th* highest bid. The game allows for an extremely large set of equilibria. Edelman et al. (2007) propose the concept of local envy freeness to select the most plausible equilibrium. In this equilibrium, no player can improve her payoff by exchanging bids with the player ranked one position above her. Varian (2007) provides an empirical analysis of Google auctions and finds that local envy freeness describes the basic properties of the ad auctions reasonably well.

In a similar vein, the concept of challenge freeness is motivated by the idea that players compete for attractive positions. Applied to the GG-model, our intuition is that an outcome is stable if players have no desire to challenge the position of the player with the best payoff in the network. In this line of reasoning, large payoff differences with the top-earner lead to instability, because players are tempted to 'challenge' this player's position.

Status rents do not affect the set of stage-game equilibria, but they do affect the payoffs of players in the core. In any strict Nash equilibrium, the core players earn less than the periphery players in the absence of status rents. Introducing status rents increases the payoffs of core players, without affecting those in the periphery. This effect on core payoffs depends on group size. Hence, status rents and group size jointly determine the *relative* payoffs between players in the periphery and the core. The main idea is that if the payoffs of the core are (sufficiently) larger than the payoffs of periphery players, those in the periphery will want to challenge the position of the core player. In this game, they can do so by investing in one more unit than the core. The only way in which the core player can avoid being challenged is by choosing an investment level that makes the extra unit unattractive (compared to a periphery payoff). Thus, only if the core invests an amount that is sufficient to (almost) equalize payoffs, a network can be challenge free.

To discuss what we mean with challenging, we order the players in terms of the stage-game payoffs that they receive in the stage-game strategy profile $\mathbf{s}$, such that $\Pi_1(\mathbf{s}) \geq \Pi_2(\mathbf{s}) \geq \cdots \geq \Pi_{n-1}(\mathbf{s}) \geq \Pi_n(\mathbf{s})$. Call player i the challenger, where $i > 1$. If player i challenges player 1, i chooses her best available strategy $s_i' \in S_i$, assuming that player 1 is committed to her current strategy s_1, and that any player $j > 1, j \neq i$ will best respond to s_i' and $s_{-i,j}$ (where $s_{-i,j}$ denotes the strategy profile in which every player except players i and j choose their strategy as specified by $\mathbf{s}$). If this best response of player j is not unique, i is pessimistic and assigns the worst possible (stage game) payoff to the outcome. In particular, this means that player i can only attract the links of the core player if she invests strictly more than the core player does. We define a challenge-free outcome in the following way.

Definition 1: *A stage-game outcome, induced by a stage-game strategy profile* **s,** *is challenge-free if and only if*

  (i)   *no player wants to challenge the player with the highest payoff (player 1), and*

  (ii)   *player 1 cannot improve her payoff without being challenged.*

Denote the best response by some player j ($j \neq i; j \neq 1$) to s_i' and $s_{-i,j}$ by s_j' and write $\mathbf{s}_j'$ for the vector of best responses of all other players. Hence, given s_1, player i believes that changing to strategy s_i' will lead to the stage-game outcome induced by strategy profile $\mathbf{s}' = (s_1, s_i', \mathbf{s}_j')$. If for all s_i' this will lead to lower (expected) payoffs than in the current stage-game outcome that follows from $\mathbf{s}$, i will not challenge player 1. That is, i will not challenge player 1 if

(2) $$\Pi_i(\mathbf{s}) \geq \Pi_i(\mathbf{s}') \ \forall \ s_i' \in S_i,$$

holds.

Here, we discuss the conditions under which Nash stars and superstars are challenge-free. Consider a star where the core invests in x_c units and all periphery players do not invest. Call this network the x_c-star. Note that there are only two payoff levels in this case: core and periphery. The stage-game payoffs for the core player are given by $\pi_c = f(x_c) - cx_c + (n-1)b$ and the stage-game payoffs for the each periphery player by $\pi_p = f(x_c) - k$.

First consider the case where the core earns more than the periphery in the Nash star, i.e. $(n-1)b \geq c\hat{y} - k$. Star networks where the core earns more than the periphery can only be challenge free if periphery players do not want to challenge the core. A periphery player can challenge the core by investing in more units than the core. In this case, the best response of all other periphery players is to move their links to the challenger. By assumption, this is what the challenging periphery player expects would happen. Hence, a periphery player will not challenge when:

$$f(x_c) - k \geq f(x_c + 1) - (x_c + 1)c + (n-2)b.$$

Rewriting gives:

(3) $$(n-2)b \leq (x_c + 1)c - k - [f(x_c + 1) - f(x_c)].$$

If (3) holds, the core player will not be challenged. Note that the RHS of (3) is strictly increasing in x_c for $x_c \geq \hat{y}$, because by construction $c > f(x_c + 1) - f(x_c)$ for investments larger than or equal to the Nash quantity $\hat{y}$. Denote the lowest value of x_c for which (3) holds by y^*. In the y^*-star the core invests so much that the payoffs are almost equalized and that the periphery lacks an incentive to challenge the core. In Appendix B.1, we show that the y^*-star is the only challenge-free outcome in this situation. A (subgame-perfect) challenge-free equilibrium is a (subgame-perfect) equilibrium of the finitely repeated game that implements a challenge-free outcome in every stage, except in the final stage(s) of the game.

When there are no status rents, or when status rents are low, the core earns less than the periphery in the Nash star. This happens when $(n - 1)b < c\hat{y} - k$. In this case, a Nash star or superstar can only be challenge free if the core does not want to challenge the periphery. We find that this is never the case. Consider the Nash star, i.e. $x_c = \hat{y}$. Core player $i > 1$ can challenge the periphery by lowering her investment, for instance to $x_i = 0$, and linking to one of the periphery players $j > 1$. If she does so, (periphery) player 1 who she challenges will be committed to not investing (and linking to i), but any other periphery player $j > 1$ is expected to best respond by investing in $\hat{y}$ units and forming no links. In this case, i will earn $\Pi(\mathbf{s}') = f(\hat{y}) - k + b$, which is larger than the payoff she earned as the core player. This means that the Nash star cannot be challenge free if the core earns less than the periphery. As the core in a superstar earns less than the core in the Nash star, the same argument applies here. Hence, if status rents are low or absent, Nash stars and superstars are not challenge free. In Appendix B.1, we show that in a class of games that includes the games in our experiment, no challenge–free outcome exists when status rents are sufficiently low. Thus, there is no challenge-free equilibrium in this case.

The concept of challenge freeness can also be applied to our treatments with exogenous networks. In this case, a periphery player cannot successfully challenge the core by investing more than she. Hence, any Nash star is challenge free, even if the core earns substantially more than the periphery.

The way we have defined challenging is specific enough to make clear predictions, but also general enough to be applicable to other settings. In laboratory settings that employ the GG-framework (Goyal et al. 2016; Rong and Houser 2015), the only challenge-free Nash equilibria are Nash stars in the treatments with 'investment limits' by Rong and Houser (2015). These are far more frequently formed than Nash equilibria that are not challenge-free across the two studies. Also in settings with public good provision on fixed networks challenge

freeness organizes the data well. Rosenkranz and Weitzel (2012) find that across several exogenous networks with two-way flow, the most stable Nash equilibrium is a star where the periphery invests and the core free-rides. This is the only challenge-free equilibrium across all (exogenous) networks. Falk and Kosfeld (2012) compare pure network formation with one-way flow and two-way flow and find that Nash networks form much more frequently under one-way flow. This is exactly what challenge-freeness predicts. Finally, the only study that provides mixed support for challenge freeness is Goeree et al. (2009). In line with challenge freeness, star networks with unequal payoffs tend to be unstable in their network formation game. Moreover, in the treatment with a single high-value agent, the periphery-sponsored star where the high value agent is in the core is the unique challenge-free network. In the experiment, most groups converge precisely towards this outcome. Other features of their data, however, do not agree with specific aspects of challenge freeness. Periphery-sponsored stars with homogeneous agents are challenge free, but are rarely observed in the experiment.[10]

Of course, challenge freeness is a static equilibrium concept and says little about the process by which it might be reached, other than that this process involves the threat of challenges. In Appendix B.2, we describe a simple dynamic model of challenges that selects outcomes as being stable if and only if they are challenge free.

4   Experimental design and procedures

In the experiment, subjects play the stage-game described in Section 3 repeatedly for 75 periods. Across treatments, we systematically vary two parameters: group size n and the level of status rents b. Table 1 summarizes this design: we have groups of either 4 or 8 subjects, who play the experimental game either with no ($b = 0$), medium ($b = 22$) or high ($b = 66$) status rents. In addition, we ran two treatments with high status rents where the links are exogenously imposed.

In the treatments with endogenous network formation we implement a partners design: i.e. subjects are randomly assigned to a group and play the experimental game with fixed partners.[11] These partners are identified by letters ranging from A to D or A to H, depending on the group size and the letters refer to the same subject throughout the experiment. The number of periods is announced in the experimental instructions (see Appendix E).

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[10] More details are available upon request.
[11] This corresponds to many cases in the world outside of the laboratory. For example, on many OSS projects, the key contributors remain active over several years (Robles et al., 2005, Crowston et al., 2012).

TABLE 1: OVERVIEW OF TREATMENTS

Treatment variable		Endogenous networks		Exogenous networks	
		Small group size $n = 4$	Large group size $n = 8$	Small group size $n = 4$	Large group size $n = 8$
No status rents	$b = 0$	**n4b0** 8 groups 32 subjects	**n8b0** 6 groups 48 subjects		
Medium status rents	$b = 22$	**n4b0** 8 groups 32 subjects	**n8b22** 6 groups 48 subjects		
Large status rents	$b = 66$	**n4b66** 8 groups 32 subjects	**n8b66** 6 groups 48 subjects	**n4b66EXO** 8 groups 32 subjects	**n8b66EXO** 6 groups 48 subjects

Notes: the first line in a cell lists depicts the treatment acronym (the first part refers to group size and the second to the status rents); the lower lines gives the number of groups and subjects in each treatment.

In every period, all subjects simultaneously decide on whom to link to and how much to invest.[12] On their decision screen, subjects can review all previous decisions in a history box. Once everyone in the session has made a decision, subjects are informed of the resulting outcome and their own payoffs. Examples of key screenshots are provided in Appendix F.

In the treatments with exogenous linking, everything is the same as in the treatments with endogenous linking except that we impose the linking decisions previously observed in the endogenous linking treatments. Hence, in the treatments with exogenous networks, subjects face exactly the same link structures as subjects in the corresponding endogenous network treatments. Subjects are informed of the links they will form in the current period and only decide on their investment in the public good. In the instructions, subjects are informed that they could in no way affect the links by their decisions. Note that subjects do pay for outgoing links and receive rents for incoming links. As with endogenous linking, subjects have access to the history box.

In all treatments, earnings are denoted in 'points'. In addition to a starting capital of 2000 points, subjects may earn points in every period. Total point earnings are exchanged at the end of the experiment at a rate of 0.10 euro for every 30 points. Table 2 gives the benefits function $f(y_i)$ (in points), as well as the costs of linking, k, the costs of investment c and the

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[12] To stay close to the GG-model, we let subjects make both decisions simultaneously. An interesting alternative would be to implement a version of the game where players first decide on contributions and only make their linking decisions after the contribution decisions have been communicated. Our conjecture is that a sequential structure would further facilitate the convergence to challenge-free equilibria.

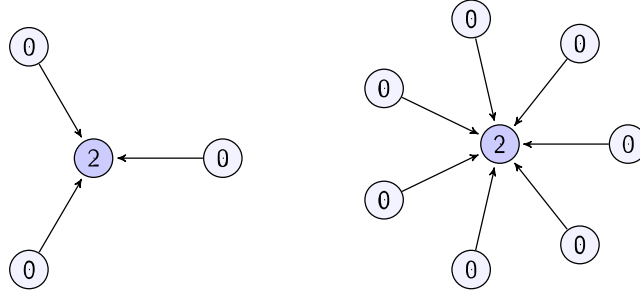TABLE 2: BENEFIT AND COST PARAMETERS IN THE EXPERIMENT

Panel a: benefits from accessing the public good

Units accessed y_i	0	1	2	3	4	5	6	7	$7+\ell$
Benefits $f(y_i)$	0	92	152	177	196	199	202	203	$203+\ell$
Marginal benefits		92	60	25	19	3	3	1	1

Panel b: cost and benefits of investing and linking

	Status rents		
	None	Medium	High
Cost per unit investment c	55	55	55
Cost per link made k	70	70	70
Benefit per link received b	0	22	66

status rents b. As specified in Section 3, the function $f(y_i)$ is increasing and concave in y_i, and $k > b$.

Sessions were run between May and July 2014 in the CREED laboratory of the University of Amsterdam and lasted about two hours. For each treatment with $n = 4$, we had a total of 8 groups while we had 6 groups for each treatment with $n = 8$. In total, 320 subjects participated in the experiment, each in only one session. We conducted 15 sessions where, depending on show-up, the number of subjects per session varied between 12 and 32, but in most sessions 24 subjects participated. We randomized treatments within a session: in each session with endogenous network formation at least two different treatments were conducted. Each subject participated in one treatment only. Subjects were recruited from the local CREED database, which consists mostly of undergraduate students from various fields. Of the subjects in our experiments, 49% are female and 61% were studying at the Amsterdam School of Economics or the Amsterdam Business School. Cash earnings were between 5.10 euro and 125.10 euro, with a mean of 30.63 euro.

The experiment was computerized using PHP/MySQL and was conducted in English. Upon entering the laboratory, subjects were randomly allocated to a separate cubicle. Communication was prohibited throughout the session. Before starting the network experiment, we elicited risk preferences using a procedure similar to Gneezy and Potters (1997). In this procedure, each subject decided how much to invest of a capital of 600 points. The amount invested was lost or multiplied by 2.5 with equal probability. The result of the investment was then added to the amount not invested. Subjects were only informed of the outcome of this part at the very end of the experiment.

Notes: Nash star networks with n=4 and n=8 players

After this, subjects read the instructions of the network game at their own pace, on-screen. While reading the instructions, a printed summary was handed out. To ensure that all subjects understood the instructions, they were required to answer several test questions (cf. Appendix E). The experiment did not continue before everyone had answered all questions correctly.

We ended each session with a short questionnaire after which we privately informed subjects of the outcome of the risk elicitation task and their aggregate earnings in the experiment. Subjects were privately paid in cash for all periods of the network game and the risk-elicitation task.

5   Predictions for the experiment

In all experimental treatments with endogenous linking, the Nash equilibria of the stage game are the same. As argued in subsection 3.1, the set of stage-game Nash equilibria is independent of our treatment variables; status rents and group size (how the set of subgame perfect equilibria in the repeated game is affected is discussed in Appendix D). Figure 1 illustrates these equilibria for the parameters of the experiment. In the figure, circles represent the players and the numbers inside these circles display their investment. A link is represented by an arrow, which points away from the player who makes it. Hence, we see a *Nash star*, where the core player invests in $\hat{y} = 2$ units and the other players form links to the core and do not invest. Furthermore, the efficient outcome is also the same across treatments: in all cases it is a superstar where the core invests in $\tilde{y} = 4$ units. As noted before, status rents and group size do not affect the set of stage-game equilibria, but they do affect the payoffs of players in the core.[13]

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[13] In Appendix C, we provide a table with the payoffs in different star networks for our parameters.

TABLE 3: BEHAVIORAL PREDICTIONS

	Endogenous networks						Exogenous networks	
	$b = 0$		$b = 22$		$b = 66$		$b = 66$	
	$n = 4$	$n = 8$	$n = 4$	$n = 8$	$n = 4$	$n = 8$	$n = 4$	$n = 8$
y^*	2	2	2	4	4	8	2	2
Prediction	instability	instability	2-star	4-star	4-star	8-star	2-star	2-star

Notes. Columns distinguish between our eight treatments. y^* is defined using eq. (3). The prediction is the outcome selected by the challenge-free refinement. When stable stars are predicted, they also constitute a subgame perfect equilibrium for the game concerned (cf. Appendix D).

These payoff differences determine whether stars are challenge-free, and therefore provide a prediction for the investment by the core player.

Table 3 summarizes the predictions based on challenge-free outcomes (cf. Appendix B.1). To start, recall that without status rents the core earns less than the periphery and will prefer to lower her investment to zero, expecting that some other player will invest the Nash amount of 2 units. As we show in Appendix B.1, no network is challenge-free for these treatments. Therefore, we do not expect that stable networks will form in the absence of status rents (this is confirmed by the dynamic model presented in Appendix B.2).

This changes when status rents are introduced. In this case, challenge freeness selects a y^*-star. In a dynamic setting, competition for the attractive core position pushes up the investments by the core such that payoffs are almost equalized. In n4b22, we expect stable Nash stars to form. With higher status rents or larger groups, we expect competition for the core position. More specifically, in treatments n8b22 and n4b66 we expect that competition leads to the formation of efficient superstars where the core invests in four units.[14] In n8b66, we expect that competition for the core position will be so intense that it encourages severe overinvestment by the core. Here, we expect the emergence of star networks where the core invests in eight units.

6   Results

We have organized the presentation of the experimental results as follows. In Section 6.1, we start with an overview of the outcomes that are observed in our treatments with endogenous network formation. We complement this overview with a discussion of cross-treatment

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[14] For our experiment, we deliberately chose the values of n and b such that we keep $(n - 2)b$ -and thus y^*- constant between treatments n8b22 and n4b66.

FIGURE 2: DEVELOPMENT OF STAR NETWORKS
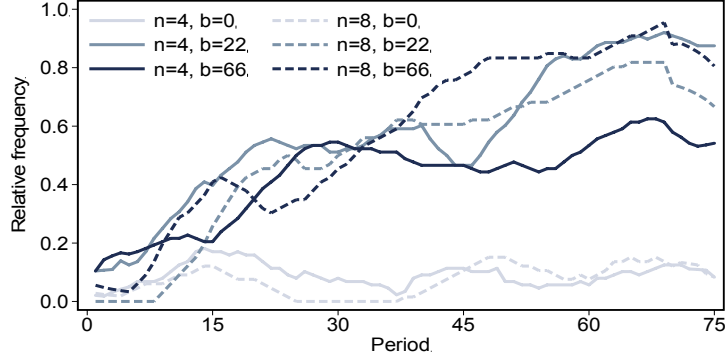
Notes: Lines show the relative frequencies of periphery-sponsored stars by treatment and period. Lines are smoothed by taking the moving average over periods $t-3$ to $t+3$ for every period t.

differences in the provision of the public good. Then we provide an overview of the efficiency levels that follow from the networks formed. In Section 6.2, we study the behavioral dynamics in the experiment and compare the outcome to our theoretical predictions. We address the question of which treatments trigger a competition for status, and we present an analysis of the frequency and stability of the outcomes that we observe. Finally, in Section 6.3 we present the results of our exogenous network treatments, which allow us to shed light on the motives underlying our results. Unless stated otherwise, all tests reported are Mann-Whitney tests (henceforth, MW). Throughout, we use two-sided tests using average statistics per group as units of observation.

6.1 Overview: star networks and public good provision

Figure 2 plots the relative frequency of stars over time. At the start of the experiment, we hardly observe any stars in any treatment. Starting around period 10, a clear distinction emerges between the two treatments without status rents and those with. With status rents, the frequency of stars steadily increases over time. In the last 25 periods of these treatments, this frequency rises to 76%. In treatment n8b66 stars are even observed in 88% of the last 10 periods. In stark contrast, there is no clear trend in the occurrence of stars in the treatments without status rents. There, such networks remain rare throughout the experiment.

Table 4 makes these results more precise and tests whether the observed differences are significant. The table confirms the picture emerging from Figure 2. Stars form substantially and systematically more often in the treatments with status rents than in the treatments without. Within these classes of treatments, differences are much smaller and mostly insignificant.

| Status rents | Group size | Relative frequency of periphery-sponsored stars | | p-values pairwise MW tests | | | | | |
| | | | | $b = 0$ | | $b = 22$ | | $b = 66$ | |
		All periods	Final 25 periods	$n = 4$	$n = 8$	$n = 4$	$n = 8$	$n = 4$	$n = 8$
$b = 0$	$n = 4$	0.09	0.09	-					
	$n = 8$	0.07	0.11	0.15	-				
$b = 22$	$n = 4$	0.58	0.86	0.00	0.00	-			
	$n = 8$	0.50	0.73	0.04	0.02	1.00	-		
$b = 66$	$n = 4$	0.43	0.53	0.09	0.09	0.32	0.61	-	
	$n = 8$	0.58	0.86	0.00	0.01	0.52	0.87	0.56	-

Notes: the left panel provides the relative frequencies of periphery-sponsored stars in all periods and in the final 25 periods. The right panel provides the results of MW tests for the differences in occurrence between treatments using the observations in all periods. In Appendix C we provide a table with the *p*-values for differences in the final 25 periods.

| Status rents | Group size | Investment in public good (all periods) | | | p-values pairwise MW tests | | | | | |
| | | | | | $b = 0$ | | $b = 22$ | | $b = 66$ | |
		Predicted	Mean (s.e.)	Median	$n = 4$	$n = 8$	$n = 4$	$n = 8$	$n = 4$	$n = 8$
$b = 0$	$n = 4$	-	1.83 (0.11)	2	-					
	$n = 8$	-	1.82 (0.09)	2	0.92	-				
$b = 22$	$n = 4$	2	2.22 (0.06)	2	0.01	0.02	-			
	$n = 8$	4	3.49 (0.33)	4	0.01	0.03	0.03	-		
$b = 66$	$n = 4$	4	3.61 (0.18)	3.5	0.00	0.02	0.00	0.75	-	
	$n = 8$	8	7.07 (0.45)	7.5	0.00	0.02	0.00	0.00	0.00	-

Notes: The left panel lists the predicted, mean and median investment in the public good by core players, conditional on a periphery-sponsored star being formed. The predicted investment is equal to y^*, except in the treatments without status rents, where no stable star is predicted. Standard errors of the mean are presented in parentheses, based on mean investments per group. The median is obtained by taking the median within each group first and then the median of these numbers per treatment. The right panel presents *p*-values for tests whether mean core investments differ between treatments, conditional on a periphery-sponsored star having formed.

Status rents and group size also have profound effects on the provision of the public good. To compare investment choices while holding network composition constant, we focus on the investment of core players in periods where stars were formed. The results are presented in Table 5. This table shows that, conditional on a star being formed, public good provision is inefficiently low (that is, below four units) in the treatments without rents and the treatment with medium rents and small group size. In treatments n4b66 and n8b22 public good provision is close to the efficient level of four units. In treatment n8b66 the core player vastly overinvests

TABLE 6: EFFICIENCY

| Status rents	Group size	Efficient stars	Mean earnings	Mean net earnings	$b=0$		$b=22$		$b=66$	
			Efficiency measure		p-values pairwise MW tests for net earnings					
					$n=4$	$n=8$	$n=4$	$n=8$	$n=4$	$n=8$
$b=0$	$n=4$	0.00	33.4 (3.0)	33.4 (3.0)	-					
	$n=8$	0.00	38.9 (1.9)	38.9 (1.9)	0.12	-				
$b=22$	$n=4$	0.01	75.9 (2.0)	60.9 (2.0)	0.00	0.00	-			
	$n=8$	0.36	99.9 (4.2)	81.6 (3.9)	0.00	0.00	0.00	-		
$b=66$	$n=4$	0.29	106.1 (6.4)	59.7 (6.6)	0.01	0.03	0.92	0.05	-	
	$n=8$	0.00	124.6 (7.4)	67.9 (6.5)	0.00	0.01	0.16	0.08	0.30	-

Notes: The first column gives the relative frequency of efficient outcomes. The efficient outcome is a periphery-sponsored star where the core invests in four units and no periphery player invests. Mean earnings are denoted per subject in points per period. For mean net earnings we subtract the status rents. Standard errors of the means are computed using each group as an individual observation. The panels on the right give *p*-values for tests whether mean net earnings differ between treatments.

with an average contribution level that is close to double the efficient amount. With status rents, any increase in group size or status rents leads to higher investment by core players. The sizable differences between treatments are all significant, except for the comparisons between n4b0 and n8b0 and between n8b22 and n4b66. By and large, the average and median investment levels accord very well with the predictions based on challenge freeness.

Investments in the public good are one of the factors that affect efficiency in this environment. The other is the links made to access the public good. We now consider both factors simultaneously by looking at treatment differences in observed efficiency. Table 6 shows the relative frequency of efficient star networks (where the core invests in 4 units), mean earnings and mean earnings net of status rents per treatment.

Efficient star networks are almost exclusively observed in n8b22 and n4b66. As noted before (cf. Table 4), stars rarely form at all without status rents. In n4b22, stars are formed but investments by the core are typically lower than the social optimum (cf. Table 5). In n8b66, we also frequently observe stars but here the core vastly overcontributes. As for earnings, as expected, these increase as status rents rise. We correct for this effect of adding money to the system by deducting the status rents from the earnings. This yields a clear difference between the treatments with and without status rents. The treatments without status rents perform particularly badly in terms of (net) earnings. Here subjects do not benefit from interacting with others and actually do worse than if they had completely refrained from making links and

FIGURE 3: PROPORTION OF GROUPS CONVERGING AND END-POINT OF THE DYNAMICS
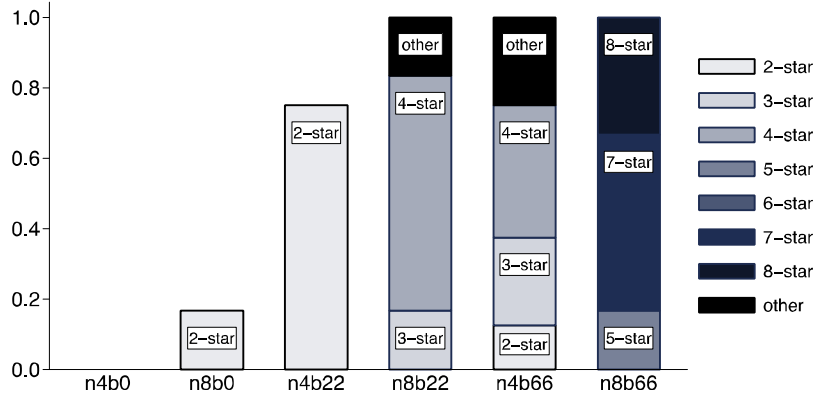
Notes: A group converges to a network if all players repeat decisions at least 5 times. Most groups converge to 'x-star' outcomes, periphery-sponsored stars in which the core player invests in x units of the public good. Most groups converge only once: only 4 of the 42 groups converged to two or more different networks. In these cases, we include the last stable network.

simply investing in two units themselves.[15] This mirrors previous experimental results reported in the literature on endogenous network formation without status rents (e.g., Falk and Kosfeld, 2012). Net earnings are much higher when there are status rents. In pairwise comparisons, either of the treatments without status rents reaches significantly lower net earnings than any of the treatments with status rents (all $p<0.05$). Net earnings are the highest in treatment n8b22. This is also the treatment where we observe efficient 4-stars the most frequently. Net earnings are higher in this treatment than in all other treatments ($p<0.10$ for all pairwise comparisons).

Next, we turn to the convergence of our data across periods. Figure 3 displays for each treatment the proportion of groups that converge to a stable outcome. If a group converges, it is almost always to a star network.[16]

Without status rents groups almost never converge to any stable outcome, independent of group size. Moreover, we do not observe any successful rotation of the core position in our experiments. The behavior that is frequently observed is closer to what would be expected in a mixed strategy equilibrium. Subjects switch frequently between not investing and forming a single link, or not linking and investing in 2 units. This is in line with the symmetric mixed strategy equilibrium. In this equilibrium, players randomize between exactly these two

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[15] In this case, a player earns 42 points.
[16] In treatment n4b66 two groups converged to networks where multiple players invest. In treatment n8b22, one group converged to a situation where 6 out of 8 players formed a periphery-sponsored star, where the core invested in 3 units and the periphery did not invest. Between the other two players, one player invested and the other did not and the latter formed a link to the former.

possibilities: (i) invest in 2 units and form no links with probability $p = \frac{14}{19} \approx 0.737$ and (ii) do not invest and form a single link with probability $1 - p = \frac{5}{19}$.[17] In the latter case, a player selects randomly any of the others to link to, each with the same probability. Inconsistent with the mixed equilibrium is that our subjects mix with a probability closer to 50% than the equilibrium suggests. In n4b0, subjects invest in 2 units and form links in 42.8% of the cases, and form a single link and do not invest in 42.2% of the cases. In n8b0, this is 31.6% and 54.6% respectively.

When there are status rents, group size and status rents have a beneficial effect on the provision of the public good. With medium status rents and small groups, groups usually converge to a star network in which the core player consistently invests the stage game Nash amount of two units.[18] When group size is doubled in treatment n8b22, all groups converge to a stable network. The most frequently observed end-point of the dynamics is a superstar in which the core player invests the efficient amount of four units. Similarly, with high status rents, investments are higher in large groups than in small groups. In fact, in this case all large groups converge to a star network in which the core player overinvests in the public good. In this treatment, the large majority of groups converge to superstar networks in which the core invests in seven or eight units, which is on average almost double the efficient investment of four units.

These results agree well with the predictions based on challenge freeness. In accordance with challenge freeness, stable Nash stars (where the core invests in two units) should only be observed in treatment n4b22 and the occurrence of large overinvestments should be limited to treatment n8b66 (cf. Table 3). Of particular interest is the comparison of treatments n4b66 and n8b22. These treatments allow us to investigate whether the earnings for the player in the core relative to the players in the periphery is essential for the results. Only when the core earns more, challenge freeness predicts that there will be competition for this position. According to challenge freeness, a periphery player has the same incentive to challenge the core in either of these two treatments; challenge freeness assumes that with a slightly higher investment than the core player a challenger will attract $n - 2$ links. In either treatment this yields a total benefit of 132 points (2x66=132; 6x22=132). In agreement with the model, the data of these two treatments are quite similar. We observe slightly more superstars in n8b22, but the difference
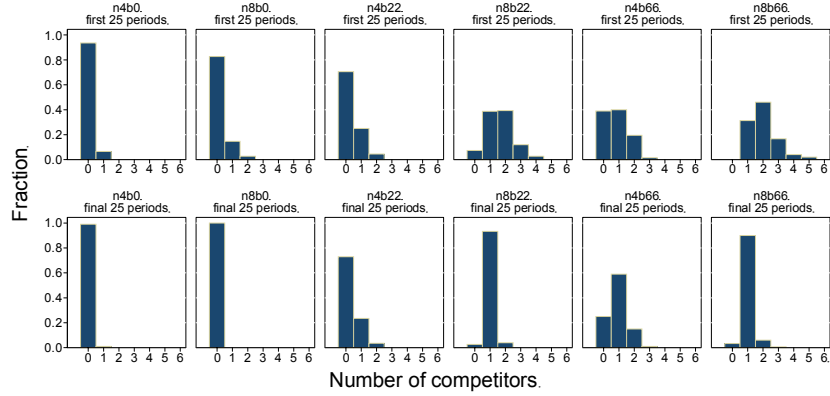
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[17] Details are available upon request.
[18] In this treatment (n4b22), the only two groups that are not classified as stable, also formed periphery-sponsored stars with a fixed core for a substantial number of periods where the core alternated between investing two and three units.

Notes: *For each treatment, the distribution of the number of players investing in more than two units is displayed, both for the first 25 periods (top row) and for the final 25 periods (bottom row).*

is not significant (p=0.60). This result allows us to better understand the group size effect noted above. It does not matter for our subjects whether a rise in status rents is created by an increase in linkers or by an increase in rents per linker. In agreement with challenge freeness, they compete for the core position to the same extent in both cases.

6.2 Behavioral dynamics in the experiment

The key element of challenge freeness is that players compete for the core position if status rents make it more attractive than a periphery position. Without such rents, players prefer that others fulfill the costly job of providing the public good to the group. Indeed, our data show that subjects (only) challenge the core position in the treatments where we expect them to do so. Here, we focus on the competition (typically between a core player and one or more challengers) that these challenges lead to.

Figure 4 shows how the distribution of competitors for the core position develops over time in our treatments with endogenous network formation. Without status rents, there are basically no subjects who consistently invest in more than two units of the good. In treatment n4b22 the core position in a Nash star is slightly more attractive than a periphery position, but not enough to support a superstar where the core consistently invests in three units or more. In agreement with this observation, we see few investments above two units and very rarely observe that multiple players invest at the same time. Clearer competition is observed in treatments n4b66 and n8b22 where the efficient superstar is predicted to emerge. In the first 25 periods, we frequently observe multiple players who invest in more than two units and compete
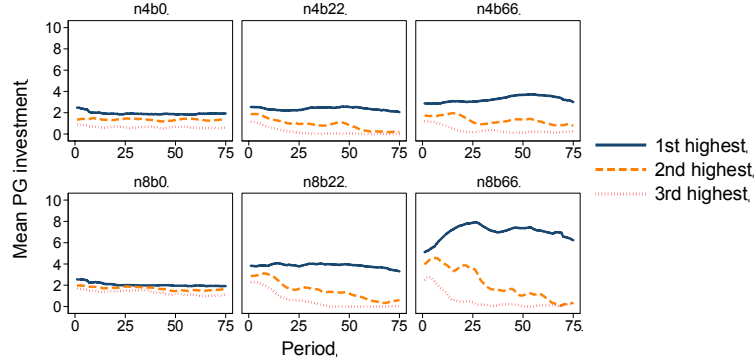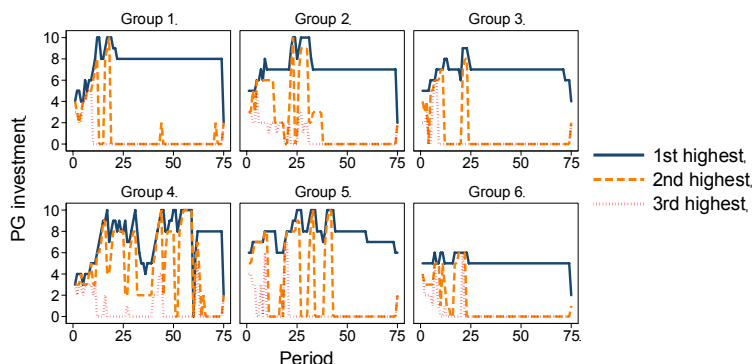
Notes: For each treatment the average investments are displayed as a function of time. The top (middle/bottom) line presents the average highest (second/third highest) investment level in the group. Lines are smoothed by taking the moving average over periods $t - 3$ to $t + 3$ for every period t.

for the core position (in 54% and 21% of the observations in n8b22 and n4b66 respectively). In the final 25 periods, the dust settles and typically only one overinvesting player remains. Very fierce competition is observed in our treatment n8b66. In the first 25 periods, we observe up to five players who simultaneously invest in more than two units. In all cases at least one player overinvests and in the majority of observations multiple players compete for the core position. The competition diminishes towards the end, and in the final 25 periods a single surviving player manages to deter the competition and is no longer challenged.

More details on how subjects compete are offered in Figure 5, which shows the top three investment levels per group over time. In the treatments without status rents, there are usually two or three subjects investing two units. This illustrates that in these treatments subjects are not able to coordinate on a fixed star network. The picture is different in treatment n4b22, where after some time on average only one subject consistently invests two units and a stable star network is formed. In treatments n4b66 and n8b22 we observe higher investments by the top contributor than in n4b22: the subject in the core learns that an efficient level of four units is needed to prevent being challenged by periphery players. Once it has become clear who is the superstar in a group, the investments by the other group members gradually fade out.[19]

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[19] In a regression, we find a negative correlation between risk aversion and being in the core of a star in treatments where we expect competition (i.e. when networks are formed endogenously and $b > 0$). We find no significant correlation between risk aversion and core positions in the other treatments. Moreover, we do not find any relation between gender and network positions. Similar results are obtained when we use public good investments as the dependent variable. More details are available upon request.

FIGURE 6: RANKED INVESTMENTS IN N8B66

Notes: For each group in treatment n8b66 the top-3 highest investments in the group are displayed over time. The top (middle/bottom) line presents the average highest (second/third highest) investment level in the group.

The most interesting dynamics are observed in treatment n8b66. At the start of the experiment, the mean investments for the second highest contributor are almost as sizable as for the top contributor: on average they invest in 4.00 units in the first 25 periods. Only after a while does this challenger start to give up. To further investigate what is going on in this treatment, Figure 6 provides a more detailed view. Here, we show the top-3 investments across periods in each of the six groups in n8b66.[20] In all groups, we see that in early periods at least two players compete for the core position by investing in very high amounts. At some point all but one player give in and a superstar forms with a core player who (over)invests in 7 or 8 units. At these levels, payoffs are to a large extent equalized and periphery players stop challenging the core player.

To investigate the stability of the networks formed, Table 7 shows the frequency of various stars and how often they were repeated, after having been formed. The outcomes predicted based on challenge freeness are listed in bold. In agreement with this concept, star networks occur only sporadically in the treatments without status rents, and if they occur, they tend to be unstable. In n4b22, the predicted 2-star is the most frequently observed and also most stable outcome. In treatments n4b66 and n8b22, the efficient 4-star is predicted to occur, and indeed it is most often observed in both treatments. In these treatments the efficient star is very stable. If it is formed, it remains unchanged in 90% of the cases. Finally in n8b66 a star network is predicted in which the superstar invests in 8 units. Here, in the experiment most often superstars are observed where the core invests in 7 or 8 units, and these outcomes are

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[20] A similar figure of the other treatments is available upon request.

TABLE 7: FREQUENCY OF PERIPHERY-SPONSORED STARS AND THEIR STABILITY

|	$b = 0$		$b = 22$		$b = 66$	
	$n = 4$	$n = 8$	$n = 4$	$n = 8$	$n = 4$	$n = 8$
0-star	5 (0.00)	3 (0.00)				
1-star	6 (0.00)	2 (0.00)	2 (0.00)			
2-star	43 (0.21)	28 (0.52)	**268 (0.66)**	1 (0.00)	9 (0.56)	
3-star	1 (0.00)		67 (0.25)	67 (0.82)	59 (0.68)	
4-star			8 (0.38)	**151 (0.85)**	**172 (0.94)**	
5-star				7 (0.00)	15 (0.60)	47 (0.81)
6-star				1 (0.00)		9 (0.33)
7-star					1 (0.00)	108 (0.92)
8-star						**91 (0.85)**
9-star						2 (0.50)
10-star						2 (0.00)
Other networks	545 (0.03)	417 (0.00)	255 (0.21)	223 (0.21)	344 (0.38)	191 (0.01)
Groups	8	6	8	6	8	6
Observations	600	450	600	450	600	450

Notes: Cells denote the frequency of the outcomes denoted in the first column across all periods. The proportion of periods that exactly the same strategy profile is played in the subsequent period is given in parentheses. Entries in bold denote the outcomes that are challenge free.

again remarkably stable. In 88% of the cases in which such a superstar is formed, it is exactly repeated in the next period.

Finally, we investigate what happens if a core player in a y^*-star deviates by lowering her investment. As already noted, y^*-stars are very stable: core players rarely lower their investments: of the 319 y^*-stars that are formed up to period 65, only 12 core players deviate by lowering their investment.[21] This strongly suggest that subjects anticipate that lowering their investment is costly, as they could be challenged and lose the attractive core position. Given the small number of core players who deviate, it is hard to make strong claims about the resulting payoffs, but still we illustrate what subjects might expect in Figure 7. Here we plot the normalized earnings of core players in y^*-stars and we split them by whether they lower their investment (at period $t = 0$) or not. As expected, the core players who lower their investment earn a higher immediate payoff (at period $t = 0$), but on average pay the price in subsequent periods. These losses outweigh the short-term gains: the aggregated (normalized) losses in periods $t = 1$ to $t = 10$ are roughly 7 times the size of the normalized gains at $t = 0$.

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[21] We focus on treatments where $y^* > \hat{y}$, to ensure that core-players can deviate by lowering their investment.

FIGURE 7: PAYOFFS FROM LOWERING INVESTMENTS AS A CORE PLAYER
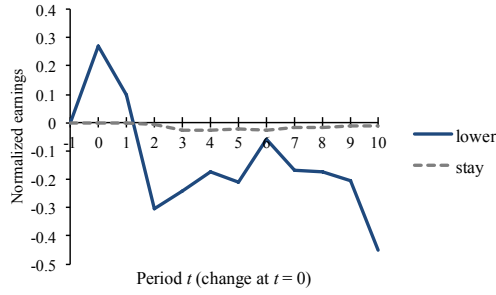
Notes: Mean payoffs of core players in y^*-stars. Earnings are normalized by normalizing the payoff in y^*-star that is formed at $t = -1$ to 0. The figure is based on y^*-stars where $y^* > \hat{y}$, to ensure that core-players can deviate by lowering their investment.

This result is reminiscent of findings in the Industrial Organization literature on contestable markets. Theoretically and experimentally, it has been shown that monopolistic incumbents can successfully be disciplined to price competitively by the threat of hit-and-run entry by potential rivals. Baumol et al. (1977) and Panzar and Willig (1977) developed the theoretical argument that an incumbent monopolist satisfies demand in such a way that it remains unprofitable for a potential rival to enter the market. Coursey et al. (1984) provide experimental support for the contestable market hypothesis in the absence of sunk costs. This disciplining effect of potential entrants survives when the entrant has to forego a sure positive profit in an alternate market (Brown-Kruse 1991) and an increasing number of potential entrants yields a downward pressure on the monopolist's price (Harrison and McKee 1985). In a more recent empirical contribution, Claessens and Laeven (2004) find that banking systems with fewer entry restrictions are more competitive.

6.3   Motives underlying investments in the public good

The evidence presented so far is consistent with the explanation based on a competition for status rents. Once the core position becomes more attractive than the periphery position because of the status rents that it generates, subjects start to challenge it. To prevent being challenged, star players are forced to invest to such an extent that the payoffs across positions are approximately equalized. In this way, status rents are dissipated. However, we cannot exclude that the results are driven by social preferences that do not depend on the possibility to challenge. For instance, subjects may be inequity averse, and therefore choose higher investments to compensate others for the gains that status rents bring. Inequity aversion may also explain why subjects prefer to avoid the core position if it is relatively unattractive in the

TABLE 8: MEAN CORE-INVESTMENTS IN EXOGENOUS AND ENDOGENOUS NETWORKS

|	Exogenous networks			Endogenous networks			
	Predicted	Mean (s.e.)	Median	Predicted	Mean (s.e.)	Median	p-value
$n = 4$	2	2.00 (0.05)	2	4	3.61 (0.18)	3.5	0.028
$n = 8$	2	2.85 (0.41)	2	8	7.07 (0.45)	7.5	0.028

Notes: The table lists the predicted, mean and median investments by core players in the public good, conditional on a periphery-sponsored star being formed. Standard errors of the mean are presented in parentheses, based on taking the mean of the mean investments per group. The median is obtained by taking the median within each group first and then the median within each treatment. The p-values come from 2-sided Wilcoxon signed-ranks tests, where we test the null-hypothesis that investments by the core are the same across treatments, conditional on a periphery-sponsored star having formed. Each pair of endogenous and exogenous groups constitutes one individual observation.

absence of status rents. Another possibility is that core players feel that they have to return the favor if they receive status rents, or that they are simply driven by altruism and prefer to give something to others as their wealth increases. To investigate the extent to which the possibility of competition for favorable positions is essential, we included the two treatments in which we impose the networks that were naturally formed in the corresponding treatments with endogenous network formation. If challenging of favorable positions drives the results, we should not observe higher investments in these control treatments than the individually rational number of two units.

Table 8 displays the mean, median and predicted public good investments by core players in star networks in the exogenous treatments, together with the benchmarks provided by the endogenous treatments. The results provide convincing support for the concept of challenge freeness. The results are particularly strong for the case where group size is small and status rents are large; here, the mean and the median are exactly at two units as predicted. Even more so, there are almost no cases where the core player invests in more than two units of the public good. But also in the case with large group size and large status rents, the results are striking: average investment is only a fraction of the level that is achieved when networks are endogenously formed. The differences between the investments in the endogenous and exogenous network treatments are significant at the 5% level.

Figure 8 shows the distribution of investment choices by core players for each of the treatments with $b = 66$, both for endogenous and exogenous networks. It is clear that with exogenous networks, core players invest substantially less than with endogenous networks. In both n4b66EXO and n8b66EXO, in periphery-sponsored stars the modal core investment is the stage-game Nash amount is two units, while we hardly ever observe such low investments with endogenous networks. An alternative explanation would be that endogenous network

FIGURE 8: DISTRIBUTION OF CORE-INVESTMENTS IN ENDOGENOUS AND EXOGENOUS NETWORKS
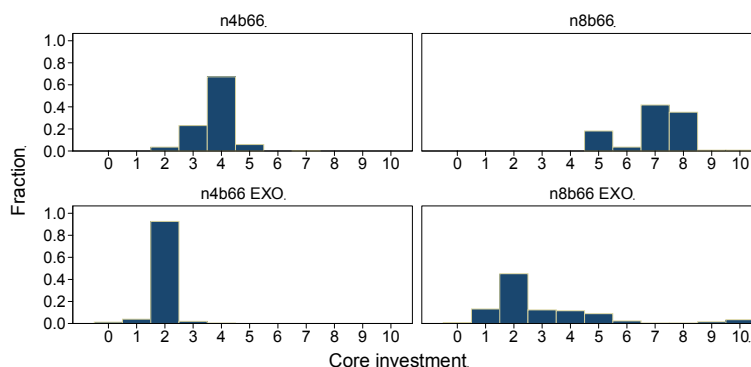
Notes: The figure shows the distributions of investment of core players in treatments with $b = 66$, conditional on a periphery-sponsored star having formed. All period/group observations are included.

formation allows selection of socially motivated types to the core position. Our data provide little support for this selection effect of competition. If it were to hold, one would expect to see these supergame effects in at least 1 out of n exogenous groups. Indeed, in n8b66EXO, we observe some cases where core players invest in more than two units, but these only account for a small number of cases. Moreover, even in these groups investments remain well below the level of 7 or 8 units that we frequently observe in the endogenous network treatments. Hence, such traces of social motives are negligible compared to the competition effect of endogenizing network formation.

Notice that this evidence underlines the importance of the possibility to compete endogenously for favorable positions. It does not preclude the existence of more complicated social preferences that depend on how the network is shaped. In the presence of status rents, for instance, players might feel the necessity to reciprocate when they benefit from the intentional creation of a valuable link, while such a motive is absent when the network is exogenous.[22] Though we cannot exclude such complex motivations, we favor the parsimonious explanation that selfish players compete for favorable positions and that the advantaged player behaves in a way to avoid being challenged by others.

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[22] In a similar vein, in the absence of status rents core player might resent free riders who could themselves take up the role of the core, but not those who are exogenously given a position in the periphery.

7   Conclusion

We have investigated the effects of status rents on the shape and stability of networks and on the level of public good provision. For this, we introduced status rents for incoming links to the endogenous network formation game of Galeotti and Goyal (2010). Our conjecture was that players would jockey to obtain attractive network positions by challenging the position of those with the highest payoffs. In the presence of status rents, this implies that players would compete for status and the winner of the competition for status would be forced to take the interests of the other group members into account. The simple concept of challenge-freeness predicts when a subgame perfect equilibrium outcome is to be expected, and if so, which equilibrium is selected. We subsequently tested these predictions in a laboratory experiment, where we varied group size and status rents across treatments. These are two factors that should systematically affect the equilibrium that is selected if people compete for status rents. Thereby, these factors determine the extent to which the public good is provided and the shape and stability of the outcome.

We find that the presence of status rents is crucial for the results. With status rents, subjects start by jockeying for the core position. Once the dust has settled and subjects have implicitly agreed on who will be in the core of the network, a stable outcome arises in which the core player consistently contributes an amount that roughly equalizes payoffs across positions. This ensures that her position cannot successfully be challenged. For specific environments, this entails contributing more than the stage-game Nash quantity and in some even more than what is efficient. In this way, the core player in a superstar prevents being challenged by the others, and periphery players maintain their links, which the superstar-core needs for her exemplary behavior. As a consequence, status rents are dissipated. Across treatments, we observe that these supergame effects – i.e., the adjustment of contributions aimed at maintaining the network (core) position – increase with the size of the status rents and with group size. In stark contrast, inefficiency reigns and groups rarely converge to equilibria when there are no status rents. These experimental results correspond closely to the concept of challenge-freeness and the selection of a subgame perfect equilibrium (if any) that it entails.

With the help of our two control treatments in which we imposed exogenous networks, we excluded the possibility that supergame effects might arise without competition for status rents. In agreement with our conjecture, the observed supergame effects largely disappear when the possibility to compete for the core position is excluded by design. Instead, if our core

players in superstars had been driven by other motivations, like altruism or inequity aversion, results should have been independent of how the positions in the network are assigned.

We therefore conclude that free competition for a favorable position is the key ingredient for the emergence of superstars in our environment. Beyond the specific setting of our experiment, this may help explain why so often a small minority in a group contributes so heavily to a public good. There is no need to assume that pure altruism or other pro-social motivations drive this behavior. Even purely self-interested individuals may do so if they care enough about the status rents that are closely linked to being at the core of the group in this way. In short, volunteers at sports teams, workshop organizers and OSS developers all contribute much more to their group than can be expected in a one-shot environment because the supergame they are involved in allows them to collect status rents from the central position that they have.

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Appendix A: Stage-game equilibria and efficient outcomes

This appendix is greatly indebted to the analysis in Galeotti and Goyal (2010). In agreement with the theoretical literature on network formation, we will restrict our attention to pure-strategy equilibria.

Some additional notation

Most of the notation is introduced in section 3 of the main text, but for the proofs we will use the following additional definitions. The marginal benefit of accessing the mth unit of the good is given by $MB(m) = f(m) - f(m-1)$.

A network is a *core-periphery network* if there are two sets of players $\widehat{N}_C$ and $\widehat{N}_P$ for which it holds that $N_i(\mathbf{g}) = \widehat{N}_C \setminus \{i\}, \forall\, i \in \widehat{N}_C$ and $N_j(\mathbf{g}) = \widehat{N}_C, \forall\, j \in \widehat{N}_P$. In such a network, the players in $\widehat{N}_C$ form the core and $\widehat{N}_P$ form the periphery. All core players form links to the other core players, but not to the periphery players and any periphery player links to all the core players but to none of the other periphery players. A core-periphery network with a single player in the core is called a *star network*.

Nash equilibria of the stage game

We start by stating our variant of Lemma 1 in Galeotti and Goyal (2010):

Lemma A.1 *In any Nash equilibrium* $\mathbf{s}^N$, *all players* $i \in N$ *access at least* $\hat{y}$ *units of the good,* $y_i^N \geq \hat{y}$, *and all players who acquire units personally will access exactly* $\hat{y}$ *units of the good, i.e. if* $x_i^N > 0$ *then* $y_i^N = \hat{y}$.

Proof. Suppose that a player $i \in N$ accesses fewer than $\hat{y}$ units of the good, i.e. $y_i < \hat{y}$. If this is the case i can strictly increase her payoff by investing as the marginal benefits strictly exceed the marginal costs for $\leq \hat{y}$, i.e. $MB(m) > c, \forall\, m \leq \hat{y}$. If a player i invests in units personally, i.e. $x_i > 0$, and she accesses more than $\hat{y}$ units of the good, $y_i > \hat{y}$, she can strictly increase her payoff by lowering x_i as $MB(m) < c, \forall\, m > \hat{y}$.

Next, we can state our version of Galeotti and Goyal's Proposition 2.

Proposition A.1 *In any strict Nash equilibrium* $\mathbf{s}^N$, *(i) a core-periphery network is formed where (ii) the core players all invest, (iii) the periphery players do not invest, (iv) aggregate*

investment equals $\hat{y}$ units and (v) the maximum number of players in the core is independent of n and b and is given by the largest integer smaller than $\frac{c\hat{y}}{k}$.

Proof. We start by showing that in every strict Nash equilibrium $\mathbf{s}^N$, $\sum_{i \in N} x_i^N = \hat{y}$ should hold. It is easy to see that by Lemma A.1, it must be that aggregate investment in $\mathbf{s}^N$ equals at least $\hat{y}$ units, i.e. $\sum_{i \in N} x_i^N \geq \hat{y}$. We define the set of all players with incoming links by $\widehat{N}_1 = \{i: \omega_i > 0\}$ and all players without incoming links by $\widehat{N}_0 = \{j: \omega_j = 0\}$. Note that in a strict equilibrium, any player $i \in \widehat{N}_1$ should invest in strictly more units than any player $j \in \widehat{N}_0$. If not, players that link to i could (weakly) improve by moving their links to j. Also, $cx_i^N > k$ should hold for all $i \in \widehat{N}_1$, as otherwise no player would link to i (but rather invest personally), hence $x_i^N > \frac{k}{c}, \forall\, i \in \widehat{N}_1$. Note that $\sum_{i \in \widehat{N}_1} x_i^N < \hat{y}$ cannot hold, as then for every $i \in \widehat{N}_1$, $y_i^N < \hat{y}$ follows and this contradicts Lemma A.1. We will now show that $\sum_{i \in \widehat{N}_1} x_i^N > \hat{y}$ cannot hold in a strict equilibrium. Assume that it holds. This implies that any $i \in \widehat{N}_1$ does not link to all other players in N_1 as otherwise $y_i^N > \hat{y}$ follows which contradicts Lemma A.1. Hence, for every $i \in \widehat{N}_1$, there exists some $\ell \neq i \in \widehat{N}_1$, for whom $g_{i,\ell} = 0$. Without loss of generality we can order the players in $\widehat{N}_1$ such that $x_1^N \geq x_2^N \geq \cdots \geq x_m^N > \frac{k}{c}$ holds. As we are considering strict equilibria, this means that no $i \in \widehat{N}_1$ will link to the last player m in the sequence, as otherwise i could (weakly) improve by linking to someone higher in the sequence. Aggregate investment by all players $i \in \widehat{N}_1 \backslash \{m\}$ should still be at least $\hat{y}$ units, as by Lemma 1 $y_i^N = \hat{y}, \forall\, i \in \widehat{N}_1$ should hold. This means that there exists some subset $\widehat{N}_1' \subseteq \widehat{N}_1 \backslash \{m\}$, whose investments add up exactly to $\hat{y}$: $\sum_{i \in N_1'} x_i^N = \hat{y}$. Take the smallest possible subset $\widehat{N}_1'$ for which $\sum_{i \in \widehat{N}_1'} x_i^N = \hat{y}$ holds. Then, as $x_i^N > \frac{k}{c}, \forall\, i \in \widehat{N}_1$, player m could strictly improve by not investing and linking to all $i \in \widehat{N}_1'$. This contradicts m being in $\widehat{N}_1$ in an equilibrium. Hence, it cannot be that $\sum_{i \in \widehat{N}_1} x_i^N > \hat{y}$ and it follows that $\sum_{i \in \widehat{N}_1} x_i^N = \hat{y}$.

    If $\sum_{i \in \widehat{N}_1} x_i^N = \hat{y}$, this implies that any $j \in \widehat{N}_0$ will have $x_j^N = 0$, as they can access $\hat{y}$ units (at lower costs than investing personally) by linking to all $i \in \widehat{N}_1$. Thus aggregate investment equals $\hat{y}$ and $\mathbf{s}^N$ must be a core-periphery network where all players $i \in \widehat{N}_1$ form the core and all $j \in \widehat{N}_0$ form the periphery. Recall, that $x_i^N > \frac{k}{c}, \forall\, i \in \widehat{N}_1$ holds. As $\sum_{i \in N} x_i^N = \hat{y}$, this provides an upper bound for the number of players that invest personally, and hence the size of the core: $|\widehat{N}_1| < \frac{c\hat{y}}{k}$.

Efficient outcomes

In any efficient outcome, it must be that aggregate investment is at least $\hat{y}$ units, i.e. $\sum_{i \in N} x_i \geq \hat{y}$. If not, all players will access fewer than $\hat{y}$ units and they can strictly increase their payoff (and hence the sum of payoffs) by investing in additional units as $MB(m) > c, \forall\, m \leq \hat{y}$. As $c\hat{y} > k$, the aggregate costs of accessing at least $\hat{y}$ units of the good are minimized by forming a periphery-sponsored star where only the core invests, i.e. $x_i \geq \hat{y}, x_j = 0, g_{j,i} = 1, g_{\ell,j} = 0, g_{i,j} = 0, \forall\, j \neq i, \ell \neq i, j$. The efficient level of investment $x_i = \tilde{y}$ by the core is such that the sum of all marginal benefits just exceeds the marginal costs of investing. That is, $\tilde{y}$ is set such that it satisfies $nMB(\tilde{y}) \geq c$ and $nMB(\tilde{y} + 1) < c$.

Appendix B: Challenge-free outcomes and dynamic stability

This appendix consists of two sections. In section B.1, we derive the set of challenge-free networks and specific predictions for our experimental treatments. In section B.2, we introduce a simple dynamic model based on the idea that players are forward-looking with limited foresight. We derive the set of stable networks and show that the stable star networks are also challenge free. For the analysis, we make two simplifying assumptions. Both assumptions are fulfilled in the parameterization in our experiment.

Assumption 1: *The benefit function is sufficiently concave:* $k > f(x + x^{'}) - f(x)$ *if* $x \geq \hat{y}$ *and* $x \geq x'$; $f(0) = 0$ *and* $f(1) > k$.

Assumption 1 lists a requirement on the concavity of $f(\cdot)$ that ensures that no player will link to multiple players if there exists some player that invested in at least $\hat{y}$. In addition, it says that there is no public good without investments and that the benefits associated with access to one unit exceed the costs of linking.

Assumption 2: $k > c(\hat{y} - 1)$

Assumption 2 provides a condition on the linking costs that prevents networks with multiple hubs being formed in equilibrium. The inequality implies that if a player i invests in at most $(\hat{y} - 1)$, none of the other players will link to i.

Assumption 2 is only invoked to prove that with sufficiently low status rents no outcome is challenge-free. The other prominent features of the analysis – that with sufficient status rents the only challenge free outcome is the one where the core player invests an amount that approximately equalizes payoffs across positions and that without sufficient status rents Nash stars and Nash super stars are not challenge free - do not need Assumption 2.

B.1   Challenge-free networks

Section 3.3 of the main text defines the concept of challenge freeness. In this appendix we derive which networks, if any, are challenge-free. We start with characterizing the set of challenge-free outcomes for general parameters.[23]

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[23] The testable prediction of our model is that an equilibrium is selected that implements a challenge-free outcome-path. A challenge-free outcome path realizes a challenge free outcome in every stage of the finitely repeated game, except in the final phase where play reverts to a stage game equilibrium. There are typically multiple ways in which this outcome-path can be supported in equilibrium. For instance, in one equilibrium a deviation from a challenge free outcome is punished by the deviation to an equilibrium where one of the periphery players takes over the profitable core position, and all other players link to this new core player in each subsequent stage, except in the final phase of the finitely repeated game where play reverts to a stage game equilibrium.

Proposition B.1.1 *Challenge-free outcome:*

(i) *If status rents are sufficiently high, i.e. when the core earns more than a player in the periphery in the Nash star, the only challenge-free network is a star where the core player invests in $x_c = \max(\hat{y}, y^*)$ and the periphery players do not invest. A challenge-free equilibrium implements the challenge-free outcome in every stage, except in the final stage(s) where a Nash star is implemented.*

(ii) *If status rents are low, i.e. when the core earns less than a player in the periphery in the Nash star, there is no challenge-free network and no challenge-free equilibrium.*

Proof. Case 1 considers part (i) and case 2 considers part (ii). In both cases, we order the players by their payoffs: $\Pi_1(\mathbf{s}) \geq \Pi_2(\mathbf{s}) \geq \cdots \geq \Pi_{n-1}(\mathbf{s}) \geq \Pi_n(\mathbf{s})$.

<u>Case 1:</u> $(n-1)b \geq c\hat{y} - k$

For this case we show that the only challenge-free outcome is a star where the core player invests in $x_c = \max(\hat{y}, y^*)$ and the periphery players do not invest. For most parameters, among which the parameters used in all of our experimental treatments, the core will earn more than the periphery in the proposed star and is therefore (by definition) player 1.[24] Note that by the definition of y^* (see section 3.3), the periphery will not challenge the core. Moreover, if players in the periphery invest anything or make any other links than to the core, they can improve their payoff by reducing their investment to zero and removing the superfluous links. This means that no network that is not a star can be challenge free. Hence, if any network is challenge free, it must be the proposed star network. To establish that this network is indeed challenge free, we show that if player 1 (the core) deviates from the proposed strategy, she will either be challenged or obtain a lower payoff.

First suppose that player 1 uses a strategy with investment $x_1 < y^*$. In this case, any player $i > 1$ can (and will) challenge player 1 by investing slightly more, i.e. $x_i' = \max(x_1 + 1, \hat{y})$, and not forming any links. This follows directly from the definition of y^* and eq. (3) in section 3.3 of the main text. Another possibility is that player 1 uses a strategy with investment $x_1 > y^*$ and $y^* \geq \hat{y}$. In this case, player 1 can strictly improve her payoff by

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[24] In the very unusual case where the core earns less than the periphery in the proposed star, no outcome will be challenge free.

reducing her investment to $x_1' = y^*$ without being challenged. Finally, if $x_1 \geq y^*$ and $y^* < \hat{y}$, player 1 can strictly improve her payoff by changing her investment to $x_1' = \hat{y}$ without being challenged. If player 1 forms any links she can strictly do better by removing them.

<u>Case 2:</u> $(n-1)b < c\hat{y} - k$

Section 3.3 of the main text shows that Nash stars and superstars are not challenge free in this case. In Nash stars and superstars, core players challenge by lowering investment (to 0) and linking to one of the periphery players, in the expectation that the latter will invest $\hat{y}$. We will now show that all other networks are also not challenge free.

Suppose that player 1 invests $x_1 \geq \hat{y}$. If player $i > 1$ challenges player 1, she invests 0 and forms a link to player 1, expecting a payoff of $\Pi_i(\mathbf{s}') = f(x_1) - k$. For the network to be challenge free, it must be that this challenge is unprofitable to i: $\Pi_i(\mathbf{s}) \geq \Pi_i(\mathbf{s}') = f(x_1) - k$. As $\Pi_1(\mathbf{s}) \geq \Pi_i(\mathbf{s})$ by construction, it must also be that $\Pi_1(\mathbf{s}) \geq f(x_1) - k$. Note that her payoff is at most $\Pi_1(s) \leq f(x_1) - cx_1 + (n-1)b$, which contradicts $\Pi_1(\mathbf{s}) \geq f(x_1) - k$ for the case we are considering. Hence, this outcome cannot be challenge free.

Now consider the possibility in which $0 \leq x_1 < \hat{y}$. Notice that because of Assumption 2, any player $i > 1$ will not link to 1 in a challenge-free outcome. If i would have a link to player 1, she prefer to challenge player 1 and withdraw her link to player 1. This means that player 1 is isolated and earns less than the payoff that she would obtain by investing $x_1 = \hat{y}$. As $\Pi_1(\mathbf{s}) \geq \Pi_i(\mathbf{s})$, player i can then always challenge by investing $x_i = \hat{y}$ and forming no links. Hence, any such network cannot be challenge free.

Predictions for the experiment

All treatments with status rents and endogenous network formation fall in Case 1. In these treatments, $y^* \geq \hat{y}$ and the y^*-star is the unique challenge-free outcome, which we take as the prediction for those treatments. The treatments without status rents (n4b0 and n8b0) fall in Case 2. In these treatments there is no challenge-free network and we predict no stable outcomes.

B.2   Dynamic behavioral model

Challenge freeness describes an equilibrium state that may or may not be achieved in a dynamic process of human choices. Here we present a simple dynamic behavioral model that describes challenges in a competition for status dynamic that is motivated by the idea that players jockey

for a position in the periphery or the core, whichever they consider most attractive. In this way, the model captures the concept of 'challenge' that underlies the refinement described above. In the dynamic model, players can use their investment decision to obtain a more attractive position. Note that the linking decisions are less useful to challenge a position than the investment decision. The reason is that *other* players decide with their links whether a player becomes part of the periphery or the core. In contrast, the investment decision is entirely at the disposal of the individual herself. To capture this difference, we assume that for the investment decision, when players form expectations about how play will unfold in the future, they look forward with limited foresight. With their linking decisions, players simply choose myopic best responses to the current investment profile.

For tractability, the stage game in the dynamic model deviates slightly from the stage game laid out in section 3.1. Figure B.2.1 illustrates the timeline in the dynamic model. In the dynamic model, each stage game played in period t consists of two phases. Investing and linking happen sequentially: in Phase 1 investments are made, and after observing all investments, links are formed in Phase 2. After this, payoffs are realized. We will argue shortly that this sequential process allows for the types of challenges that underlie our concept of challenge freeness. Therefore, the model provides a useful framework to explore the dynamic process that might underlie this equilibrium refinement. We will now discuss both phases, and the connections between them in more detail.

FIGURE B.2.1: TIMING IN THE DYNAMIC BEHAVIORAL MODEL

Period t			Period $t+1$		
Phase 1 Investment $\mathbf{x}_t$	Phase 2 Link formation $\mathbf{g}_t$	Payoffs realize $\Pi_t(\mathbf{x}_t, \mathbf{g}_t)$	Phase 1 Investment $\mathbf{x}_{t+1}$	Phase 2 Link formation $\mathbf{g}_{t+1}$	Payoffs realize $\Pi_{t+1}(\mathbf{x}_{t+1}, \mathbf{g}_{t+1})$

In Phase 1 of period t, one randomly assigned player i updates her investment $x_{i,t}$. No other player changes her investment, i.e. $x_{j,t} = x_{j,t-1}, \forall j \neq i$. Together, this gives the vector of investments $\mathbf{x}_t = (x_{1,t}, x_{2,t}, \dots, x_{n,t})$. In Phase 2, every player $\ell \in N$ (that is, also player i) observes $\mathbf{x}_t$ and decides on her links $\mathbf{g}_{\ell,t} = (g_{\ell,1,t}, g_{\ell,2,t}, \dots, g_{\ell,n,t})$. The linking decisions of all players jointly define the (directed) network architecture in period t : $\mathbf{g_t} = (\mathbf{g_{1,t}}, \mathbf{g_{2,t}}, \dots, \mathbf{g_{n,t}})$. Payoffs are then realized: $\Pi_t(\mathbf{x}_t, \mathbf{g}_t) = (\Pi_{1,t}, \Pi_{2,t}, \dots, \Pi_{n,t})$. Note that this structure allows for the two types of challenges discussed above. First, if a core player in a star earns more than the periphery, a selected periphery play can challenge by investing more than

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the core does. Second, if there are no status rents, the core player in a star can, whenever selected, challenge by reducing her investment to zero.

When we model how players make their investment and link decisions, we make the following behavioral assumptions. We assume that all players make links using myopic best response, given investments $\mathbf{x}_t$. That is, any player $\ell \in N$ chooses $\boldsymbol{g}_{\ell,t}$ such that:

$$\Pi_{\ell,t}(\boldsymbol{g}_{\ell,t}|\mathbf{x}_t) \geq \Pi_{\ell,t}(\boldsymbol{g}'_{\ell,t}|\mathbf{x}_t), \forall \boldsymbol{g}'_{\ell,t} \neq \boldsymbol{g}_{\ell,t}, \forall\, \ell \in N.\,{}^{25}$$

For player i who updates her investment $x_{i,t}$ in period t, we assume that she is forward looking with limited foresight, taking future responses of the other players into account. The way we model forward-looking behavior can be interpreted as a 'dynamic level-k model'. We assume that a player who updates her investment considers the next two periods, while she expects that other others will look only one period ahead. This is akin to 'level-k' models, where a player with level k plays a best response to other players who reason $k - 1$ steps ahead. Our assumption that $k = 2$ lines up well with experimental evidence on beauty contest games (Nagel 1995; Duffy and Nagel 1997). That is, player i who updates her investment $x_{i,t}$ in period t, considers periods t and $t + 1$, and i expects that the randomly assigned player j who updates her investment $x_{j,t+1}$ at $t + 1$ only considers period $t + 1$ itself. Player i anticipates that linking decisions will be made by myopic best response at t and $t + 1$ (as described above), and believes that player j expects links to follow from myopic best response at $t + 1$. Given these expectations, player i chooses the investment that maximizes her expected payoff in the current period t and the immediate next period $t + 1$:

$$\mathbf{E}\Pi_i = (1 - \alpha)\mathbf{E}\Pi_{i,t} + \alpha\mathbf{E}\Pi_{i,t+1}.$$

This means that when $\alpha = 0$, i puts all weight on the immediate expected payoff while $\alpha = 1$ puts all weight on the future expected payoff. We take α as the reduced form weight of any aspect relating to time preferences. It not only captures patience, but also the belief that a certain outcome will persist. A player may well put relatively more weight on the future than on the present ($\alpha > \frac{1}{2}$). This would reflect the belief that the outcome in $t + 1$ will persist. A

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[25] Note that a player's myopic best response for her links is independent of the links of other players in our game with one-way flow. For some $\mathbf{x}_t$, there exist multiple best replies in the linking decisions, i.e. when two players invest in exactly the same amount. In this case, we assume that players will not change their links, i.e. for player i to attract the links that player j has at $t - 1$ she should invest strictly more than j. Note also that the myopic best response by other players agrees with the assumption that we made when introducing challenges in the main text.

strategy profile is stable if for all players $i \in N$:

$$\mathbf{E}\Pi_i\big(x_{i,t} = x_{i,t-1}, \mathbf{x}_{t-1}\big) > \mathbf{E}\Pi_i\big(x_{i,t} = x_i', \mathbf{x}_{t-1}\big), \forall\, x_i' \neq x_{i,t-1},$$

holds. As the link decisions follow mechanically by myopic best response, we suppress the dependence of the expected payoffs on the network architecture.

We first discuss the conditions under which star networks are stable in the dynamic model. A star network is stable if neither the core-player i nor any periphery player j changes her investments when given a chance to reconsider her choice.

Consider first the core-player i. The myopic best response of i is to invest $x_i = \hat{y}$, which yields a Nash star. However, if the sum of status rents is sufficiently low, the core position earns less than the periphery and a forward-looking core player may try to challenge the periphery by choosing $x_i < \hat{y}$. On the other hand, if the sum of status rents is sufficiently large, the core position earns more than the periphery. In this case, a forward-looking core player will anticipate that her position may be challenged by one of the periphery players. As a result, i considers choosing $x_i > \hat{y}$ to avoid being challenged. Player i expects to be challenged by periphery player j if:

$$\mathbf{E}\Pi_j\big(x_{j,t+1} = x_{i,t} + 1\big) > \mathbf{E}\Pi_j\big(x_{j,t+1} = 0\big).$$

With $x_{j,t+1} = x_{i,t} + 1$, all players $\ell \neq i, j$ will link to j at $t+1$ and $\mathbf{E}\Pi_j\big(x_{j,t+1} = x_{i,t} + 1\big) = f(x_{i,t} + 1) - (x_{i,t} + 1)c + (n-2)b$. If j does not invest, she will remain in the periphery of the star with i in the core and $\mathbf{E}\Pi_j\big(x_{j,t+1} = 0\big) = f(x_{i,t}) - k$. Using this, i expects that no periphery player will challenge when:

$$f(x_{i,t}) - k > f(x_{i,t} + 1) - (x_{i,t} + 1)c + (n-2)b.$$

Rewriting gives:

(B.2.1) $\qquad (n-2)b < (x_{i,t} + 1)c - k - \big[f(x_{i,t} + 1) - f(x_{i,t})\big].$

If (B.2.1) holds, core player i expects not to be challenged. Note that this is the same condition as in (3). Hence, we can use the same definition of y^* as used in our derivation of challenge-free outcomes.

Proposition B.2.1: *The behavioral model generates the following predictions:*

(i) *When status rents are sufficiently high, i.e. when the player in the core of the Nash star earns more than a player in the periphery, there exists a lower bound on α above which the only stable outcomes are the challenge-free periphery-sponsored stars where the core player invests $\max(\hat{y}, y^*)$ units and no periphery player invests.*

(ii) *When status rents are low or absent, i.e. when in the Nash star the core player earns less than a player in the periphery and there is no challenge-free outcome, there exists a lower bound on α above which all Nash stars and superstars are unstable.*

Proof. We first derive the decisions of the core players in periphery-sponsored stars. We do this for two separate cases. In case I, we consider the case where status rents are relatively high, i.e. when $y^* > \hat{y}$ and, in case II, we look at the decisions of core players when the reverse holds. Then, we derive the conditions under which periphery players in a periphery-sponsored star leave their investments unchanged.

Core player case I: $y^* > \hat{y}$

First, we show that if no other player $j \neq i$ invests at $t - 1$, then if core player i is given the chance to revise her choice, she will choose $x_{i,t} = y^*$. This rules out all other periphery-sponsored stars (where the periphery does not invest) than the y^*-star as stable outcomes.

Consider the situation where core player i is given the chance to change her investment. At $t - 1$, none of the other players invested, i.e. $x_{j,t-1} = 0 \; \forall j \neq i$. For expositional reasons, we suppress that all expected payoffs below are conditional on the investments of others at t. For the y^*-star to be stable, $\mathbf{E}\Pi_i(x_{i,t} = y^*) > \mathbf{E}\Pi_i(x_{i,t} = x'_{i,t}) \; \forall x'_{i,t} \neq y^*$ must hold. This implies that

(B.2.2) $\quad \mathbf{E}\Pi_i(x_{i,t} = y^*) > (1 - \alpha)\mathbf{E}\Pi_{i,t}(x_{i,t} = x'_{i,t}) + \alpha\mathbf{E}\Pi_{i,t+1}(x_{i,t} = x'_{i,t}) \; \forall x'_{i,t} \neq y^*,$

should hold. If i invests in y^* units, she expects to be in the core of the y^*-star at t and $t + 1$. Her expected payoff is then $\mathbf{E}\Pi_i(x_{i,t} = y^*) = f(y^*) - cy^* + (n - 1)b$, for which we simply write $\mathbf{E}\Pi_i(x_{i,t} = y^*) = \pi_C^*$. Below, we will show that any other investment $x'_{i,t} \neq y^*$ will lead to lower expected payoffs at $t + 1$, i.e. $\pi_C^* > \mathbf{E}\Pi_{i,t+1}(x_{i,t} = x'_{i,t}), \forall x'_{i,t} \neq y^*$. Then, expected payoffs can only be higher if there exists a profitable deviation in the current period, i.e. when $\mathbf{E}\Pi_{i,t}(x_{i,t} = x'_{i,t}) > \pi_C^*$. In this case, (B.2.2) holds when:

$$(B.2.3) \qquad \alpha > \frac{\mathbf{E}\Pi_{i,t}\left(x_{i,t}=x'_{i,t}\right)-\pi^*_C}{\mathbf{E}\Pi_{i,t}\left(x_{i,t}=x'_{i,t}\right)-\mathbf{E}\Pi_{i,t+1}\left(x_{i,t}=x'_{i,t}\right)}, \forall\, x'_{i,t} < y^*, \mathbf{E}\Pi_{i,t}\left(x_{i,t}=x'_{i,t}\right) > \pi^*_C.$$

Note that in this case, $\mathbf{E}\Pi_{i,t}\left(x_{i,t} = x'_{i,t}\right) > \pi^*_C > \mathbf{E}\Pi_{i,t+1}\left(x_{i,t} = x'_{i,t}\right)$ and there exists a lower bound $\bar{\alpha} \in (0,1)$ for which (B.2.3) holds. Hence, if i is sufficiently forward looking ($\alpha > \bar{\alpha}$), she will choose $x_{i,t} = y^*$.

Now we will show that $\pi^*_C > \mathbf{E}\Pi_{i,t+1}\left(x_{i,t} = x'_{i,t}\right), \forall\, x'_{i,t} \neq y^*$ is indeed true. When i invests in more than y^* units, she expects not to be challenged at $t + 1$, but she will earn a strictly lower payoff than in the y^*-superstar in both periods.[26] Hence, profitable deviations can only follow from lower investments than y^*. If $x_{i,t} < y^*$, i expects to be challenged at $t + 1$, i.e. there will be some player j who she expects will invest $x_{j,t+1} = \max\{\hat{y}, x_{i,t} + 1\}$ and no player will link to i at $t + 1$. At $t + 1$, i could either link to j or not. (i) If she does not link to j (or any other player), her expected payoff at $t + 1$ will be $\mathbf{E}\Pi_{i,t+1}\left(x_{i,t} \in [0, y^*)\right) = f\left(x_{i,t}\right) - cx_{i,t}$. Note that this payoff is maximal for $x_{i,t} = \hat{y}$, but that even in this case it is strictly smaller than the payoff of a periphery player in a Nash star: $\pi^N_P = f(\hat{y}) - k$. The payoff of a periphery player in the y^*-star ($\pi^*_P = f(y^*) - k$) is strictly larger than π^N_P as $y^* > \hat{y}$. When $\pi^*_C > \pi^*_P$, this implies $\pi^*_C > \pi^*_P > \pi^N_P > \mathbf{E}\Pi_{i,t+1}\left(x_{i,t} \in [0, y^*)\right)$; hence, investing $x_{i,t} < y^*$ leads to lower expected payoffs at $t + 1$ than investing $x_{i,t} = y^*$. $\pi^*_C > \pi^*_P$ is true in most cases, among which all of our experimental treatments.[27] (ii) If i does link to j, her expected payoff at $t + 1$ is given by: $\mathbf{E}\Pi_{i,t+1}\left(x_{i,t} \in [0, y^*)\right) = f\left(x_{i,t} + x_{j,t+1}\right) - cx_{i,t} - k$. Given that $x_{j,t+1} = \max\{\hat{y}, x_{i,t} + 1\}$, this expected payoff must be less or equal than π^N_P, and therefore it must also be strictly smaller than π^*_P. Again, if $\pi^*_C > \pi^*_P$ this implies that any investment $x_{i,t} < y^*$ will lead to lower expected payoffs at $t + 1$. All in all, $\mathbf{E}\Pi_{i,t+1}\left(x_{i,t} = y^*\right) > \mathbf{E}\Pi_{i,t+1}\left(x_{i,t} = x'_{i,t}\right) \forall\, x'_{i,t} \neq y^*$.

Core player case II: $y^* \leq \hat{y}$

We will show that in this case superstars will not form and Nash stars are stable for all values of α when the core in the Nash star earns more than the periphery in the Nash star. This is the case when $(n - 1)b > c\hat{y} - k$. When the reverse holds, there exists a lower bound on α above which Nash stars must be unstable.

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[26] Remember that for values above $\hat{y}$, the marginal benefits of investing are strictly lower than the marginal costs.
[27] If $\pi^*_C < \pi^*_P$, the core could potentially earn a higher payoff by investing less than y^*. If this is the case, the behavioral model predicts that competition would push investments up to y^*, but that the y^*-star will be unstable.

If i invests in the stage game Nash amount or more, i.e. $x_{i,t} \geq \hat{y}$, she expects not to be challenged as $y^* \leq \hat{y}$. Note that in this case $\mathbf{E}\Pi_i(x_{i,t} = \hat{y}) > \mathbf{E}\Pi_i(x_{i,t} > \hat{y})$, which implies that superstars will not be formed when $y^* \leq \hat{y}$. If i chooses $x_{i,t} = \hat{y}$, a Nash star is expected to result at both t and $t+1$ and i will be in the core and her expected payoffs are π_C^N.

For a Nash star to be stable, $\mathbf{E}\Pi_i(x_{i,t} = \hat{y}) > \mathbf{E}\Pi_i(x_{i,t} = x'_{i,t})$, $\forall x'_{i,t} \neq \hat{y}$ should hold. We just established that i will not invest more than $\hat{y}$, but she may want to invest less than $\hat{y}$ in order to induce others to invest. First note that the expected payoffs at t are maximized by investing $x_{i,t} = \hat{y}$. If i invests less, she earns a strictly lower payoff at t as no other invests, and she will access fewer than $\hat{y}$ units. Hence, any profitable deviation should arise from higher expected payoffs at $t+1$, i.e. a Nash star is stable when:

$$(\text{B.2.4}) \qquad \alpha < \frac{\pi_C^N - \mathbf{E}\Pi_{i,t}(x_{i,t} = x'_{i,t})}{\mathbf{E}\Pi_{i,t+1}(x_{i,t} = x'_{i,t}) - \mathbf{E}\Pi_{i,t}(x_{i,t} = x'_{i,t})}, \forall x'_{i,t} < \hat{y}.$$

Note that both the denominator and the numerator of (B.2.4) are strictly positive, as $\pi_C^N > \mathbf{E}\Pi_{i,t}(x_{i,t} = x'_{i,t})$ and the only relevant cases are those for which $\mathbf{E}\Pi_{i,t+1}(x_{i,t} = x'_{i,t}) > \mathbf{E}\Pi_{i,t}(x_{i,t} = x'_{i,t})$ holds. Consider that i invests $x_{i,t} < \hat{y}$. At $t+1$, if some other player j updates, there are four possible outcomes: (1) j invests $x_{j,t+1} = \hat{y} - x_{i,t}$ and links to i, and i links to j; (2) j invests $x_{j,t+1} = \hat{y} - x_{i,t}$ and links to i (and i does not link to j); (3) j invests $x_{j,t+1} = \hat{y}$ and j does not link to i and i does not link to j; or (4) j invests $x_{j,t+1} = \hat{y}$ and j does not link to i but i does link to j. The expected payoffs for i in outcomes (1), (2) and (3) are strictly lower than π_C^N, which means that the RHS in (B.2.4) is strictly larger than one.[28] Hence, the only possible restriction on α comes from the situations described in outcome (4). In these situations, $\mathbf{E}\Pi_{i,t+1}(x_{i,t} \in [0, \hat{y})) = f(\hat{y} + x_{i,j}) - cx_{i,t} - k$, which is maximized when $x_{i,t} = 0$ and in this case $\mathbf{E}\Pi_{i,t+1}(x_{i,t} = 0) = \pi_P^N$. When i does not invest, she expects $\mathbf{E}\Pi_{i,t}(x_{i,t} = 0) = 0$ and (B.2.4) yields:

$$(\text{B.2.5}) \qquad \alpha < \frac{\pi_C^N}{\pi_P^N}.$$

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[28] That payoffs are lower than π_C^N in case (1) follows from Assumption 2.

When status rents are absent or low, the core earns less than the periphery in a Nash star, i.e. $\pi_C^N < \pi_P^N$. This is the case when $(n-1)b < c\hat{y} - k$. It follows from (B.2.5) that Nash stars are unstable if players are sufficiently forward looking.

If status rents are relatively high, the core earns more than the periphery in a Nash star, i.e. $\pi_C^N > \pi_P^N$ (i.e. when $(n-1)b > c\hat{y} - k$) and (B.2.5) always holds. Hence, if $y^* \leq \hat{y}$ and $\pi_C^N > \pi_P^N$, the core in a Nash star will not change her investment and Nash stars may be stable.[29]

Periphery players (cases I and II)

We have now derived the investment level that stabilizes the investments by core players. That is, when $\pi_C^N > \pi_P^N$ the core player will invest in $x_{i,t} = \max(\hat{y}, y^*)$ units. For the corresponding Nash star or superstar to be stable, a periphery player $j \neq i$ should not want to challenge the core player i. Consider a periphery player j. If j sticks to investing $x_{j,t} = 0$, she expects to be in the periphery of a $x_{i,t}$-star both at t and $t+1$, unless the core player is allowed to change her investment at $t+1$. In this case she expects a Nash star to form at $t+1$.[30] She expects to earn:

$$\mathbf{E}\Pi_j(x_{j,t} = 0) = (1-\alpha)\pi_P^* + \alpha\left(\frac{1}{n-1}\pi_P^N + \frac{n-2}{n-1}\pi_P^*\right) = \pi_P^* - \frac{\alpha}{n-1}(\pi_P^* - \pi_P^N).$$

First note that investing $x_{j,t} \in (0, y^*]$ will lead to lower expected payoffs than not investing. In this case, $x_{j,t} \leq y^* \leq x_{i,t}$ and (by Assumption 1) no-one will link to j at t or $t+1$. Hence, j will be better off by not investing and linking to i at t and $t+1$. Then, the only possible profitable deviation is when j challenges i by investing in more units. If $x_{j,t} > x_{i,t}$, j expects that all others than i will link to her at t and $t+1$, and if i is given the chance to update at $t+1$ she will lower her investment and also link to j. This implies that she expects to earn:

(B.2.6) $\mathbf{E}\Pi_j(x_{j,t} > y^*) = (1-\alpha)\big(f(x_{j,t}) - cx_{j,t} + (n-2)b\big) + \alpha\Big(\frac{1}{n-1}\big(f(x_{j,t}) -$

$cx_{j,t} + (n-1)b\big) + \frac{n-2}{n-1}\big(f(x_{j,t}) - cx_{j,t} + (n-2)b\big)\Big)$

Note that the payoffs in (B.2.6) are largest when j invests in the smallest possible amount above i, i.e. when $x_{j,t} = x_{i,t} + 1$. Then, if $\Pi_j(x_{j,1} = 0) > \mathbf{E}\Pi_j(x_{j,1} = y^* + 1)$ the y^*-star is stable.

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[29] Note that if $y^* < \hat{y}$, the y^*-star will not be stable as the core can improve by investing $\hat{y}$, but in the $\hat{y}$-star (the Nash star) the core will not change her investment.
[30] Of course, the $x_{i,t}$-star can also be a Nash star. This is the case in n4b22.

This is the case when:

$$(\text{B.2.7}) \quad (n-2)b < (y^*+1)c - k - \big(f(y^*+1) - f(y^*)\big) - \frac{\alpha}{n-1}\big(f(y^*) - f(\hat{y}) + b\big)$$

Note the similarity between the inequalities in (B.2.1) and (B.2.7). Inequality (B.2.1) was used to derive the value of y^*, i.e. the investment level at which a core player does not expect to be challenged. As the RHS in (B.2.7) is smaller than the RHS in (B.2.1), the core might actually be challenged in some cases. Note however that differences are very small and decreasing in n.[31] Thus, with sufficiently large status rents and forward-looking players, periphery-sponsored stars where the core invests in y^* units are stable.

Uniqueness

Now we show that the $\max(\hat{y}, y^*)$-stars are the only stable outcomes when $\pi_C^N > \pi_P^N$. First note that if a pair of players i, j exists for which $x_{j,t-1} \geq x_{i,t-1} > 0$ and $x_{j,t-1} \geq \hat{y}$ holds, the outcome is unstable as i will earn a higher expected payoff by not investing. If i continues to invest $x_{i,t} = x_{i,t-1}$, she expects (by Assumption 1) not to attract any links at t and $t+1$ as $x_{j,t-1} \geq x_{i,t-1}$ and $x_{j,t-1} \geq \hat{y}$. Then, at $t+1$ she could either link to j or not. If she does so, she expects to earn $f\big(x_{j,t-1} + x_{i,t-1}\big) - cx_{i,t-1} - k$, while if she does not she expects to earn $f\big(x_{i,t-1}\big) - cx_{i,t-1}$. Note that both are strictly smaller than π_P^N, the payoff that would result if at $t+1$ she does not invest. This implies the following lemma:

Lemma B.2.1: *If there is some player j who invests in the stage-game amount $\hat{y}$ or more, i.e. $x_{j,t-1} \geq \hat{y}$, then any outcome where some other player i has positive investment is unstable.*

Which gives us the following useful corollary:

Corollary B.2.1: *All stable outcomes are either:*
  (i)   *stars where the core invests in a positive amount and no periphery player invests,*
  (ii) *inefficient outcomes where all players have lower investments than $\hat{y}$*

If $\pi_C^N > \pi_P^N$, the $\max(\hat{y}, y^*)$-star is the only stable outcome when all outcomes described in situation (ii) of Corollary B.2.1 are unstable. In situation (ii) of Corollary B.2.1, $x_{i,t-1} <$

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[31] If this does happen, a cycle between y^*-stars and (y^*+1)-stars is predicted by the model.

$\hat{y} \, \forall \, i \in N$. There exists some value of investment x_{low}, such that $k > f(y^* + x_{low}) - f(x_{low})$. That is, players who choose an investment of at least x_{low} will not form a link to any player i who invests $x_i \leq y^*$. Denote the number of players who are below this threshold and who may choose to form a link by $n_0 = |j \in N : x_j \leq x_{low}|$. If $n_0 \geq (n-1)$, the strategic situation boils down to the choice of a core player in a periphery-sponsored star, which we described above. When i updates, she will choose $x_{i,t} = \max(\hat{y}, y^*) \geq x_{i,t-1}$ (provided she is sufficiently forward-looking) and the outcome must be unstable. At the other extreme, when $n_0 = 0$, player i expects that any other player j who revises her investment at $t+1$ will choose $x_{j,t+1} = \hat{y}$, unless i increases her investment. If she remains at $x_{i,t} = x_{i,t-1} \in (0, x_{low}]$, she expects to earn $f(x_{i,t-1}) - cx_{i,t}$ at $t+1$, while if she does not invest, she expects to earn π_P^N which is strictly larger. Hence, not investing will lead to a higher expected payoff for i than not changing her investment (provided she is sufficiently forward-looking) and the outcome must be unstable. Extending this argument shows that for any value of n_0, a player who updates will have a profitable deviation by either not investing of investing in $\hat{y}$ or above to attract links. Hence, any outcome in (ii) of Corollary B.2.1. is unstable when $\pi_C^N > \pi_P^N$ and only the $\max(\hat{y}, y^*)$-star is stable. Recall that all Nash stars and superstars are unstable when the reverse holds.

Predictions for the experiment

For all treatments with $b > 0$, we have $\pi_C^N > \pi_P^N$ and the behavioral model predicts that the $\max(\hat{y}, y^*)$-star will form. This means, that we expect a 2-star in treatment n4b22, a 4-star in treatments n4b66 and n8b22 and an 8-star in treatment n8b66. In the treatments without rents (n4b0 and n8b0), we expect that all periphery-sponsored stars will be unstable as $\pi_C^N < \pi_P^N$ in these treatments. Table B.2.1 summarizes the predictions based on the model. Note that this dynamic behavioral model in which the concept of challenges is implemented in a way that mirrors the concept used for the equilibrium refinement yields predictions that are identical to those that follow from challenge-freeness.

We also compute the required lower bound on α for each treatment. For n4b0, n8b0 and n4b22 $y^* = \hat{y} = 2$. For n4b22, $\pi_C^N > \pi_P^N$ and the 2-star (the Nash star) is stable for any α. For n4b0 and n4b22, we obtain the following expected payoffs:

$$\mathrm{E}\Pi_i(x_{i,t} = 0) = \alpha(f(2) - k) = 82\alpha,$$
$$\mathrm{E}\Pi_i(x_{i,t} = 1) = (1 - \alpha)(f(1) - c + (n-1)b) + \alpha(f(3) - c - k) = 37 + 15\alpha,$$

$$\mathbf{E}\Pi_i\big(x_{i,t} = 2\big) = f(2) - 2c + (n-1)b = 42.$$

Nash stars are unstable when (B.2.5) or (B.2.3) is violated, i.e. when one of the following two conditions is satisfied:

$$\alpha > \frac{\pi_C^N - \mathbf{E}\Pi_{i,t}(x_{i,t}=0)}{\mathbf{E}\Pi_{i,t+1}(x_{i,t}=0) - \mathbf{E}\Pi_{i,t}(x_{i,t}=0)} = \frac{\pi_C^N}{\pi_P^N} = \frac{f(2) - 2c + (n-1)b}{f(2) - k} = \frac{42}{82},$$

$$\alpha > \frac{\pi_C^N - \mathbf{E}\Pi_{i,t}(x_{i,t}=1)}{\mathbf{E}\Pi_{i,t+1}(x_{i,t}=1) - \mathbf{E}\Pi_{i,t}(x_{i,t}=1)} = \frac{(f(2) - 2c + (n-1)b) - (f(1) - c + (n-1)b)}{(f(3) - c - k) - (f(1) - c + (n-1)b)} = \frac{f(2) - f(1) + c}{f(3) - f(1) - k} = \frac{1}{3}.$$

Hence, Nash stars are unstable when $\alpha > \frac{1}{3}$ and all periphery-sponsored stars are unstable when $\mathbf{E}\Pi_i\big(x_{i,t} = 0\big) > \mathbf{E}\Pi_i\big(x_{i,t} = 1\big)$, which is the case when $\alpha > \frac{37}{67}$.

For treatments n4b66, n8b22 and n8b66, $y^* > \hat{y}$ and (B.2.3) should hold for the y^* to be stable. Below, we give the expected payoffs for our game for investing in y^* or below.

$$\mathbf{E}\Pi_i\big(x_{i,t} = 0\big) = \alpha(f(2) - k),$$
$$\mathbf{E}\Pi_i\big(x_{i,t} = 1\big) = (1-\alpha)(f(1) - c + (n-1)b) + \alpha(f(3) - c - k).$$
$$\mathbf{E}\Pi_i\big(x_{i,t} = 2\big) = (1-\alpha)(f(2) - 2c + (n-1)b) + \alpha(f(2) - 2c),$$
$$\mathbf{E}\Pi_i\big(x_{i,t} \in (2, y^*)\big) = (1-\alpha)(f(x_{i,t}) - cx_{i,t} + (n-1)b) + \alpha(f(x_{i,t}) - cx_{i,t}),$$
$$\mathbf{E}\Pi_i\big(x_{i,t} = y^*\big) = f(y^*) - cy^* + (n-1)b.$$

It is easily computed that for any level of α both $\mathbf{E}\Pi_i\big(x_{i,t} = y^*\big) > \mathbf{E}\Pi_i\big(x_{i,t} = 0\big)$ and $\mathbf{E}\Pi_i\big(x_{i,t} = 2\big) > \mathbf{E}\Pi_i\big(x_{i,t} \in (2, y^*)\big)$ hold. Hence, the only relevant bounds on α come from $\mathbf{E}\Pi_i\big(x_{i,t} = y^*\big) > \mathbf{E}\Pi_i\big(x_{i,t} = 1\big)$ and $\mathbf{E}\Pi_i\big(x_{i,t} = y^*\big) > \mathbf{E}\Pi_i\big(x_{i,t} = 2\big)$. Computing these bounds yields:

$$\alpha > \max\left\{\frac{c(y^*-1) - (f(y^*) - f(1))}{k + (n-1)b - (f(3) - f(1))}, \frac{c(y^*-2) - (f(y^*) - f(2))}{(n-1)b}\right\}.$$

For n8b22 this gives $\alpha > \max\{0.44, 0.43\} = 0.44$, for n4b66 $\alpha > \max\{0.33, 0.33\} = 0.33$ and for n8b66 $\alpha > \max\{0.61, 0.60\} = 0.61$.

	Endogenous networks						Exogenous networks	
	$b = 0$		$b = 22$		$b = 66$		$b = 66$	
	$n = 4$	$n = 8$	$n = 4$	$n = 8$	$n = 4$	$n = 8$	$n = 4$	$n = 8$
y^*	2	2	2	4	4	8	2	2
star stable	No	No	Yes	Yes	Yes	Yes	n.a.	n.a.
Lower bound on α	$\alpha > 0.33$	$\alpha > 0.33$	$\alpha \geq 0$	$\alpha > 0.44$	$\alpha > 0.33$	$\alpha > 0.61$	$\alpha \geq 0$	$\alpha \geq 0$

Notes. Columns distinguish between our eight treatments. y^* is defined using eq. (B.2.1). The bounds on α (the weight attributed to future payoffs) denote the values for which the outcome in the two top rows is predicted by the model.

Appendix C: Additional tables

Table C.1: Payoffs and welfare in different star networks

Core investment		$b = 0$					$b = 22$				$b = 66$		
		$n = 4$			$n = 8$		$n = 4$		$n = 8$		$n = 4$		$n = 8$
	π_P	π_C	W	π_C	W	π_C	W	π_C	W	π_C	W	π_C	W
$x_C = 1$	22	37	103	37	191	103	169	191	345	235	301	499	653
$x_C = 2$	82	42	288	42	616	108	354	196	770	240	486	504	1078
$x_C = 3$	107	12	333	12	761	78	399	166	915	210	531	474	1223
$x_C = 4$	126	-24	354	-24	858	42	420	130	1012	174	552	438	1320
$x_C = 5$	129	-76	311	-76	827	-10	377	78	981	122	509	386	1289
$x_C = 6$	132	-128	268	-128	796	-62	334	26	950	70	466	334	1258
$x_C = 7$	133	-182	217	-182	749	-116	283	-28	903	16	415	280	1211
$x_C = 8$	134	-236	166	-236	702	-170	232	-82	856	-38	364	226	1164
$x_C = 9$	135	-290	115	-290	655	-224	181	-136	809	-92	313	172	1117
$x_C = 10$	136	-344	64	-344	608	-278	130	-190	762	-146	262	118	1070

Notes: Payoffs for core (π_C) and periphery (π_P) players in different star networks where the periphery players do not invest. W denotes the welfare level, which is defined as the sum of payoffs.

Table C.2: MW tests for differences in the relative frequencies in periphery-sponsored stars in the final 25 periods.

p-values final 25 periods		$b = 0$		$b = 22$		$b = 66$	
		$n = 4$	$n = 8$	$n = 4$	$n = 8$	$n = 4$	$n = 8$
$b = 0$	$n = 4$	-					
	$n = 8$	0.49	-				
$b = 22$	$n = 4$	0.00	0.00	-			
	$n = 8$	0.02	0.02	0.29	-		
$b = 66$	$n = 4$	0.04	0.08	0.07	0.51	-	
	$n = 8$	0.00	0.00	0.50	0.53	0.28	-

Appendices for online publication

Appendix D: Subgame perfect equilibria of the repeated game

The finitely repeated game has a plethora of repeated game equilibria, including those where a stage-game equilibrium is played in each of the T periods. Here, we are interested in equilibria in which players earn higher payoffs than when they repeatedly play a stage-game equilibrium. We focus on equilibria in which superstars are consistently formed, which includes the efficient superstar. In addition, we restrict our attention to strict subgame perfect equilibria. In the GG model, all efficient outcomes are superstars. We denote the efficient investment level by the core player in the superstar by $\tilde{y}$.

One way to support efficient equilibria is by the use of punishment strategies. Like Benoit and Krishna (1985) we consider the use of 'optimal punishments'. The optimal punishment strategy yields the worst possible payoff for the punished player i that is feasible in a subgame perfect equilibrium. The average payoff for the punished player i from the optimal punishment in K periods of punishment is denoted by $w_i(K)/K$, where $w_i(K)$ is the total payoff of the punished player in these K periods. Benoit and Krishna show that this payoff is bounded by:

$$v_i \leq w_i(K)/K \leq w_i(1),$$

where v_i is i's *minmax* payoff and $w_i(1)$ her worst possible payoff in a stage-game equilibrium.

One way to support (efficient and inefficient) superstars is by rotating the core position.

Proposition D.1: *In all of our experimental games with endogenous network formation, efficient superstars with a rotating core position can be supported as part of a subgame perfect equilibrium until period $T - Q$, where $1 \leq Q < T$.*

Proof. Suppose that all players observe a perfectly correlated signal θ_t at the beginning of each period t. This signal is an independent draw from the set $\{1, \ldots, n\}$. Each integer is drawn with equal probability. Consider the strategy profile $\mathbf{s}^N$, where each player's strategy s_i^N adheres to:

"In each period, the player who is assigned the core position is determined by the draw of θ_t, i.e. if $\theta_t = j$, player j will be in the core position in period t. In a period, the core player does

not form any links, and all other players only form a link to this core player. In the first T-Q periods the core player invests $y^S > \hat{y}$ and in the final Q periods the core player invests the stage-game Nash level $\hat{y}$. If some player i deviates in period t, play switches to the punishment regime and the deviating player will be punished in periods $t + 1$ to T by the optimal punishment strategy."

The strategy profile $\mathbf{s}^N$ constitutes a subgame perfect equilibrium if it satisfies the one-stage-deviation principle. That is, the strategy profile $\mathbf{s}^N$ is a subgame perfect equilibrium if and only if:

$$\pi_i(s_i^N, s_{-i}^N) > \pi_i(s_i', s_{-i}^N) \ \forall \ i \in N, \forall \ s_i' \ ,$$

where s_i' indicates a deviant strategy of player i, which differs from the equilibrium strategy s^N only in period t and conforms to $\mathbf{s}^N$ thereafter (see for instance, Theorem 4.1 in Fudenberg and Tirole 1991, p.109, for a proof).

Let π_C^S and π_P^S denote the stage-game payoff of being, respectively, in the core or the periphery of the superstar where the core invests in y^S. Likewise, we write π_C^N and π_P^N for the payoff of being, respectively, in the core or the periphery of the Nash star where the core invests in $\hat{y}$.

In $\mathbf{s}^N$, the final Q periods consist of a sequence of stage-game equilibria, hence, a profitable one-stage-deviation can only exist in the first $T - Q$ periods. First consider deviations by the core in these periods. The optimal deviation by the core player in a superstar is to invest in the Nash level $\hat{y}$, which implies that a Nash star would result. Hence, by deviating in period $t \leq T - Q$, the sum of payoffs in periods t to T of core player i will be:

$$\pi_i(s_i', s_{-i}^N) = \pi_C^N + (T - t)\frac{w_i(T-t)}{T-t}.$$

The expected payoff from following s_i^N is $\bar{\pi}^S = \frac{n-1}{n}\pi_P^S + \frac{1}{n}\pi_C^S$ in each of the first $T - Q$ periods and $\bar{\pi}^N = \frac{n-1}{n}\pi_P^N + \frac{1}{n}\pi_C^N$ in each of the final Q periods. In every period $t \leq T - Q$, the core player in the superstar will not deviate if:

(D.1) $\qquad \pi_C^S + (T - Q - t)\bar{\pi}^S + Q\bar{\pi}^N > \pi_C^N + (T - t)\frac{w_i(T-t)}{T-t}.$

As $\bar{\pi}^S > \bar{\pi}^N > w_i(1) \geq \frac{w_i(T-t)}{T-t}$, it suffices to consider only period $t = T - Q$. Using this, we can rewrite (D.1) to obtain:

(D.2) $$Q > \frac{\pi_C^N - \pi_C^S}{\bar{\pi}^N - w_i(Q)/Q},$$

which gives a condition for the minimal length of the 'Nash phase' that is needed to avoid deviation by the core.[32] As $\bar{\pi}^N > w_i(1) \geq \frac{w_i(T-t)}{T-t}$ and $\pi_C^N > \pi_C^S$, the right hand side of (D.2) is always positive.

If $b = 0$, we have $v_i = w_i(1) = \pi_C^N$. Using this in (D.2), we can compute for our game that $Q \geq 3$ if $n = 4, b = 0$ and $Q \geq 2$ if $n = 8, b = 0$.[33] Similarly, in our games with status rents, the worst stage-game equilibrium payoff is the periphery position in the Nash star. Using this as the average punishment payoff $w_i(Q)/Q$ in case of deviation, we find that $Q \geq 11$ if $n = 4, b = 22$, $Q \geq 5$ if $n = 8, b = 22$, $Q \geq 2$ if $n = 4, b = 66$ and $Q \geq 2$ if $n = 8, b = 66$ are needed to sustain the efficient superstar with $y^S = \tilde{y} = 4$. This shows that no core player will deviate in the first $T - Q$ periods for the above bounds on Q.

Now consider deviations by a periphery player j. Note that within a period, the periphery player best responds by linking to the core in the superstar. If a periphery player deviates, she will be punished in all $T - t$ remaining periods. The expected future payoffs in case of deviation are thus $w_i(T - t)$. As $\bar{\pi}^S > \bar{\pi}^N > w_i(1) \geq \frac{w_i(T-t)}{T-t}$, the expected future payoff of adhering to the strategy s_j^N is strictly larger than the future payoffs of deviation. Hence, no periphery player will deviate, which shows that the strategy profile $\mathbf{s}^N$ constitutes a subgame perfect equilibrium. Q.E.D.

Superstars with a fixed core player

Given that in practice rotation schemes are rarely implemented, we now focus on equilibria where a fixed periphery-sponsored star is formed in all periods. We divide the game in two phases: a 'superstar phase' where a superstar with a fixed core is played in the first $T - Q$ periods, and an 'end phase' which consist of the final Q periods.

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[32] Proposition D.1 holds whenever (D.2) is fulfilled. We have restricted the proposition to our experimental games in order to keep the notation as simple as possible.

[33] More specifically, if $n = 4, b = 0$ we have $Q > \frac{11}{5}$ and if $n = 8, b = 0$ we have $Q > \frac{66}{35}$.

Proposition D.2: *Consider the set of equilibria where (1) on the equilibrium path a periphery-sponsored star with a fixed core player is formed and (2) in a punishment phase the same network is formed in each of the remaining periods; then status rents are necessary for the formation of superstars in the repeated game equilibrium.*

Proof. In this type of equilibrium, the efficient superstar is played in periods 1 to $T - Q$ and a Nash star is played in the final Q periods. In every period, the same player i fills the core position. Note that we rule out rotations on the equilibrium path as well as in a possible punishment phase. Now, consider the following strategy profile $\mathbf{s}^N$:

"In each period, the same player i is assigned the core position. This player does not form any link, and all other players only form a link to this core player. In the first $T - Q$ periods the core player invests the superstar level $y^S > \hat{y}$ and in the final Q periods the core player invests the stage-game Nash level $\hat{y}$. If some player j deviates in period t, play switches to the punishment regime and the deviating player will be punished in periods $t + 1$ to T by the optimal punishment strategy."

First, consider deviations by the core player. As before, the optimal deviation by the core in the superstar phase is to lower her investment to $\hat{y}$, which results in a Nash star. Hence, the core will not deviate in the first $T - Q$ periods if:

$$(D.3) \qquad (T - Q - t + 1)\pi_C^S + Q\pi_C^N > \pi_C^N + (T - t)w_i(1)$$

and will have a profitable deviation if the reverse holds. If $\pi_C^S \leq w_i(1)$ it is sufficient to consider only period $t = 1$, while if $\pi_C^S > w_i(1)$ it is sufficient to consider only the final period of the superstar phase, i.e. $t = T - Q$.

First consider the game without status rents. As before, $w_i(1) = \pi_C^N$. As $\pi_C^N > \pi_C^S$ for any $y^S > \hat{y}$, we consider period $t = 1$. Using this in (D.3) reduces the condition to $\pi_C^S > \pi_C^N$ which is not true. Thus, the reverse sign holds in (D.3) and a profitable deviation exists for the core player. Hence, the strategy profile $\mathbf{s}^*$ does not constitute a subgame perfect equilibrium in the absence of status rents. Q.E.D.

Now, we will show that superstars with a fixed core can indeed be sustained in our treatments with status rents. In our treatments with status rents $w(1) = \pi_P^N$. In treatment n4b22, $\pi_P^N > \pi_C^S$

for any $y^S > \hat{y}$, therefore we consider period $t = 1$. In this case, the minimal length of the Nash phase becomes:

$$Q > \frac{\pi_C^N - w_i(1) + T(w_i(1) - \pi_C^S)}{\pi_C^N - \pi_C^S}.$$

Computing this for $y^S = \tilde{y}$, gives $Q \geq 46$, which implies that an efficient superstar with a fixed core can be supported but only from period 1 to 29. In the other treatments with status rents (i.e. n8b22, n4b66 and n8b66) $\pi_C^S > \pi_P^N$, which implies that it is sufficient to consider the last period of the superstar phase. Using this in eq. (D.3) yields:

(D.4) $$Q > \frac{\pi_C^N - \pi_C^S}{\pi_C^N - w_i(1)},$$

which provides a condition for the minimal length of the Nash phase. As $w(1) = \pi_P^N$, and the payoff in the periphery of the Nash star is strictly smaller than π_C^S when $y^S = \tilde{y} = 4$, condition (D.4) implies that $Q \geq 1$ in n8b22, n4b66 and n8b66. In the final Q periods, the Nash star will be played, which is a stage-game Nash network. Hence, the core player has no profitable one-stage-deviation. Note that also superstars with higher core-investment than 4 units could be supported in this manner. Superstars can be supported in this way until the penultimate period as long as $\pi_C^S > \pi_P^N$. Table C.1. in Appendix C lists the payoffs in different star networks. In n8b22, superstars where $y^S \leq 4$ can be supported until the penultimate period, in n4b66 this is the case for $y^S \leq 5$ and in n8b66 for $y^S \leq 10$.

Finally, consider the periphery players in the game with status rents. Again, within a period, the periphery players best respond by linking to the core in the superstar. If a periphery player deviates, she will be punished in all $T - t$ remaining periods. The average future payoffs in case of deviation are thus $w_i(1)$. As $\pi_P^S > \pi_P^N \geq w_i(1)$, the future payoffs of adhering to the strategy are strictly larger than the future payoffs of deviation. Hence, no periphery player will deviate, which shows that the strategy profile $\mathbf{s}^N$ constitutes a subgame perfect equilibrium in the treatments with status rents, and that efficient superstars can be sustained until period $T - 1$.

Appendix E: Experimental instructions and test questions

All text in *red italics* is treatment specific. Treatment specific text is denoted by: <n4> and <n8> for $n = 4$ and $n = 8$ respectively, <ENDO> and <EXO> for endogenous and exogenous networks respectively and <b0>, <b22> and <b66> for the respective level of status rents. All public good investments and links in examples and test questions are independently and randomly generated for each subject.

Welcome!

Welcome to this experiment on decision-making. During the experiment, you are not allowed to communicate with other participants. If you have any questions, please raise your hand. One of the experimenters will come to you to answer your question.

During the experiment you can earn points. These points are worth money. How many points (and hence how much money) you earn depends on your own decisions, the decisions of others and chance. Your decisions are anonymous. They will not be linked to your name.

Every 30 points are equivalent to 0.10 euro.

At the end of the experiment the points that you earned will be converted to euros and the amount will be paid to you privately, in cash.

Today's experiment consists of two parts. You will spend most time on the second part. The second part will be explained after you have finished the first part. Your decision in the first part has no influence on the proceedings of the second part and your decisions in the second part do not affect the proceedings of the first part.

Instructions first part

You are now given 600 points. You must decide how many points you want to invest in a lottery. The points that you do not invest will be added your total earnings at the end of the experiments and paid out to you in cash.

The lottery: You have a chance of 50% of losing the amount you invest and a 50% chance of winning two and a half times the amount you invested.

Whether you win or lose in the lottery is determined by chance. For this, you choose whether you want to play heads or tails. If the outcome of the lottery is the same as your choice, you win. The chance of heads or tails is equal: both occur with 50% probability. The outcome of the lottery will be announced to you at the end of the experiment.

In summary, your earnings in the lottery are determined as follows. If you decide to invest X points in the lottery and you win the lottery, you earn the number of points that you did not invest in the lottery plus two and a half times the number of points that you did invest in the lottery. Thus, your earnings will then be:

$600 - X + 2.5\ X.$

If you lose then you will only earn the points that you did not invest. Your earnings will then be:

$600 - X.$

If you have any questions, please raise you hand and one of the experimenters will come to you to answer your question. If everything is clear, click below to make you decision for the lottery.

○ heads   ○ tails

Invest: ☐ points

Instructions second part

Please read the following instructions carefully. After reading the instructions we will ask you several questions to test whether you understand the experiment. The experiment will continue

after you answered all questions correctly. While reading the instructions, you can browse back and forth between pages by using the menu on the top of your screen.

Your total earnings consist of the points you earn in the first part of the experiment (the lottery) and the sum of all points that you earn in the second part of the experiment. At the beginning of the second part you will receive a starting capital of 2000 points. This will also be added to your earnings.

As before, every 30 points are equivalent to 0.10 euro

The second part of the experiment consists of 75 rounds. You have now been randomly placed in a group of <n4> *4* <n8> *8* participants. The composition of this group will not change during the experiment. In this group you will be randomly assigned a role. This role will be indicated by a letter: <n4> *"A", "B", "C" or "D"* <n8> *"A", "B", "C", "D", "E", "F", "G" or "H"*. The letters <n4> *"A", "B", "C" and "D"* <n8> *"A", "B", "C", "D", "E", "F", "G" and "H"* will thus refer to the same participant throughout the entire experiment.

Everybody in your group has received the exact same instructions. However, it may be that people that are not in your group will participate in a different experiment.

Costs and benefits

Every round you can earn points by having 'access' to units of a good. The number of points that you earn depends on the number of units that you have access to. This is shown in the following table:

Units	0	1	2	3	4	5	6	7	8	9	10	10+i
Benefits	0	92	152	177	196	199	202	203	204	205	206	206+i

The table shows for instance that you earn 152 points if you have access to 2 units and that you earn 204 points if you have access to 8 units of the good.

There are two ways to access units of the good.
1. You buy units of the good yourself.

2. You <ENDO> *make* <EXO> *have* a 'link' to another participant. In this case you have access to the units that the other participant has bought.

<b22 b66> *In addition, you will earn points if other participants make a link to you. For each link that another participant makes to you, you will receive* <b22> *22 points.* <b66> *66 points.*

Buying units and <ENDO> *making* <EXO> *having* links is costly.

The cost of <ENDO> *making* <EXO> *having* a link is 70 points for each role. Every round, you can maximally <ENDO> *make* <EXO> *have* one link to each of the other roles. This means that you cannot <ENDO> *make* <EXO> *have* more than 3 links.

<EXO> *You yourself will not decide on your links, like others will not decide on their links. When you decide on how many units you want to buy, you will be informed about the links that you will have in the current round. The number of units that you buy does not affect links in the current or future periods. Similarly, the links that others buy neither affect links in the current of future rounds. The participants in this experiment do not have any influence on how the links evolve.*
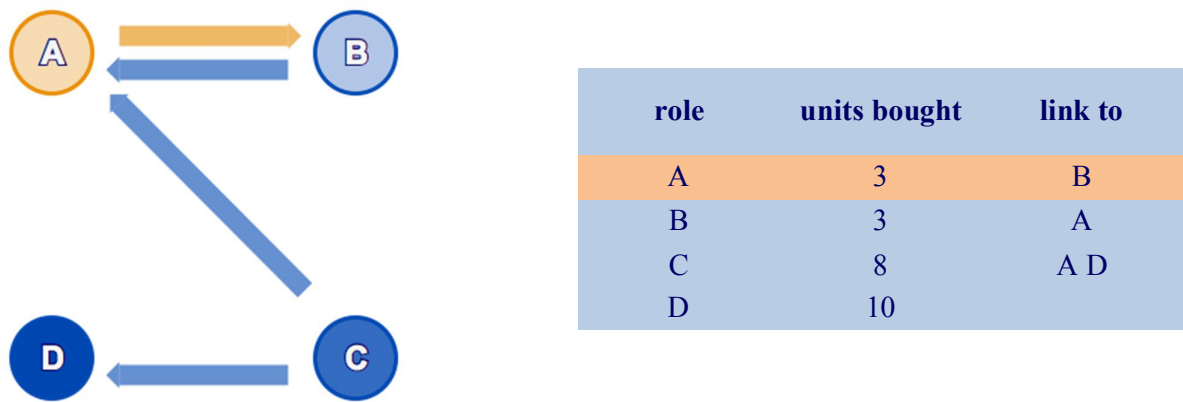
The cost of buying units is 55 points per unit. Every round, you can maximally buy 10 units of the good.

In summary:

Cost per unit	55
Cost per link	70
<b22 b66> ***Benefits per link to your role***	<b22> *22* <b66> *66*

Example

role	units bought	link to
A	3	B
B	3	A
C	8	A D
D	10	

The table and the figure above show a possible outcome of a round. The table and figure merely serve as an example, the content does not give any information on what to expect in the experiment. The numbers chosen for this example have been chosen randomly and are different for each participant.

The decisions of your role are displayed in orange and the decisions of the other roles are displayed in blue. In the example, your role is A. In the figure, roles are indicated by the letters <n4> *A, B, C and D* <n8> *A, B, C, D, E, F, G and H*. The number of units a participant bought is indicated by the colored circles. The larger the acquisition of a participant is, the darker is the circle at the corresponding role. In the example, the participant in role B bought 3 unit(s) and the participant in role D bought 10 units. The blue circle at role D is thus darker than the blue circle at role B. The acquisitions of all participants are also listed in the table.

In the figure, links are indicated by arrows. The arrow points away from the one who made the link. In this case, A <ENDO> *made* <EXO> *has* a link to B, B <ENDO> *made* <EXO> *has* a link to A, C <ENDO> *made* <EXO> *has* links to A and D and the participant in <n4> *role D* <n8> *roles D, E, F, G and H* <ENDO> *made* <EXO> *has* no links. These decisions are also listed in the table.

In the example your role is A. In the example above, your earnings would be calculated as follows:

	Cost/benefits
You bought 3 units	-165
You <ENDO> *made* <EXO> *have* 1 link(s)	-70
Access to 6 units	202
<b22 b66 ENDO> *2 link(s) made to you* <b22 b66 EXO> *2 link(s) to you*	<b22> *44* <b66> *132*
Earnings this round	<b22> *11* <b66> *99*

Practice questions I

Your group of four participants:

◯ Is the same in every round

◯ Changes from round to round

Which statement is correct:

◯ Your role is the same in every round

◯ Your role is determined randomly every round

How many points do you earn if you access 3 units of the good?

_____ points

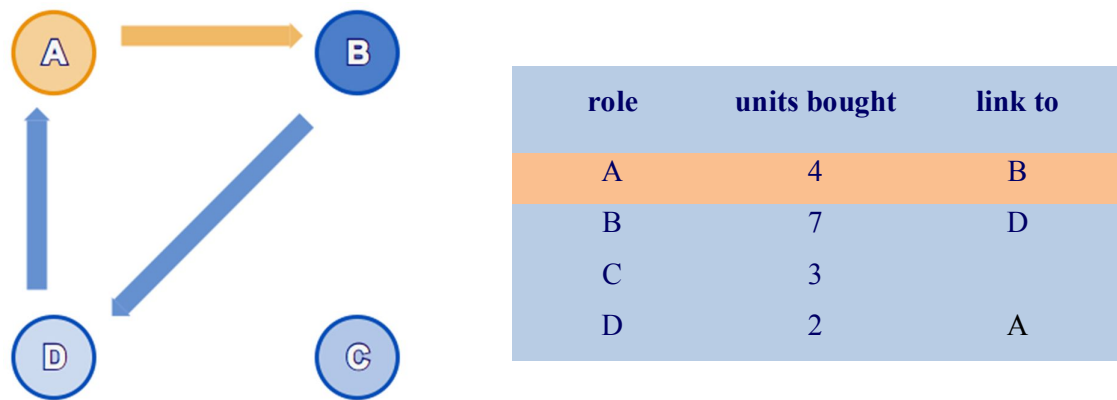How many points does it cost to <ENDO> *make* <EXO> *have* a link to another participant?

_____ points

<b22 b66 ENDO> *How many points do you earn for each link that is made to you?*

<b22 b66 EXO> *How many points do you earn for each link to you?*

_____ points

Practice questions II (identical setup for Practice questions III)

role	units bought	link to
A	4	B
B	7	D
C	3	
D	2	A

The table and the figure above show a possible outcome of a round. The table and figure merely serve as an example, the content has been generated randomly and gives no information on what to expect in the experiment.

What are your total costs for <ENDO> *making* <EXO> *having* links in the example above?
_____ points

In the example above you bought 4 unit(s) of the good. How many points does this acquisition cost?
_____ points

How many units of the good do you access in total in the example above?
_____ points

What are your benefits of accessing units of the good in the example above?
_____ points

<b22 b66 ENDO> *How many points do you earn for the links that are made to your role?*
<b22 b66 EXO> *How many points do you earn for the links to your role?*
_____ points

What would be your earnings in the example above?
_____ points

End of instructions

You have reached the end of the instructions. You can still go back by using the menu above. If you are ready, click on 'continue' below. If you need help, please raise your hand

Hand-out printed summary

Summary

Your total earnings consist of the points you earn in the first part of the experiment (the lottery) and the sum of all points that you earn in the second part of the experiment. At the beginning of the second part you will receive a starting capital of 2000 points. This will also be added to your earnings.

Every 30 points are equivalent to 0.10 euro

The second part of the experiment consists of 75 rounds. You have now been randomly placed in a group of <n4> *4* <n8> *8* participants. The composition of this group will not change during the experiment. In this group you will be randomly assigned a role. This role will be indicated by a letter: <n4> *"A", "B", "C" or "D"* <n8> *"A", "B", "C", "D", "E", "F", "G" or "H"*. The letters <n4> *"A", "B", "C" and "D"* <n8> *"A", "B", "C", "D", "E", "F", "G" and "H"* will thus refer to the same participant throughout the entire experiment.

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Benefits	0	92	152	177	196	199	202	203	204	205	206	206+i

The table shows for instance that you earn 152 points if you have access to 2 units and that you earn 204 points if you have access to 8 units of the good.

There are two ways to access units of the good.
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Buying units and <ENDO> *making* <EXO> *having* links is costly.

The cost of <ENDO> *making* <EXO> *having* a link is 70 points for each role. Every round, you can maximally <ENDO> *make* <EXO> *have* one link to each of the other roles. This means that you cannot <ENDO> *make* <EXO> *have* more than 3 links.

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The cost of buying units is 55 points per unit. Every round, you can maximally buy 10 units of the good.
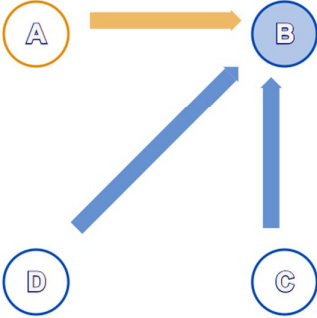
In summary:

Cost per unit	55
Cost per link	70
<b22 b66> **Benefits per link to your role**	<b22> *22* <b66> *66*

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Appendix F: Screen shots

You are in role A

HISTORY

Results of round 23

role	units bought	link to
A	0	B
B	3	
C	0	B
D	0	B

Previous round | Next round

You earned **107** points in round 23

CURRENT DECISION

Your decision in round 24

Indicate to whom you want to link:

☐ B
☐ C
☐ D

Indicate how many units you want to buy:

[ ] units

OK

RESULTS

role	units bought	link to
A	6	
B	0	A
C	0	A
D	7	
E	0	D
F	0	D
G	0	D
H	0	D
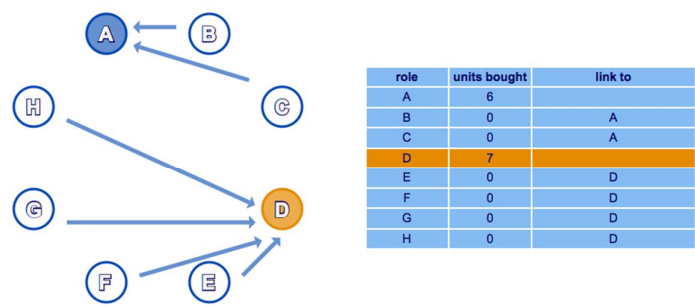
Round 9 of 75

	Cost/benefits
You bought 7 units	-385
You made 0 link(s)	-0
Access to 7 units	203
4 link(s) made to you	264
Earnings this round	**82**

In total you earned 10197 points

Next round