Building Up Social Capital in a Changing World: a network approach

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Summary

This paper models the dynamic process through which a large society may succeed in building up its "social capital" by establishing a stable and dense pattern of interaction among its members. In the model, agents interact according to a collection of infinitely repeated Prisoner's Dilemmas played on the current social network. This network not only specifies the playing partners but, crucially, also determines how relevant strategic information diffuses or new cooperation opportunities are found. Over time, the underlying payoffs randomly change, i.e. display some "volatility", which leads agents to react by creating new links and removing others. The process is ergodic, so we use numerical simulations to "compute" its long-run invariant behavior and obtain the following conclusions: (a) Only if payoff volatility is not too high can the society sustain a dense social network. (b) The social architecture endogenously responds to increased volatility by becoming more cohesive. (c) Network-based strategic effects are an essential buffer that preclude the abrupt collapse of the social network in the face of growing volatility. These conclusions, largely in tune with those of the social-capital literature, are further studied analytically in a companion paper through the use of mean-field techniques.

Keywords: Social Capital, Prisoner's Dilemma, Search, Social Networks, Volatility

JEL: C72, D74, D83

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1 Introduction

The network of agent interaction (the social network, for short) is the backbone on which an economic system operates. Its role is two-fold. On the one hand, of course, it determines how agents *come into contact* to carry out their economic activities. But, complementary to this, the social network also maps how the relevant *information* underlying those activities *flows* among the agents. A proper understanding of many economic phenomena, therefore, require a good grasp of the reciprocal interplay between network architecture and economic behavior, preferably approached in a dynamic scenario.

In principle, the social network should be conceived as an endogenous outcome of agents' decisions, much in the same way as any other economic choice. Networking decisions, however, are particularly interesting in that they display the following two features:

(i) they are "instrumental" *investment* decisions, subject to the considerations of cost, expectations, and depreciation.

(ii) They produce unintended large externalities (informational and otherwise) on other agents.

The above suggests considering the gradual buildup of the network as an accumulation of social capital. The term "social capital" has been used in recent times with a variety of different meanings, some of them perhaps too vague or devoid of operational content.[1] Here, I focus on one of the most widely agreed incarnations of this concept. I identify the stock of social capital enjoyed by a certain community with the density and stability of its social network. This, of course, is motivated by the implicit assumption that some dense and stable interaction has positive welfare implications, and should typically be correlated with high overall payoffs. (Admittedly, this assumption may not suitable for some applications, as stressed, for example, by Durlauf (1999).)

To address the aforementioned issues in a simple and paradigmatic context, I propose a model where players are involved in a collection of pairwise Infinitely Repeated Prisoner's Dilemmas (IRPD). Every pair of agents directly linked by the social network play an *idiosyncratic* version of this game (i.e. cooperation and relative opportunistic gains typically differ across pairs). These games are played independently, in the sense that the choices made in each of them (cooperation or defection) are adopted independently at each stage by the players involved. The different games, however, are not *strategically* independent since the behavior of a player in one of the games she plays can be made dependent on what has previously happened in other games.[2] Such information on past

[1] Even though the concept has a longer history, it was James Coleman (see Coleman (1988)) who focused the attention of the sociological, and then economic, literature on the notion of social capital. For a good and recent overview on the use and possible misuse of this concept, see Woolcock (2000), whose discussion mostly focuses on development issues.

[2] This feature of the model is reminiscent of the well-known paper of Bernheim and Whinston (1990), which explore the implications for collusion of multi-market strategic interaction. The relationship with this work is discussed in some detail in Section 6.

behavior, however, is not assumed to diffuse instantaneously. Rather, it is supposed to "travel" gradually (one step/link at a time) along the network. Of course, only when it arrives to any particular player can the latter's choice be affected by it – say, triggering a punishment to a then-revealed defector.

In this context, it is apparent that the range of incentive-compatible behavior that can be supported in the infinitely repeated population game must be crucially dependent on the architecture of the underlying network. And reciprocally, of course, the particular network that should prevail – more specifically, which links will be formed and which removed – also has to depend on the payoffs that can be earned in an incentive-compatible fashion. To formalize these considerations, I define the notion of *Pairwise-Stable Network* (PSN), that combines standard ideas from the literature on repeated games with the concept of pairwise stability found in the matching and network-formation literatures. Informally, a PSN is a network in which each of its extant links supports bilateral cooperation when every player uses optimal trigger strategies in all of her (repeated) interactions.

The first task undertaken in the paper is to *characterize* those networks that qualify as PSN. I find that rather fine details of the architecture of the network are important to understand pairwise stability. For example, a key factor supporting the stability of a link between two players hinges upon the existence of other "valuable" neighbors who could punish a deviation without much delay (because they are "close" to both players). In other words, some measure of network cohesiveness (or generalized clustering) is typically important in supporting network stability.

The essential approach of the paper, however, is not static (i.e. concerned with equilibria *per se*) but dynamic. The aim, therefore, is to shed light on how the interplay between cooperation and link formation shape the social network over time. To address these concerns, I postulate a population adjustment process through which agents gradually adapt their behavior to the changing circumstances of their environment. This process, which is taken to proceed on a "slow" time scale relative to the rate at which the stage game is repeated, consists of the following three components.

1. *Update of payoff conditions.* The payoffs of existing links are changed (redrawn afresh) with some independent probability, say $\varepsilon > 0$. This probability – a key parameter of the model – is interpreted as a stylized measure of environmental volatility.

2. *Search and link creation.* Each player receives, with some independent probability, the opportunity of forming one fresh new link. In that event, she observes the relevant payoff information concerning the players she "knows" – i.e. those in her network component – as well as, occasionally, of some other she does not know (i.e. a former "stranger" with whom she had no network path).

3. *Removal of unstable links.* Those links which cannot support cooperation (i.e. do not induce bilateral incentives for it) are eliminated.

The above law of motion is shown to induce a stochastic process which is *ergodic*. Its long-run behavior, therefore, is summarized univocally (i.e. *independently* of initial conditions) by its unique invariant distribution. This invariant distribution may be characterized in some particular scenarios – for example, when the support of admissible payoffs is low or when the payoff environment is stable ($\varepsilon = 0$). These cases represent useful benchmarks of comparison, but they are not the most interesting. In general, however, an analytical characterization of the long-run distribution or its direct computation for specific setups seems unfeasible. But, by virtue of ergodicity, there is another route possible: long-run invariant magnitudes of any variable of interest can be "computed" indirectly through simulations for any given setup. This follows from the fact that, along any simulation path, the empirical averages computed over time must converge almost surely to the theoretical means induced by the invariant distribution.

In the present paper, I rely on such a numerical approach to understand the long-run behavior and trade-offs concerning the following key variables of the model:

- *network density*, as given by the average degree (or connectivity) of the agents.
- *network cohesiveness*, as reflected by the average distance between the neighbors of any given node.
- *network span*, as embodied by the size of the network components.
- *payoff performance*, as measured by the average payoff earned per interaction.

The main regularities observed can be succinctly advanced as follows.

(a) The long-run density of the network depends negatively on ε, the extent of payoff volatility. So happens as well with the average payoff per link, which implies that volatility is detrimental both for the accumulation of social capital as well as for its return.

(b) As payoff volatility rises, the population's (uncoordinated) adjustment has the endogenous (side) effect of increasing the cohesiveness of the social network and thus partially offsetting the negative impact.

(c) Whenever the society is able to sustain a dense social network, its architecture displays a high span – in particular, it includes a comprehensive "largest component" that includes almost all connected individuals with any social capital.

(d) The harmful effects of volatility are strongly mitigated by the strategic deterrence on opportunistic behavior availed by the social network. If, *ceteris paribus*, every bilateral IRPD game were played independently, those effects would be much stronger and materialize abruptly.

The above conclusions underscore the point that a "stable environment" (i.e. one where agents' payoff conditions do not change too fast) is generally an important requirement for a successful accumulation of social capital. In addition, there are other important insights pertaining to the way in which the architecture of social interaction responds *endogenously* to changes in that environment. In a nutshell, the essential two features of the network that bear on this issue are *cohesiveness* and *span*. First, concerning cohesiveness, one finds that the network becomes more cohesive as the environmental volatility increases. Intuitively, this may be interpreted as the (uncoordinated) way in which society enhances the "strategic leverage" of network effects and thus maintains cooperation in the face of higher volatility. Increased cohesiveness, however, is not achieved at the cost of a narrower network span. The latter is kept as wide as possible, with almost all individuals who are not isolated (i.e. have some social capital) belonging to a *single* giant component. The intuitive basis for this conclusion should be clear: by preserving a wide network span, search remains an effective tool against volatility by allowing for quick adaptation to environmental changes.

In sum, therefore, the general theme stressed by the paper is that network strategic effects play an important social role in the face of volatility. To gain some further understanding on this phenomenon, the paper also relies on mean-field analytical techniques widely used in statistical physics for the study of complex systems. Very schematically described, the aim of mean-field analysis is to formulate a stylized "model" of the original model where the randomness and micro-detail of the latter is replaced by the expected (and therefore deterministic) motion of a suitably representative construct. Here, I restrict to the simplified approach along these lines undertaken in Vega-Redondo (2002), which has been developed in Marsili, Vega-Redondo, and Slanina (2003) to enjoy better foundations and encompass additional phenomena. As it turns out, the qualitative implications of the mean-field framework appear to be in essential accordance with the numerical simulations and also shed useful light on a number of interesting issues.

The rest of the paper is organized as follows. Next, Section 2 presents the model – first, its static version in Subsection 2.1, then its dynamic counterpart in Subsection 2.2. The analysis of the model starts in Section 3 with the characterization of pairwise-stable networks. It proceeds with the dynamics in Section 4, which consists of two subsections: Subsection 4.1, that establishes some basic dynamic results (e.g. the ergodicity of the process), and Subsection 4.2 that contains the bulk of our numerical analysis. In this latter subsection, the discussion starts with a benchmark scenario, followed by the consideration of a number of extensions and variants. Next, in Section 5, a simple mean-field analysis of the model is performed, comparing its conclusions with the numerical simulations. Finally, in Section 6 the related literature is reviewed, while Section 7 offers some concluding remarks and a number of possible courses for future research.

2 Model

2.1 Statics

Let $N = \{1, 2, ..., n\}$ be a finite population of agents who interact in pairs as reflected by the prevailing social network. Each pair of interacting agents, i, $j \in N$, is involved in an infinite repetition of a Prisoner's Dilemma (PD) with *idiosyncratic* payoffs given by the table

$$\begin{array}{c|c|c|} {}_{i} \quad {}^{j} & C & D \\ \hline C & \zeta_{ij} & \zeta_{ij} - \nu \\ \hline D & \zeta_{ij} + \nu & 0 \\ \hline \end{array} \tag{1}$$

where $\nu > \zeta_{ij} (= \zeta_{ji}) > 0$. As customary, C and D will be labelled as "Cooperate" and "Defect," respectively. Thus, the payoff ζ_{ij} obtained by both players if they jointly cooperate is ij-specific and, in the dynamic framework to be considered later on, it will change over time. For simplicity, the payoff of joint defection is normalized to zero, whereas in case of a unilateral defection the gain ν obtained by the defector over ζ_{ij} is made equal to the loss incurred her partner.

The pattern of bilateral interaction (i.e. which pairs of agents actually play) is specified by the *social network*. This network is the result of players' connecting decisions, which are captured by a certain *directed graph* $\vec{g} \subset N \times N$, where the nodes are the players and each directed link $(i, j) \in \vec{g}$ represents the decision of player i to connect to player j. Since, in equilibrium, agents' payoffs must always be non-negative (see Section 3), it is convenient to suppose that every linking decision leads to play and therefore the *social network* induced by $\vec{g}$ is simply the undirected graph $g \subset N \times N$ defined as follows:

$$\forall i, j \in N, \qquad (i, j) \in g \Longleftrightarrow [(i, j) \in \vec{g} \vee (j, i) \in \vec{g}] \, .$$

Thus, for any such network g and any player i, the set of her neighbors (i.e. the players with whom i interacts) is simply given by:[3]

$$N_i \equiv \{j \in N : (i, j) \in g\}$$

Usually, the more compact notation ij (or ji) will be used to denote the link between player i and j. Furthermore, we shall write $g - ij$ or $g + ij$ to represent the networks obtained from g by, respectively, adding or removing a link ij.

As explained, given the prevailing network g, all pairs of players i and j such that $ij \in g$ are involved in an Infinitely Repeated Prisoner's Dilemma (IRPD) with idiosyncratic stage payoffs given by their respective ζ_{ij} – cf. (1). Each of these different IRPD are played "in parallel," i.e. one round of each of them is

[3] Note, of course, that if $(i, j) \in g$, it follows that $(j, i) \in g$ as well.

played at every stage. They are *choice independent* in the sense that players' decisions in any one of them do not restrict the feasible choices available in others. They need *not* be, however, *strategically independent* since the behavior in any of them may be contingent on the information of what has occurred in others, as I presently explain.

In the latter respect, the key feature of the model is the assumption that the information on how players have behaved in the past diffuses through the social network only gradually. To fix ideas, suppose that at every stage in which two connected players interact according to their repeated game, each of them informs the other one of any relevant news she has learned since they last "met" – most crucially, of course, of any deviation by other players from notionally prescribed behavior. This, in effect, implies that all strategic information required to support desired behavior must "travel" along the network one link at a time. The architecture of the network, therefore, must generally have an important bearing on the extent of cooperation that the population as a whole can muster in an incentive-compatible manner.

To simplify matters, I postulate that players rely on *trigger strategies.* In the present context (see Remark 1 for further discussion), this is taken to mean that the strategies of any given player $i \in N$ display the following format:

(a) first, player i chooses, separately with each neighbor $j \in N_i$, whether to start their bilateral ij interaction by cooperation or defection;

(b) subsequently, she *immediately* reacts to the news that one of her own neighbors, say $j \in N_i$, did not start cooperating with some $k \in N_j$ by "punishing" her, i.e. by switching to irreversible defection in the corresponding bilateral IRPD played with j.

Note that, under the assumption that every player relies on trigger strategies, the only *separate* choices that she faces are those contemplated in (a), i.e. whether to start the interaction with each of her neighbors by cooperation or defection. Once this decision is made, all ensuing behavior is then unambiguously determined by (b). Formally, this allows one to identify (given g) a trigger strategy of a player i as a mapping $s_i^g : N_i \rightarrow \{C, D\}$.

Next, I specify the payoffs of the game. Given any strategy profile $s^g = (s_1^g, ..., s_n^g)$, any player i and some neighbor $j \in N_i$, let $\{\psi_{ij}^\tau(s^g)\}_{\tau=0}^\infty$ represent the flow of stage payoffs for player i univocally induced by s^g on the link $ij \in g$. Then, denoting by $\delta \in (0,1)$ the common discount factor displayed by all agents, the (normalized) discounted payoff induced by that payoff flow is $(1 - \delta) \sum_{\tau=0}^\infty \delta^\tau \psi_{ik}^\tau(s^g)$. Thus, aggregating across all of player i's links, her overall payoff function is defined by:

$$\pi_i(s^g) \equiv \sum_{k \in N_i} \left\{ (1-\delta) \sum_{\tau=0}^{\infty} \delta^\tau \psi_{ik}^\tau(s^g) \right\}.$$

Finally, before addressing the issue of network stability, it is convenient to introduce the following notation. Given the social network g, let $\hat{s}^g = (\hat{s}_1^g, ... \hat{s}_n^g)$

represent the strategy profile where every player starts cooperating with each of her neighbors. On the other hand, given any player i and one of her neighbors $j \in N_i$, denote by $\hat{s}^g \overset{ij}{\sim} a$ the modification of profile $\hat{s}^g$ where player i starts by choosing action $a \in \{C, D\}$ on her link ij. The basic criterion of strategic stability postulated here is embodied by the notion of *Pairwise-Stable Network* (PSN). Informally, a PSN simply consists of a network where, for every separate link, the two players involved have incentives to use it for cooperation. This notion implicitly embodies the idea that, unless both of the players connected by each link can separately confirm its incentives for cooperation, that link will vanish.

Definition 1 *An undirected graph* $g \subset N \times N$ *is said be a* Pairwise-Stable Network *if for all* $ij \in g$,

$$\pi_i(\hat{s}^g \overset{ij}{\sim} C) \equiv \pi_i(\hat{s}^g) \geq \pi_i(\hat{s}^g \overset{ij}{\sim} D).$$

To end this subsection, the following remark clarifies certain interesting issues concerning the use of trigger strategies in the present context.

Remark 1 – ***Trigger strategies, maximal punishment, and perfection:*** As formulated, the PSN concept directly embodies the assumption that players restrict to trigger strategies. This restriction was justified above on the grounds of simplicity. But in line with well-known results on the theory of repeated games (see Abreu(1988)), a further justification may be grounded in the fact that those strategies induce *maximal* punishments. They can be used, therefore, to support *any* incentive-compatible behavior.

Trigger strategies, however, raise in the present context a conceptual problem concerning credibility (or perfection). In particular, it is not generally optimal for a player to punish a neighbor when news about the latter's deviant behavior arrives since, by eschewing punishment, indefinite cooperation may be sustained. A natural way to address this problem is to modify the stability concept (and, correspondingly, enrich the set of admissible strategies) so that any potential defector is given the possibility of anticipating, and reacting optimally to, ensuing punishment. A modification along these lines is outlined in Remark 3, where the analysis is seen to embody more complex considerations but nevertheless yield analogous insights.[4] ⊠

2.2 Dynamics

In this paper, our aim is to undertake a fully dynamic analysis of the process by which social networks adapt to the environment. Thus, we must embed

[4]Another possible concern pertaining to the PSN notion is that it contemplates single-link deviations – i.e. does not allow players to assess the benefit of simultaneous deviations in several links. This is in the spirit of much of the recent literature on network stability (cf. the seminal paper by Jackson and Wolinsky (1996)), which often interprets such a restricted notion of stability as a reflection of bounds on the sophistication of agents. It seems intuitive, however, that allowing agents to contemplate multi-link deviations should not alter the gist of the analysis.

the equilibrium (static) approach reflected by the PSN concept into a dynamic framework. A description of this framework is the object of the present subsection.

Let time be modelled discretely, with $t = 0, 1, 2, ...$ indexing the consecutive time periods. At every t, each agent $i \in N$ supports a certain set of links (her "active" links), which consist of those he chose in the past and still maintains. These links are included the set $\vec{g}_i(t) \subset \{i\} \times N$. As in the static framework, we posit that agent i interacts at t with all her neighbors $N_i(t)$ in the *undirected* graph $g(t) = \{jk \in N : jk \in \vec{g}_j(t) \wedge kj \in \vec{g}_k(t)\}$, i.e. active and passive links are equivalent in terms of their implications for play. Their sole difference resides in the fact that a player's active links are taken on her own initiative, while the passive ones depend on the decisions of others. To bound the state space of the process, it is convenient to postulate that any given player can support at most m active links, a parameter of the model. This could be justified if, for example, in order to support a link an agent must devote some resources in limited supply (e.g. time).

Each of the links $ij \in g(t)$ prevailing at t has a certain payoff potential associated to it, as captured by the cooperation payoff $\zeta_{ij}(t)$ in the stage PD game played by i and j. Such information is sufficient to assess the stability of network $g(t)$. This suggests identifying the state of the system prevailing at any given t with the pair $\omega(t) = \{[\vec{g}_i(t)]_{i \in N}, [\zeta_{ij}(t)]_{ij \in g(t)}\}$, the only restriction being that each $\vec{g}_i(t)$ consists of at most m elements and every $\zeta_{ij}(t)$ belongs to the suitable range of payoffs (see below).

The social dynamics defining the law of motion across consecutive states embodies three distinct components: payoff update, link formation and search, removal of unstable links. I take up each of these in turn.

1. Payoff update

First, we suppose that the payoff of each link may be subject to a random update of its associated payoff. More precisely, with some independent probability ε, every link $ij \in g(t)$ has its payoff changed from $\zeta_{ij}(t)$ to $\zeta'_{ij}(t)$ where the latter drawn afresh from some non-negative real interval $[\underline{\zeta}, \overline{\zeta}]$ according to a stationary (and common) probability distribution with continuous density f_ζ. For future reference, denote by $\omega'(t) = \{[\vec{g}_i(t)]_{i \in N}, [\zeta'_{ij}(t)]_{ij \in g(t)}\}$, the new state thus generated (note that links are not affected at this stage, i.e. $g'(t) = g(t)$)

2. Link formation and search

In every period, every player $i \in N$ may enjoy two alternative (for simplicity, exclusive) routes of search and consequent formation of fresh links: component-bound "local" search and unrestricted"global" search. Whereas the first route is conceived as the more common way of accessing new information (i.e. mediated by the social network), the second one is regarded as more extraordinary (and thus only occasional). Formally, we posit that, with independent probability p, the first option arises, whereas with probability $(1 - p)q$ the second one occurs. I describe each of these alternative options in turn.

(2.a) Local search

Given $g(t)$, let $M_i(g(t))$ represent the set of players who are *not* direct neighbors of i but belong to the same *component* as i in $g(t)$ – i.e. there is a path in $g(t)$ joining them to node i. These are the potential new partners of player i when she receives a local (component-bound) search opportunity.

Specifically, such a local-search opportunity amounts to observing fresh and independent payoff draws ζ_{ij} (according to the probability density f_ζ) for all $j \in M_i(g(t))$. On the basis of this information, player i is allowed to establish *one* new link, possibly removing one of the pre-existing links with players in $N_i(t)$ if she already supports the maximum number of m links. More specifically, it is postulated that player i chooses a new link with some $j \in M_i(g(t))$ if, and only if, both of the following conditions hold:

(i) The payoff drawn afresh $\zeta_{ij} \geq \zeta_{ik}$ for all $k \in M_i(g(t))$.

(ii) If $|N_i(t)| = m$, $\zeta_{ij} > \zeta_{i\ell}$ for some $\ell \in N_i(t)$.

Thus, the creation of new links is supposed *gradual*, i.e. at most one at a time is formed. In case that (i) applies for more that one $j \in M_i(g(t))$, any of those individuals is selected with the same probability. On the other hand, if (ii) applies, then the link $i\ell$ to the current neighbor ℓ with the lowest payoff is removed. Again, if several of those exist, each one is chosen with equal probability.

Note that in selecting a new partner according to (i)-(ii), agents are postulated to abstract from the pairwise (in)stability of the new link to be formed. This is done for the sake of simplicity. I have also considered a variation of the model where players only form links that are perceived as pairwise stable (given the links and payoffs in the prevailing $\omega'(t)$). This alternative formulation, however, does not alter our results (neither analytical or numerical) and therefore I have chosen to ignore the formal complexities it entails.

(2.b) Global search

If some player i receives a revision opportunity through global search, she gets the possibility of forming one new link with another randomly selected individual j, possibly not in her component (all of them are *a priori* equally probable). Again, associated to this new potential partner a payoff ζ_{ij} is drawn according to the probability density f_ζ. Then, as above, the link is established, subject to the possible removal of a pre-existing link if the number of those links is maximum and one of them has a lower payoff.

3. Removal of pairwise-unstable links

Let $\omega''(t) = \{[\vec{g}_i''(t)]_{i\in N}, [\zeta_{ij}''(t)]_{ij\in g(t)}\}$ be the state induced by the two former components of the law of motion. Then, for every link $ij \in g''$, let the players i and j involved in the link evaluate whether both of the following incentive-compatibility conditions hold:

$$\begin{aligned} \pi_i''(g'' \overset{ij}{\sim} C) &\geq \pi_i''(g'' \overset{ij}{\sim} D) \\ \pi_j''(g'' \overset{ji}{\sim} C) &\geq \pi_j''(g'' \overset{ji}{\sim} D). \end{aligned}$$

If either of these conditions is violated, the link ij is judged unstable by the players and thus is removed. Once such a check of pairwise-stability has been completed for all links in g'', let $\omega'''(t)$ refer to the resulting state where only the links that have been assessed as pairwise-stable remain. This state is then carried over to the next period, by making $\omega(t+1) = \omega'''(t)$.

3 Static analysis: characterization of Pairwise-Stability

As in the presentation of the model, it is useful to start with an equilibrium (thus static) approach, then turning to a full dynamic analysis of the network formation process. Proposition 1 below initiates this course by providing an intuitive characterization of Pairwise-Stable Networks. This characterization hinges upon a certain measure of cohesiveness of the network, as embodied by the (geodesic) distances separating the neighbors of the different players.

Formally, for any given player $i \in N$, and any two of her neighbors $j, k \in N_i$, we define the *i-excluding distance* between j and k, denoted by $d^i(j,k)$, as the length of the shortest path joining j and k which does not involve player i. The interpretation of this distance is straightforward: it is the number of steps (and therefore periods, in the repeated game) which would be required for any information held by j (or k) to reach k (or j) without the concourse of player i. As usual, it is postulated that $d^i(j,j) = 0$ for any $j \in N_i$, while if no i-excluding path exists between k and j it will be convenient to posit that $d^i(j,k) = \infty$.

Proposition 1 *Consider any network $g \subset N \times N$ and let $[\zeta_{ij}]_{ij \in g}$ stand for the possible cooperation payoffs that can be earned for each of its links. Then, g is a Pairwise-Stable Network (PSN) if, and only if, for all $ij \in g$:*

$$\sum_{k \in N_i} (\zeta_{ik} + \frac{1-\delta}{\delta}\nu)\ \delta^{d^i(j,k)} \geq 2\frac{1-\delta}{\delta}\nu \tag{2}$$

Proof. Consider any link $ij \in g$ and focus, for concreteness, on player i. Pairwise-stability of this link requires that player i has incentives to cooperate with j under the threat that, if she were to do otherwise, all his neighbors $k \in N_i$ will switch to defection once they learn about it – an event that, for each of them, occurs $d^i(j,k)$ periods after the contemplated defection takes place.

If player i cooperates with j, she anticipates an intertemporal payoff:[5]

$$\pi_i(g \overset{ij}{\sim} C) = \sum_{k \in N_i} \zeta_{ik}.$$

[5] Recall that stage payoffs are normalized by the factor $(1-\delta)$.

Instead, if player i defects unilaterally upon j, her anticipated payoff is:

$$\begin{aligned}\pi_i(g \overset{ij}{\sim} D) &= (1-\delta)(\zeta_{ij}+\nu) \\ &\quad + \sum_{k\in N_i\setminus\{j\}} \left\{ \left[\sum_{s=0}^{d^i(j,k)-1} (1-\delta)\delta^s \zeta_{ik} \right] + (1-\delta)\delta^{d^i(j,k)}(\zeta_{ik}-\nu) \right\} \\ &= (1-\delta)(\zeta_{ij}+\nu) + \sum_{k\in N_i\setminus\{j\}} \left[(1-\delta^{d^i(j,k)+1})\zeta_{ik} - (1-\delta)\delta^{d^i(j,k)}\nu \right].\end{aligned}$$

Therefore, the stability condition

$$\pi_i(g \overset{ij}{\sim} C) \geq \pi_i(g \overset{ij}{\sim} D)$$

can be written as follows:

$$\delta\zeta_{ij} + \sum_{k\in N_i\setminus\{j\}} \delta^{d^i(j,k)}\delta\zeta_{ik} \geq (1-\delta)\nu - \sum_{k\in N_i\setminus\{j\}} (1-\delta)\delta^{d^i(j,k)}\nu$$

which is readily seen to be equivalent to (2). ■

Remark 2 ***Network stability in the absence of network effects:***

If players did not rely on network (population-wide) effects in their strategic considerations, cooperation could be supported through any particular link ij if, and only if, it could be done bilaterally. That is, if

$$\zeta_{ij} \geq \frac{1-\delta}{\delta}\nu, \tag{3}$$

which is simply the condition that would follow from (2) if $d^i(j,k) = \infty$ for all $k \neq i$. In general, network-based effects can only help in supporting cooperation, i.e. (3) implies (2). It should be emphasized, however, that even in the absence of those effects, the social network may have an important role to play through its bearing on search and innovation. This, in fact, will be confirmed in Subsection 4.2.2), which studies a scenario without network *strategic* effects. ⊠

Remark 3 ***Network stability with higher player sophistication:***

In Remark 1, we discussed the possibility of allowing players a superior degree of sophistication that would allow them to anticipate the stage at which others would punish her for a deviation, thus reacting optimally to it through non-trigger strategies. Space limitations prevent us from developing in detail the implications of this variation. The interested reader, however, may verify that, as a counterpart of (2), the condition that would characterize pairwise-stability in that case would read as follows:

$$\zeta_{ij} - \frac{1-\delta}{\delta}\nu \geq \min\{0, -\sum_{k\in N_i\setminus\{j\}} (\zeta_{ik} - \frac{1-\delta}{\delta}\nu)\delta^{d^i(j,k)-1}. \tag{4}$$

To understand the implications of the above condition, it is useful to compare it with the following inequality:

$$\zeta_{ij} - \frac{1-\delta}{\delta}\nu \geq - \sum_{k \in N_i \setminus \{j\}} (\zeta_{ik} + \frac{1-\delta}{\delta}\nu)\delta^{d^i(j,k)-1} \tag{5}$$

which is a mere rewriting of (2), the condition characterizing PSN in Proposition 1. One then observes that similar qualitative considerations arise in both cases – i.e. the number, payoff value, and relevant distances of neighbors continue to be the key factors involved. In (4), however, the higher sophistication assumed on the part of players (which allows them a preemptive reaction to punishment) leads to weaker deterrence against deviations. This, in turn, weakens somewhat – but certainly does not destroy – the role of network cohesiveness in promoting inter-player cooperation. ⊠

4 Network dynamics

4.1 Ergodicity and other basic results

As a extreme benchmark case, suppose that *no* fresh links are ever formed through search (i.e. $p = q = 0$) and prevailing payoffs are *never* subject to update ($\varepsilon = 0$). Then, the dynamics reduces to a mere chain of link removals, as the links which are deemed unstable are being withdrawn by the agents involved. Eventually, it reaches a stationary state, where the induced network is pairwise stable in the sense of Definition 1. In fact, it is obvious that the sets of pairwise-stable and stationary networks coincide, which provides a simple dynamic foundation of the PSN concept.

But, of course, our primary interest and focus pertains to the full-fledged dynamics where $p, q, \varepsilon > 0$. In this case, link removal is countered by search and link formation, and the underlying payoff conditions are subject to occasional change. A first basic step in the analysis concerns the establishment of conditions under which the induced Markov process is sure to be ergodic. For, as advanced, such ergodicity provides the theoretical basis for the later use of numerical simulations in elucidating the long-run behavior of the system.

To address these matters formally, recall that $f_\zeta(\cdot)$ stands for the probability density with governs every fresh draw of payoffs, whose support is given by a non-negative interval $[\underline{\zeta}, \overline{\zeta}]$. Further remember from (3) that $\frac{1-\delta}{\delta}\nu$ is the payoff threshold that marks the bilateral supportability of cooperation between a pair of "isolated" agents. In this light, the following result states that ergodicity is guaranteed as long as, for any cooperation payoff ζ_{ij} redrawn afresh, there is some prior uncertainty as to whether it may be supported bilaterally, i.e. in the absence of network effects.

Proposition 2 *Assume* $\underline{\zeta} < \frac{1-\delta}{\delta}\nu < \overline{\zeta}$ *and* $\varepsilon, q > 0$. *Then, provided the population N is large enough, the social dynamics described in Subsection 2.2 is governed by an ergodic stochastic process.*

Proof. The induced process is clearly aperiodic. Therefore, to establish the desired conclusion, it is enough to show that there is some particular state to which there is positive probability of returning, from any other state ω, in some finite number of steps. In the argument, the state ω^e where there are no links established between players will play this recurrent role.

Consider any arbitrary state $\omega = \left[(\vec{g}_i)_{i\in N}, (\zeta_{ij})_{ij\in g}\right]$ prevailing at some point in time. The first point to note is that, if n is large enough, there is positive probability that the network might be eventually divided into two or more disjoint components. To see this, suppose that n is even and let the population be partitioned into two disjoint subsets, say $N_1 = \{1, 2, .., \frac{n}{2}\}$ and $N_2 = \{\frac{n}{2} + 1, \frac{n}{2} + 2, ..., n\}$. Further suppose, without loss of generality, that $\zeta_{ij} < \overline{\zeta}$ for all $ij \in g$. Then, let revision opportunities arise (possibly through global search) so that players in N_1 obtain payoff options ζ_{ij} with players $j \in N_2$ satisfying:

$$\overline{\zeta} > \zeta_{ij} > \max\{\frac{1-\delta}{\delta}\nu, \max_{k\in N_2} \ \zeta_{ik}\},$$

and reciprocally for players in N_2. These revision opportunities induce pairwise-stable and payoff-improving links for each player in N^q over those that could be supported with agents in the complementary set N^r $(q, r = 1, 2,\ q \neq r)$. Therefore, if n is large enough (in particular, it is enough that $n \geq 2(2m + 1)$, where m is the maximum number of links supportable by an agent), all links across N_1 and N_2 would eventually be removed.

Now suppose that players are divided into such disjoint components, N_1 and N_2, and let each player in N^q in turn receive a global revision opportunity with some player in N^r $(r \neq q)$ whose associated payoff is higher than any prevailing one (but lower than $\overline{\zeta}$). Then, the corresponding link is formed, removing one of her pre-existing ones. Next suppose that this freshly formed link is subject to a payoff update, with the consequence that its payoff is lowered below $\frac{1-\delta}{\delta}\nu$. This leads to the link being removed, since it is the only link which currently connects the sets N_1 and N_2 and, therefore, players cannot rely on network effects to support cooperation with it. By proceeding in this fashion with all players in turn as needed, it is clear that the process would reach the empty network. By construction, the chain of steps involved is finite and displays positive probability. The proof, therefore, is complete. ■

The former result indicates that when the link-removal process is complemented by search in a non-stationary environment, the process becomes ergodic and thus its long-run behavior is independent of initial conditions. It is instructive to disentangle the effect played by global search $(q > 0)$[6] and volatility $(\varepsilon > 0)$ in this conclusion. First, if there were no global search (i.e. $q = 0$) but volatility were maintained, it is easy to adapt the argument of Proposition 2 to

[6] For the present qualitative discussion concerning the ergodicity of the process, only the presence or absence of global search is the relevant consideration. In general, of course, the intensity of local search (i.e. the magnitude of p, in comparison with other parameters) will have an important role in the (quantitative) performance of the process

show that ergodicity would still hold, although the absorbing long-run outcome would be the empty social network ω^e. But the most interesting case to consider is the polar one where search (both local and global) remains in place and the underlying environment displays no volatility ($\varepsilon = 0$). This scenario represents a specially useful benchmark of reference in order to understand the key effect of volatility in the model. A clear-cut picture is provided by the following result.

Proposition 3 *Assume $\underline{\zeta} < \frac{1-\delta}{\delta}\nu < \overline{\zeta}$ and $q > 0$. Then, if $\varepsilon = 0$, the social dynamics leads almost surely to a path where the network reaches the maximum connectivity and the induced total payoff (aggregated over the whole population) converges to it maximum value $2mn\overline{\zeta}$.*

Proof. To establish the desired conclusion, the key role is played by the following two observations:

(1) Consider any $\eta > 0$ such that $\overline{\zeta} - \eta > \frac{1-\delta}{\delta}\nu$. Then, since the density $f_\zeta(\cdot)$ is assumed continuous on its support $[\underline{\zeta}, \overline{\zeta}]$ and revision opportunities are independent across players and time, the following conclusion applies. For all $\theta \in (0, 1)$, there is some T such that if $t \geq T$, there is probability no lower than $1 - \theta$ that every player i has received (in preceding periods $\tau < t$) at least m link formation opportunities with distinct partners j and associated payoffs $\zeta_{ij} > \overline{\zeta} - \eta$.

(2) Any of the link opportunities described in (1) are pairwise stable. Therefore, choosing θ and T as above, there is probability no lower than $1 - \theta$ that, if $t \geq T$, every player i is supporting m links at t (the maximum number), all of them with associated payoffs no lower than $\overline{\zeta} - \eta$.

Then, since η and θ in (1)-(2) can be chosen arbitrarily small, the desired conclusion immediately follows. ■

The previous result indicates that, in the absence of payoff volatility, the accumulation of social capital must eventually reach a maximum level. This serves to highlight the key role to be played by ε as the leading parameter of the ensuing discussion.

4.2 Numerical analysis

Building upon the basic results presented in the previous Subsection, I now conduct a more exhaustive analysis of the model based on numerical simulations. For the sake of focus, the analysis deals with a scenario displaying rather stringent payoff conditions, in which the main issues arise in a stark fashion. In particular, our essential concern is to understand how the interplay between environmental volatility and the dynamics of the social network shapes the long-run performance of the system.

Specifically, the simulation setup involves $100 (= n)$ individuals who display a common discount rate $\delta = 3/4$ and interact according to an IRPD game with *stage* payoffs as given by (1) for $\nu = 4$. The cooperation payoffs ζ_{ij} are drawn, randomly and independently, according to a uniform distribution over the interval $[\underline{\zeta}, \overline{\zeta}] = [0.4, 1.4]$. Thus, as required by Proposition 2, the threshold $\frac{\nu(1-\delta)}{\delta} = \frac{4}{3}$ which marks the possibility of supporting cooperation bilaterally (cf. (3)) belongs to the payoff support and thus ergodicity is guaranteed. Payoff conditions, however, are rather "tight" in that the probability $\Pr[\zeta_{ij} \geq \frac{1-\delta}{\delta}\nu]$ for a fresh draw to exceed the aforementioned threshold is just 1/15.

Finally, it is postulated that the independent probability at which an individual receives a revision opportunity based on local search is equal to $p = 0.1$, while in case no such opportunity arises the conditional probability for enjoying an instance of global search is $q = 0.01$. The maximum number of links that any given player can actively support is set to $m = 2$ (therefore, the average network degree is at most 4).

In the above described scenario, the numerical analysis is divided in two parts. First, in Subsection 4.2.1, we consider the leading case where players may take full advantage of network effects in supporting cooperation – that is, strategic behavior is "network-based" and pairwise stability is given by Definition 1. Then, in Subsection 4.2.2, we turn to studying how matters are affected if players do *not* rely on such network effects and all cooperation must be supported bilaterally.

4.2.1 Network-based strategic behavior

The analysis will focus throughout on the four variables contemplated in our earlier discussion: *network density* (average node degree), *network cohesiveness* (average neighbor distance), *network span* (relative size of the largest components), and *payoff performance* (average payoff earned per link).

To start the discussion, Figure 1 shows sample paths for the first of the indicated variables – the average degree – under three different volatility rates, $\varepsilon = 0.01,\ 0.07,\ 0.013$. Each of these paths begins from an empty network (i.e. no links are present at $t = 0$) and spans a relatively narrow time window of only 30000 periods. Naturally, one observes a jagged path in each case, a mere reflection of the underlying randomness of the process. By virtue of ergodicity, however, we know that, if the simulation run is extended far enough in time, not only the empirical mean of the variable (computed over time) should converge a.s. to a well-defined limit value but this value should be independent of the initial conditions.

Indeed, such implication of ergodicity is sharply confirmed by the simulations if we lengthen the time horizon to half million periods ($T = 5 \times 10^5$), as shown in Figure 2. There one observes that, for each of the three volatility rates considered, the empirical means converge quite rapidly to a common value, even for alternative paths starting from *polar initial conditions*. Specifically, two such initial conditions are considered in that diagram. One of them corresponds to the empty network, as described before. A second polar case is given by a path that starts at a configuration where all players are connected to their neighbors

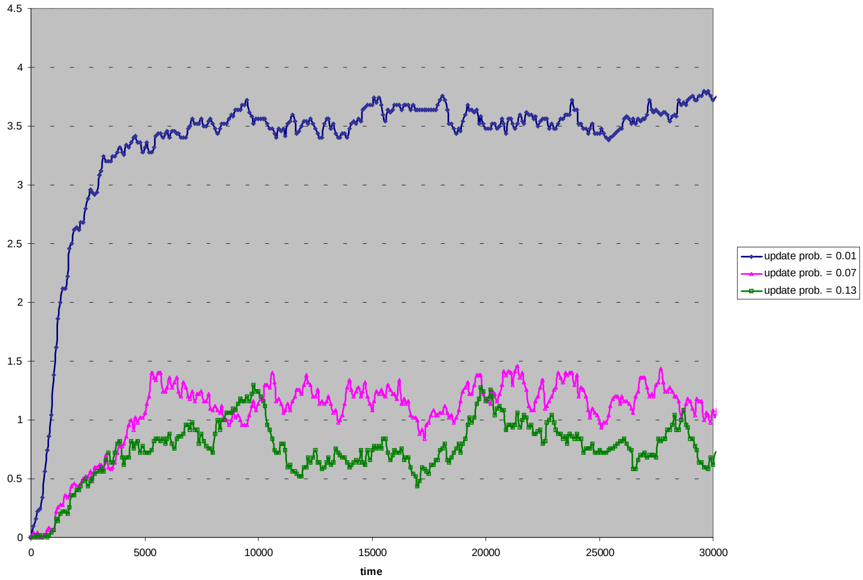

Figure 1: Average degree, short time horizon.

through their maximum number of (two) active links and earning the maximum possible payoff $\overline{\zeta}$.[7]

Equally clear-cut convergence of the empirical means has been confirmed as well in the simulations for the other three variables of interest: neighbor distance, large-component shares, and average payoff. (These results, however, are not are not shown here for lack of space.) As explained, such a convergence allows one to rely on the empirical values obtained as suitable approximations of the corresponding long-run magnitudes, i.e. those induced by the unique invariant distribution of the process. In what follows, the aim will be to understand how these long-run magnitudes depend on the leading parameter of our analysis, the volatility rate ε.

The results in this respect are summarized in Figures 3-6. First, Figure 3 shows that payoff volatility has a negative effect on the density of the social network (as measured by the average node degree). Intuitively, this follows from the fact that, as ε rises, there is a larger fraction of existing links that lose its pairwise stability due to payoff update. This phenomenon may be heuristically understood as a sort of depreciation of the accumulated social capital. It reflects, in effect, a negative drift on the stock of existing links, which were gradually accumulated over time through separate instances of successful search.

[7] To be more concrete, what is done in this case in order to construct the initial conditions is to have every player i support a link to players $i+1$ and $i+2$ with $\zeta_{i,i+1} = \zeta_{i,i+2} = \overline{\zeta}$, where these indices are interpreted as "modulo n".

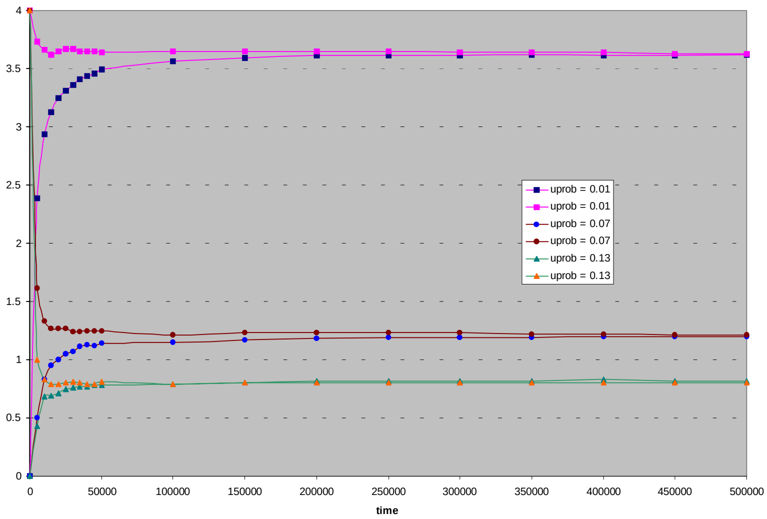

Figure 2: Empirical mean of the network average degree, polar initial conditions.

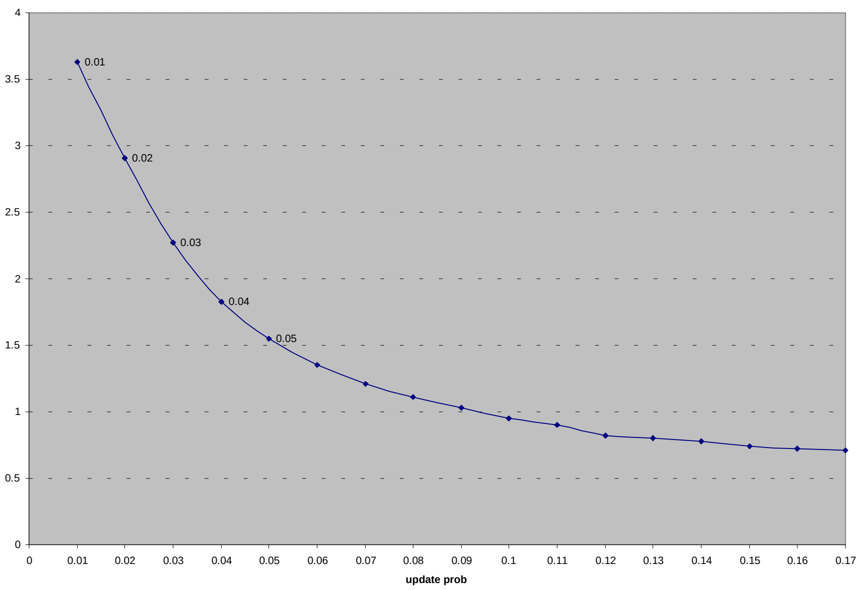

Figure 3: Payoff volatility and long-run average degree.

Next, Figure 4 depicts what is possibly one of the most remarkable regularities found in the analysis. It shows that, as ε grows, the social network endogenously adapts to increased volatility by becoming more *cohesive* in the long run – i.e. the average neighbor distance falls.[8] This is in line with what has been learned so far about the role played by network effects in enhancing the incentives for cooperation (recall, for example, the characterization of pairwise-stability in Proposition 1). Thus, in this sense, what we find is that the social dynamics responds to increased volatility by *endogenously* building up the strength of these network effects. Agents, unwittingly, adjust myopically their links over time so that the social network ends up adapting to higher volatility by raising its long-run cohesiveness. This, in the end, has the beneficial (but unintended) effect of deterring opportunistic behavior more effectively as such a network-based deterrence becomes more critical.

Finally, it is worth emphasizing that the aforementioned considerations are to be regarded as quite strong. For, in particular, they are strong enough to prevail over the general decrease in connectivity that results as ε grows (recall Figure 3). By itself, such a decrease in overall connectivity tends to increase path lengths and thus would entail, absent the considerations explained, a consequent increase in average neighbor distance.

Figure 5 describes the long-run effect of payoff volatility on the size of the largest two components. The first interesting point to observe is that, independently of ε, most of the connected players belong to a *single* major component, the second-largest component remaining very small throughout. This conclusion is somewhat reminiscent of the well known results of Theory of Random Graphs which assert that, beyond a certain "connectivity threshold", there arises a *single* giant component in the graph. (These mathematical results, however, do not appear to readily applicable here since, in our case, the formation of the social network is very much the result of a non-random mechanism.) On the other hand, concerning the effect of ε on the relative size of the largest component, the expected negative dependence is observed, which is another reflection of the detrimental effect of volatility on the stock of social capital that was already discussed in connection to Figure 3.

As a further graphical manifestation of this phenomenon, Figure 5 also includes two insets depicting the networks prevailing at the end of the time horizon for two contrasting scenarios: one where payoff volatility is low ($\varepsilon = 0.02$) and another where it is relatively high ($\varepsilon = 0.12$). These insets do not only provide more tangible confirmation that the long-run network structure is indeed polarized (i.e. a single giant component coexisting with a more or less sizable set of disconnected players). They also illustrate that, as explained above pertaining to the cohesiveness of the network, higher volatility leads to lower neighbor distances – this is heuristically suggested by the existence of a significant number

[8] For certain nodes, the distances between some of their neighbors could be infinite, i.e. there could be no path joining them other than the one passing through the node in question. To avoid this problem in computing average distances, I truncate the neighbor distance in those cases to be equal to n, just above the maximum possible *finite* distance of $n-1$. This convention is of minor actual relevance and does not affect the main gist of the analysis.

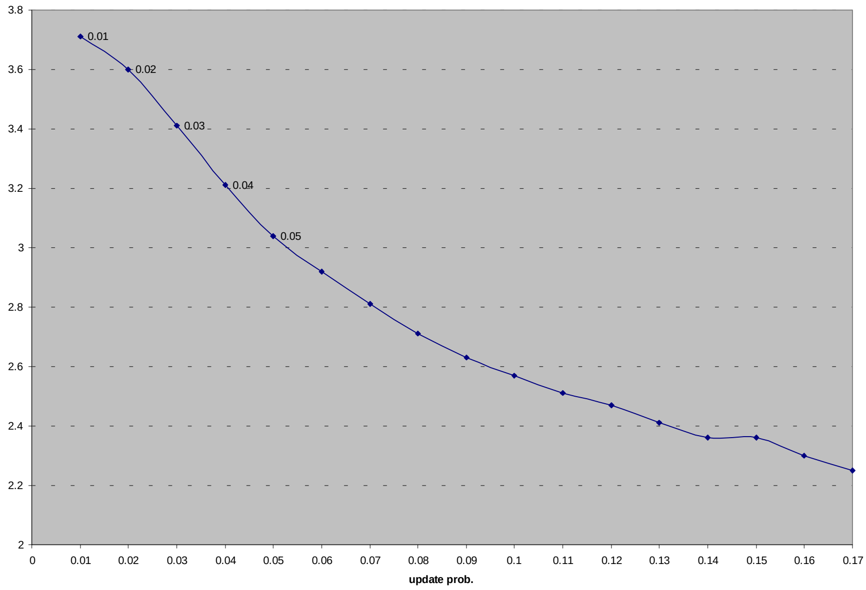

Figure 4: Payoff volatility and long-run average neighbor distance.

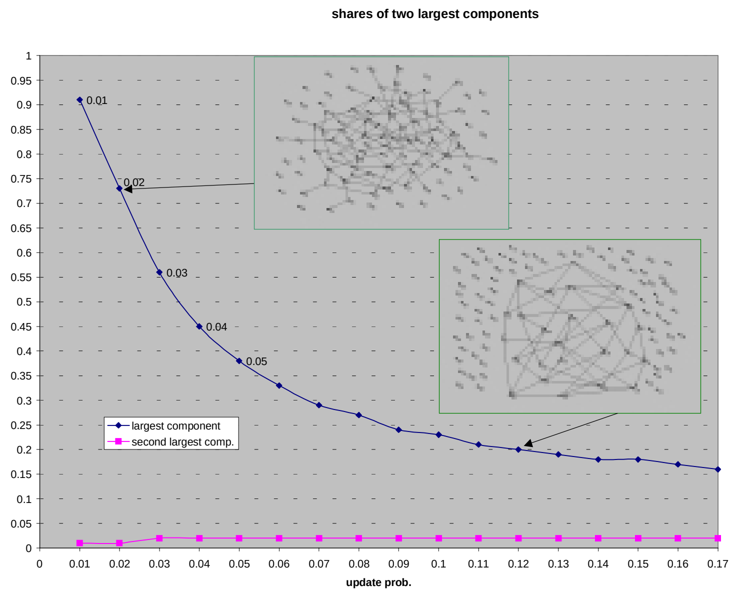

Figure 5: Payoff volatility and long-run share of two largest components.

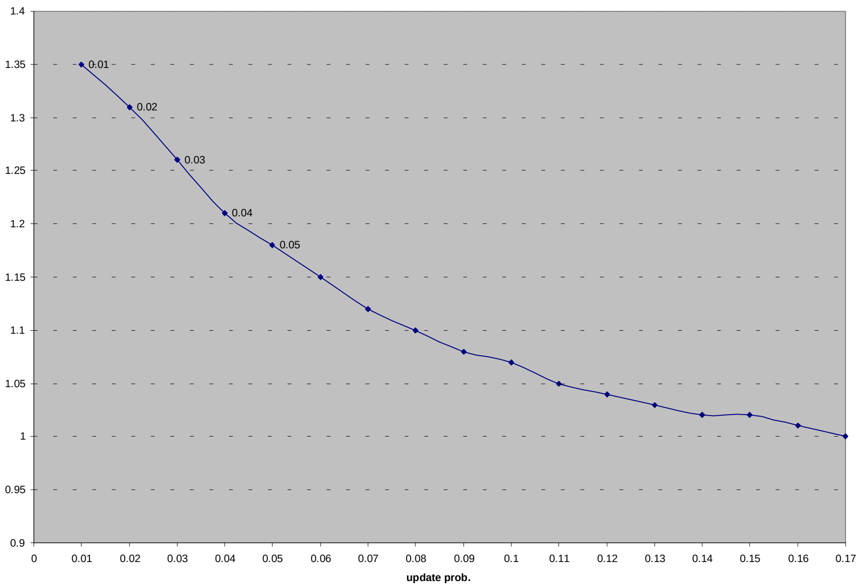

Figure 6: Payoff volatility and long-run average payoff

of paths with "loose" end nodes for the lower ε, while no such paths exist in the second case.[9]

Finally, let us turn to Figure 6, which describes the negative effect of payoff volatility on the long-run average payoff earned per interaction (or link). The evidence gathered here serves as an interesting complement to that displayed in Figure 3. It shows that, as ε grows, there is not only a decrease in the network connectivity (i.e. games being played) but also in the average payoff earned *per link*. The decline in network density was formerly explained as a kind of social-capital depreciation that renders a growing fraction of preexisting links unstable. In contrast, the present negative effect on the average payoff earned per existing link should be largely understood as a consequence of the narrower scope of search brought about by the decreasing size of the network's largest component. This more confined (and thus less effective) search deteriorates, even when successful, the expected level of attainable payoffs.

4.2.2 Network-free strategic behavior

To shed further light on the results obtained for our leading scenario in the previous section, it is most instructive to compare it with one devoid of network-based strategic effects. Thus suppose that, as described in Remark 2, players' strategic

[9] To be precise, it turns out that the neighbor distance of the first network ($\varepsilon = 002$) is 3.6 whereas that of the second ($\varepsilon = 0.12$) is 2.7.

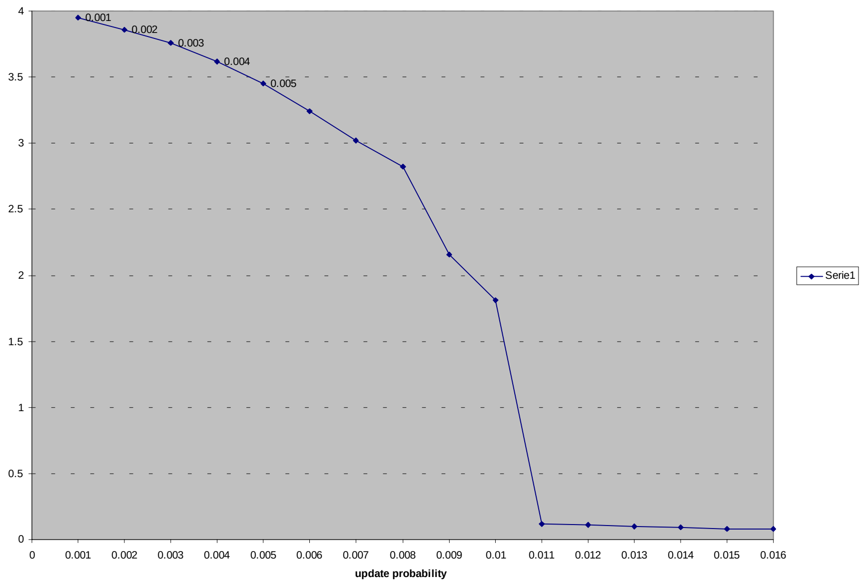

Figure 7: No network effects: payoff volatility and long-run average degree

behavior no longer is influenced by these effects. This may be understood as reflecting a different norm or convention used in the society – one where players react to each of their partners only according to the information gathered on their corresponding bilateral play. Then, strategically speaking, every pairwise interaction is to be regarded as fully independent of any other. This leaves the social network with the only, but yet important, role of defining the channels through which the information diffuses and the population conducts ordinary ("local") search.

Rather than pursuing a completely parallel analysis to that undertaken before, let us restrict attention to only two of the variables where the contrast is more acute and interesting: average node degree (network density), and average neighbor distance (network cohesiveness). By relying on ideas analogous to those used in the proof of Proposition 2, it is straightforward to show that the stochastic process induced in this case is ergodic and thus the long-run values for these variables are uniquely defined. Under the same underlying parameters as above, their dependence on ε is displayed in Figures 7 and 8.

The main points of contrast with the leading network-based scenario which spring up from these results can be summarized as follows.

1. The bite on long-run network density caused by increased volatility manifests itself at much lower rates than in the original scenario. Specifically, the average degree starts to face a significant fall at values of ε that are *one order of magnitude* smaller than before.

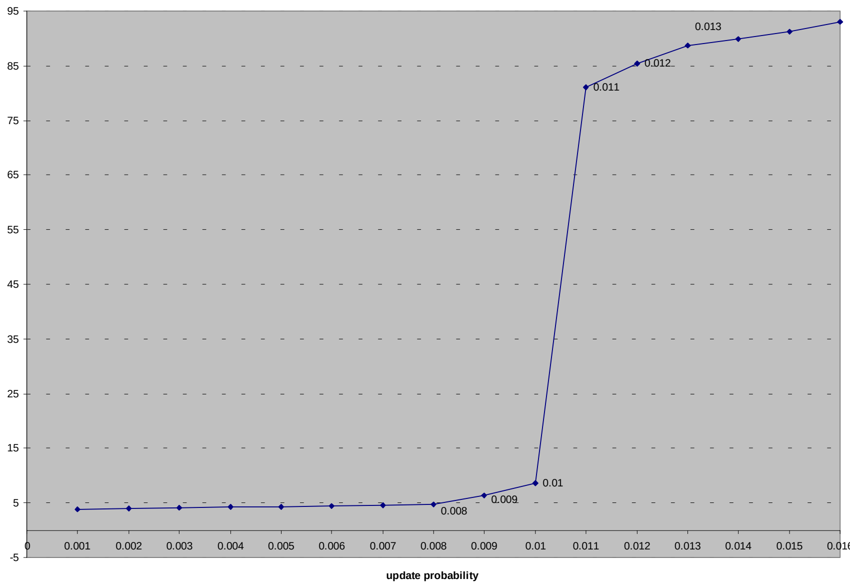

Figure 8: No network effects: payoff volatility and long-run average neighbor distance

2. An additional, and very telling, difference with the leading framework concerns the abruptness now observed in the transition from a high to a low regime in network density. In the absence of network strategic effects, this transition takes place quite sharply, in at least two complementary senses. On the one hand, the full change is essentially completed within a range for ε that, again, is shorter than in the original framework by an order of magnitude. On the other hand, the shape of the "curve" which traces this change is essentially concave (i.e. displays increasing differences) within the relevant range of significant network connectivity. In contrast, the analogous curve in the leading setup displays an opposite curvature, with increases in ε leading to progressively less sizable changes in the network degree.

3. The behavior of cohesiveness in the present case (as measured by the average neighbor distance) also displays a marked contrast with the results obtained in the leading scenario with network strategic effects. There, we stressed that an increase in ε leads to rising network cohesiveness, as the endogenous way in which the social network dynamics ends up partially offsetting the negative effects of increased volatility. Now, however, cohesiveness entails no relevant payoff consequences, and therefore an increase in ε induces a corresponding rise in neighbor distance. As explained above, this may be simply interpreted as a reflection of the fact that, absent other

considerations, lower connectivity tends to increase any measure of graph distance – also average neighbor distance.

5 Mean-field analysis

In this section, the objective is to complement the former numerical analysis by resorting to a mean-field analysis of the model. This is the approach commonly applied in statistical physics for the study of large complex systems of interacting entities.[10] In a nutshell, what underlies this approach is the presumption that, in the presence of a large number of stochastic interactions, the aggregate behavior of the system can be reasonably well understood (i.e. "modelled") in expected terms. This, in essence, amounts to positing a *deterministic* representation of the process that disregards fluctuations and only depends on the average (or expected) magnitudes of the variables involved.

The mean-field description of the model considered here is particularly simple, since its limited aim is to shed light on the sharp contrast between the network-based and network-free scenarios observed in Subsections 4.2.1 and 4.2.2. The primary focus is on modelling how volatility affects stability of existing links while, for example, the effect of network architecture on search is introduced in an open-ended fashion. As indicated, a substantially richer modelling of these and other features (e.g. the evolving cohesiveness of the network of the overall degree distribution) is carried out in the companion paper by Marsili, Vega-Redondo, and Slanina (2003).

The mean-field dynamics (MFD) studied below focuses on one of the key variables of the model: the average node degree, a measure of network density. To clarify its different components, I present the dynamics in three stages. First, I formalize the mechanism of link removal induced by the requirement of pairwise stability. Second, I specify how this mechanism operates in the presence of payoff volatility. Lastly, I introduce the process of search and creation of new links.

Given any *possible* link $ij \in N \times N$, let $\lambda_{ij}(t) \in \{0, 1\}$ specify whether this link is in place at t (an event which is signified by $\lambda_{ij}(t) = 1$) or not (denoted by $\lambda_{ij}(t) = 0$). Then, for any such link ij, the dynamics of link-removal (due to pairwise instability) may be formulated as follows:

$$\lambda_{ij}(t+1) = \lambda_{ij}(t) \cdot \mathcal{I}[\zeta_{ij}(t+1) - \beta_{ij}(t+1)], \tag{6}$$

where:

- $\zeta_{ij}(t+1)$ is the cooperation payoff prevailing at $t+1$ for the game played by i and j (it may normalized to zero when no link connects i and j),
- $\mathcal{I}[\cdot]$ is an indicator function defined by $\mathcal{I}[y] = 0$ if $y < 0$ and $\mathcal{I}[y] = 1$ if $y \geq 0$, and

[10] See, for example, the classical monograph by Stanley (1971).

- $\beta_{ij}(t+1)$ the threshold for the cooperation payoff ζ_{ij} that is required – given the prevailing network and other payoffs (cf.(5)) – for the pairwise stability of the link ij, i.e. $\beta_{ij}(t+1) = \max\{\varphi_{ij}(t+1), \varphi_{ji}(t+1)\}$ where

$$\varphi_{ij}(t+1) = \frac{1-\delta}{\delta}\nu - \sum_{k \in N_i(t) \setminus \{j\}} \delta^{d^i(k,j)(t+1)} (\zeta_{ik}(t+1) + \frac{1-\delta}{\delta}\nu) \quad (7)$$

and $\varphi_{ji}(t+1)$ is defined reciprocally.

Next, combining (6) with the process of payoff update that affects each link with probability ε, the following law of motion results:

$$\mathbf{E}_t[\lambda_{ij}(t+1)] = (1-\varepsilon)\lambda_{ij}(t) + \varepsilon\ \lambda_{ij}(t) \int_{\beta_{ij}(t)}^{\overline{\zeta}} f_\zeta(z)\ \mathrm{d}z, \quad (8)$$

where f_ζ is the continuous density that governs every payoff draw and the implicit assumption above is that the point expectation on β_{ij} is "static", i.e. $\beta_{ij}(t+1) = \beta_{ij}(t)$. Under those conditions, the above expression simply reflects the idea that any existing link ij which is not subject to a payoff update is taken to remain in place and, for those which do experience such an update, their probability of remaining in place is $\Pr\{\zeta_{ij} \geq \beta_{ij}(t)\}$.

Then, the key approximation step undertaken by the mean-field approach is twofold. Firstly, it identifies the expected and actual motion, so that the average degree at $t+1$, denoted by $\kappa(t+1)$, is made equal to:

$$\kappa(t+1) \equiv \frac{1}{n} \sum_{i \in N} \sum_{j \neq i} \mathbf{E}_t \left[\lambda_{ij}(t+1)\right].$$

Secondly, it replaces the link-specific magnitudes in (8) – in particular, each $\beta_{ij}(t)$ – by an average $\hat{\beta}(t)$ computed across all links ij prevailing at t. This leads to the following difference equation:

$$\begin{aligned}
\kappa(t+1) &= \left[(1-\varepsilon) + \varepsilon \int_{\hat{\beta}(t)}^{\overline{\zeta}} f_\zeta(z)\ \mathrm{d}z\right] \left[\frac{1}{n} \sum_{i \in N} \sum_{j \neq i} \lambda_{ij}(t)\right] \\
&= \left[1 - \varepsilon + \varepsilon \left(1 - \int_{\underline{\zeta}}^{\hat{\beta}(t)} f_\zeta(z)\ \mathrm{d}z\right)\right] \kappa(t) = [1 - \varepsilon \int_{\underline{\zeta}}^{\hat{\beta}(t)} f_\zeta(z)\ \mathrm{d}z]\ \kappa(t)
\end{aligned}$$

Finally, the process of search and creation of new links is introduced. Since this component of the dynamics plays a secondary role for our present concerns, we model the creation of new links in a reduced form through a general differentiable function $\phi(\kappa)$ of the current degree $\kappa \in [0, 2m]$, where recall that m is the maximum number of links that any given individual can support (therefore, $2m$ is the maximum average degree). Then, the properties assumed on agents' search require the following boundary conditions:

$$\begin{aligned}\phi(0) &= \eta \int_{\frac{1-\delta}{\delta}\nu}^{\overline{\zeta}} f_\zeta(z)\ \mathrm{d}z \\ \phi(2m) &= 0.\end{aligned}$$

The first condition is a consequence of the fact that, when there are no links available, only global search can contribute (if successful) some links. On the other hand, the second condition simply follows from the fact that no more links can be created when agents are already at maximum link-supporting capacity. Finally, it is natural to postulate that, below this capacity, search yields some expected increase in connectivity, i.e.

$$\phi(\kappa) > 0,\ \forall \kappa < 2m$$

while, at low connectivity, we have:

$$\phi'(0) = 0. \tag{9}$$

The latter condition has been explicitly derived from an explicit formalization of local search in Marsili, Vega-Redondo, and Slanina (2003). It is intuitive since when only very few links are in place, the network is composed of isolated pairs and thus local search is fruitless.

Bringing together the different components of the dynamics introduced above, we arrive at the following difference equation:

$$\kappa(t+1) = [1 - \varepsilon \int_{\underline{\zeta}}^{\hat{\beta}(t)} f_\zeta(z)\ \mathrm{d}z]\ \kappa(t) + \phi(\kappa(t))$$

which, for analytical tractability, is convenient to transform into the analogue differential equation:

$$\dot{\kappa}(t) = -\varepsilon[\int_{\underline{\zeta}}^{\hat{\beta}(t)} f_\zeta(z)\ \mathrm{d}z]\ \kappa(t) + \phi(\kappa(t)) \tag{10}$$

where the parameters ε and η, or the value of the function $\phi(\cdot)$ are then interpreted as rates in continuous time.

The above general formulation is applicable either if network-based strategic effects are present or they are not. These two alternative scenarios only differ in the specification of the threshold $\hat{\beta}(t)$. Starting with the latter case, the absence of network effects is simply captured by the constant identification of $\hat{\beta}(t)$ with $\nu\frac{(1-\delta)}{\delta}$ (cf. Remark 2). This particularizes the dynamics (10) as follows:

$$\dot{\kappa}(t) = -\varepsilon[\int_{\underline{\zeta}}^{\nu\frac{(1-\delta)}{\delta}} f_\zeta(z)\ \mathrm{d}z]\ \kappa(t) + \phi(\kappa(t)). \tag{11}$$

To see how this formulation leads to the sharp phase transition observed in the simulations, suppose that, as we have maintained throughout, $\underline{\zeta} < \nu\frac{(1-\delta)}{\delta} < \overline{\zeta}$. Then, first note that for small ε, (11) yields a unique globally stable state at $\kappa_{\max} = 2m$ with maximum connectivity. On the other hand, it can also be shown that, as ε rises, there is a threshold on ε which marks a discontinuity in the qualitative behavior of the dynamics akin to that observed in the simulations. To make this point in the starkest manner, it is useful to focus on the extreme case where $\eta = 0$ and thus $\phi(0) = 0$. (The reader can easily check that an analogous conclusion would be reached for small positive η.)[11] Let $\hat{\kappa}(\varepsilon)$ stand for the highest equilibrium degree which is asymptotically (locally) stable according to the mean-field dynamics. Then, the claim is that there are some $\bar{\varepsilon}$ and $\bar{\kappa}$, both strictly positive, such that

$$\begin{aligned} \varepsilon &< \bar{\varepsilon} \Rightarrow \hat{\kappa}(\varepsilon) \geq \bar{\kappa} && (12) \\ \varepsilon &\geq \bar{\varepsilon} \Rightarrow \hat{\kappa}(\varepsilon) = 0. && (13) \end{aligned}$$

To verify this claim, note that, in order to have an asymptotically state at some κ^*, it is required that

$$\varepsilon[\int_{\underline{\zeta}}^{\nu\frac{(1-\delta)}{\delta}} f_{\zeta}(z)\ \mathrm{d}z]\ \kappa^* > \phi'(\kappa^*).$$

Therefore, a necessary and sufficient condition for such a condition to hold at some interior $\kappa^* > 0$ is that

$$\varepsilon[\int_{\underline{\zeta}}^{\nu\frac{(1-\delta)}{\delta}} f_{\zeta}(z)\ \mathrm{d}z] < \max_{\kappa\in[0,2m]} \frac{\phi(\kappa)}{\kappa}.$$

Hence it follows that the threshold $\bar{\varepsilon}$ contemplated in (12)-(13) is given by:

$$\bar{\varepsilon} = \left[\int_{\underline{\zeta}}^{\nu\frac{(1-\delta)}{\delta}} f_{\zeta}(z)\ \mathrm{d}z\right]^{-1} \max_{\kappa\in[0,2m]} \frac{\phi(\kappa)}{\kappa},$$

which is always well-defined, in view of (9). In turn, $\bar{\kappa}$ may be readily defined as follows:

$$\bar{\kappa} \equiv \min_{\kappa} \arg\max_{\kappa} \frac{\phi(\kappa)}{\kappa},$$

that is sure to be positive, again by virtue of (9).

Conditions (12)-(13) imply that whether or not the mean-field dynamics (MFD) can sustain in a robust (or locally stable) fashion some *positive* network density depends *discontinuously* on the volatility parameter. This, I now argue, is in line with the simulation results obtained for the original stochastic system

[11] In that case, the statement that $\hat{\kappa}(\varepsilon)$ falls discountinuously to zero as ε exceeds the threshold would have as counterpart that $\hat{\kappa}(\varepsilon)$ is an infinitesimal in η (i.e. converges to zero as $\eta \downarrow 0$). Here, of course, we implicitly assume that $\phi(\kappa)$ is jointly continuous in both κ and the underlying η.

and sheds some new light on it. The MFD reflects average or expected motion, and by construction abstracts from stochastic fluctuations. However, when such fluctuations do operate, the MFD still singles out what sort of behavior that may be observed with some persistence, both across nodes and/or time. Only the behavior of those states that are locally stable in the MFD may be representative or typical in the original stochastic process. In this light, a rather minimalist[12] implication of the mean-field analysis above can be summarized as follows: as volatility rises, the corresponding network density should exhibit an abrupt decrease to very low levels when the volatility rate ε exceeds some underlying threshold. This, in essence, is what was observed in the numerical simulations of the process in the absence of network-based effects.

By way of contrast, let us now turn our attention to the polar scenario where such network effects do impinge on agents' strategic behavior. The consequence of this feature on the MFD formulation given by (10) is that $\hat{\beta}(t)$ can no longer be assumed constant but has to be posited dependent on $\kappa(t)$ – the state of the system – through a certain function $h(\cdot)$. This leads to a particularization of (10) as follows:

$$\dot{\kappa}(t) = -\varepsilon\left[\int_{\underline{\zeta}}^{h(\kappa(t))} f_\zeta(z)\ \mathrm{d}z\right]\ \kappa(t) + \phi(\kappa(t)). \tag{14}$$

In view of (7) and (8), it is natural to postulate that this function should be decreasing and satisfies:

$$h(0) = \frac{1-\delta}{\delta}\nu \tag{15}$$

and[13]

$$h(2m) < \underline{\zeta}. \tag{16}$$

Denote by $F(\kappa) \equiv -\varepsilon[\int_{\underline{\zeta}}^{h(\kappa)} f_\zeta(z)\ \mathrm{d}z]\ \kappa + \phi(\kappa)$ the function governing the dynamics in (14). Then, (15) and (16), in combination with (9), imply that there are some (relative) neighborhoods of $\kappa = 0$ and $\kappa = 2m$, W_0 and W_{2m} respectively, such that

$$\begin{aligned} \kappa &\in W_0\backslash\{0\} \Rightarrow F(\kappa) < 0 && (17)\\ \kappa &\in W_{2m}\backslash\{2m\} \Rightarrow F(\kappa) > 0. && (18) \end{aligned}$$

[12]Here, I am only concerned with reproducing this qualitative feature of the model. However, a substantially richer set of implications (both qualitative and quantitative) may be obtained if one is ready to complicate the mean-field description of the dynamics and model explicitly some additional components (e.g. search). The interested reader is referred to MSV for an elaboration along these lines.

[13]Condition (16) implicitly presumes that m is large enough and that, as it seems intuitive, average payoffs do not decrease, or neighbor distances increase, with connectivity. In any case, this condition is amply satisfied in the simulations reported in Subsection 4.2 when the network degree is high (i.e. for nodes in the large and dense component) if we follow the mean-field approach of estimating the "typical" β_{ij} through expression (7) by replacing the payoffs and neighbor distances in it by their average values.

These conditions imply that both ends of the state space $[0, 2m]$ are locally stable for the MFD in the present case. Thus, if we rely again on the notation $\hat{\kappa}(\varepsilon)$ to denote the highest equilibrium degree which is asymptotically stable according to the present MFD, it now follows that $\hat{\kappa}(\varepsilon) = 2m$ for all $\varepsilon \geq 0$. This suggests that an abrupt fall in connectivity to very low levels should not necessarily happen in the original process when players's behavior is affected by network effects, which is indeed the conclusion illustrated in the numerical simulations.[14]

What explains the contrast between the two network-based and the network-free scenarios? The mean-field description of the process suggests a quite transparent answer. When network effects are present, an agent with high connectivity also tends to have, on average, a local interconnected network architecture which deters opportunistic behavior, even when any of her links are subject to a negative redraw of its payoff. This, in essence, is what is reflected by (18) in the MFD, itself a consequence of the fact that

$$-\varepsilon[\int_{\underline{\zeta}}^{h(2m)} f_\zeta(z)\ \mathrm{d}z]\ \kappa = 0,$$

independently of ε. In contrast, if network effects are absent, there is always a negative drift on connectivity induced by volatility, a phenomenon captured in (11) by the term

$$-\varepsilon[\int_{\underline{\zeta}}^{\nu\frac{(1-\delta)}{\delta}} f_\zeta(z)\ \mathrm{d}z]\ \kappa < 0,$$

for all $\varepsilon > 0$ and $\kappa > 0$. This fact makes it impossible that a sizable network density might be supported under large volatility and, in combination with (9), implies the sharp discontinuous collapse of connectivity as ε goes above a certain threshold.

6 Related literature

The approach pursued here bears on a number of different topics, not only in the fields of game theory and economics but also in sociology or the analysis of complex systems. Let me refer to each of them in turn.

First, we may view the theoretical framework proposed as similar in spirit to that of the evolutionary literature, where players are assumed to interact through a certain game and the long-run configuration is obtained through a gradual stochastic process of learning and adjustment. The early part of this literature (cf. Kandori, Mailath, and Rob (1993), Young (1993), or Ellison (1993)) considered a set where the pattern of interaction of players (global or

[14] In fact, one can further specialize the MFD with additional assumptions (e.g. linearity of $h(\cdot)$ or uniformity of the payoff distribution) to conclude that $\kappa = 0, 2m$ are the only asymptotically stable states under network effects – cf. Vega-Redondo (2002). In this case, there is of course an additional unstable equilibrium $\check{\kappa}(\varepsilon) \in (0, 2m)$ which separates the basins of attraction of the other two, and which can be seen to vary continuously with ε.

local) is fixed throughout, but recent work extends the analysis to a context where the network is not fixed but coevolves with players' game decisions – see e.g. Droste *et al.* (1999), Goyal and Vega-Redondo (1999), or Jackson and Watts (1999).

The latter approach, of course, bears a close relationship to the booming body of literature whose specific concern is the study of pure models of network formation. One of the earliest papers in this field was Aumann and Myerson (1989), with the more recent paper by Jackson and Wolinsky (1996) having played an important role in reviving interest in this topic. Whereas the approach of these papers is mostly static,[15] an explicit dynamic approach to the problem is undertaken in Bala and Goyal (2000).

In the vast area of repeated games, there are two papers, Kandori (1992) and Ellison (1994), which share some motivation with our approach. They propose a model where a large population of players are repeatedly and randomly matched to play a Prisoner Dilemma game. They find that, in this context, it may be still possible to induce cooperation through a social norm (equilibrium) that reacts to any deviation by punishing subsequent partners. In a sense, the relationship of these papers to our work is parallel to that displayed by the early evolutionary literature with fixed and global interaction structure. That is, they embed players' interaction in a population context but abstract from the effect of social structure by postulating a fixed and global pattern of play.

Still in the area of repeated games, two additional related papers are Bernheim and Whinston (1990) and Haag and Lagunoff (2000). The former studies a model of multimarket collusion where a group of firms participating in some common set of markets may decide to make their behavior in any one of them depend on what has been observed in other markets. Naturally, this enhances the collusion (i.e. cooperation) potential in ways analogous to those considered here. The key difference is that the flow of information is instantaneous and interaction is joint (but segmented), so that no phenomena arise analogous to those channeled here through the social network.

Instead, the paper by Haag and Lagunoff does study a setup where players are involved in repeated interaction with partners specified by some *given* social network. Its approach, however, is mostly normative and static. An additional important difference is that players are always forced to play the same action – cooperate or defect – with everyone of their neighbors, so that the effect of the social network on behavior is made much more powerful than in the model studied in this paper.

The study of social networks has hardly been a preserve of economists or game theorists. Rather, it has long been a primary object of study by sociologists or applied psychologists. Besides the research it has spawned in connection to the notion of social capital (which is discussed later), prominent sociologists such as Mark Granovetter (1973) or Ronald Burt (1982) have placed it at the center of sociological inquiry. For example, the notions of "weak ties" highlighted by

[15] For example, Jackson and Wolinsky rely on a notion of pairwise-stability that is akin that introduced in Definition1 .

Granovetter, or "structural holes" due Burt have given rise to a large body of theoretical and empirical work in sociology, which still continues to thrive. Other early and well-known research was carried out by Milgram (1967), an applied psychologist, who demonstrated through a clever simple experiment the surprising low number of steps which tend to separate any two arbitrarily chosen individuals in many large social networks. This phenomenon, which led to the term "small world" (network), has recently attracted much attention by physicists and other researchers interested in the study of complex systems (cf. Watts and Strogatz (1998) and Newman *et al.* (2000)).

Finally, I close this brief review by referring to the literature on social capital, the notion that has been used in the Introduction to motivate the present approach. Rather than attempting a necessarily superficial survey of the vast and diverse range of research that goes under this heading, it should be more useful to focus on the work of Coleman (1988), arguably the author who (together with Putnam (1993)) brought the concept of social capital to prominence in socio-economic analysis. He is also one of the authors who has conceived it more in line with the view espoused here – see e.g. Coleman (1990, Ch. 12). For him, social capital is an inherently relational concept, to be regarded as an attribute of the social network. It is the key factor explaining the intensity and stability of socioeconomic interaction and also represents the basis of trust in repeated interaction (in particular, Coleman often uses the Prisoner's Dilemma as the paradigmatic setup to address this issue). However, for such a trust to emerge, what he calls the closure of the social network (analogous to our notion of cohesiveness) is generally key. He argues, moreover, that social capital is often underprovided, since the strong externalities associated to it are typically not internalized by individuals' own link-investment decisions. Finally, he stresses that social capital is a stock which, left to itself, depreciates with time and that, if it is to be (re)built successfully, must have inter-agent relations enjoy a sufficiently stable environment. The reader will recognize in these points many of the features that have informed (both in modelling and motivation) the analysis undertaken in this paper.

7 Summary and possible extensions

This paper has studied a stylized model of network formation in which players are involved in an infinitely repeated Prisoner's Dilemma with each of her neighbors. Information on past behavior flows gradually along the network, a feature that impinges crucially on the range of network configurations that can be supported in a pairwise stable fashion. The underlying payoff conditions change over time, which in turn may affect the stability of established links and create the opportunity to form new ones. The analysis has focused on the interplay between the emerging characteristics of the endogenous network, the long-run performance of the system, and the key parameters of the model – most importantly, the volatility rate at which the payoffs of current links is updated. Through the complementary use of both numerical simulations and mean-field analysis, we have found that, when players's strategic behavior is network-based, the architecture of the network adapts to increasing volatility by becoming more cohesive and thus is able to sustain a higher level of social capital and induce more cooperative behavior. Instead, if strategic behavior is shaped in a strictly bilateral fashion (i.e. is network-free), the effect of volatility is much more acute and its detrimental consequences manifest themselves much more abruptly.

The model is quite narrow and stylized in a number of respects and therefore it could be fruitful to enrich it along various directions. Let me conclude with some suggestions.

A natural extension would involve enlarging the set of games under consideration, possibly to other sorts of simple bilateral games (e.g. coordination games) or playing the field contexts. Along these lines, one further possibility would be to suppose that, as often considered in the literature (recall the previous summary), each player must take the *same* action in *all* games she plays. The interrelation between the network considerations brought about by this crucial modification and the informational aspects studied here may add novel insights to existing models.

Concerning payoff volatility, it would be interesting to allow for the (arguably realistic) possibility that the realizations induced by any fresh payoff update may be correlated in some dimension. For example, the payoffs enjoyed by a particular individual might display positive correlation (possibly understood as the reflection of the player's idiosyncratic characteristics) or, in a somewhat polar vein, the payoff draws obtained by different individuals could include an aggregate component. Any of these modifications is bound to yield important implications on the network dynamics and its long-run architecture.

Finally, payoffs might be subject to some exogenous or endogenous trend. Concerning the first possibility (an exogenous trend), it would be interesting to understand the implications of letting payoffs be subject to some negative drift, a "Red-Queen phenomenon" reflecting an outside forward-moving environment. As for the second possibility (a endogenous trend), it might be postulated that the payoffs earned by the different agents must be scaled (or normalized) by population-average payoffs or that new payoffs are drawn according to a moving distribution anchored to average or frontier conditions. In either case, a supplementary competitive pressure would be added to the model that may well introduce new considerations, as well as endow the model with a genuinely dynamic (or growth) perspective.

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