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Antoci, Angelo and Sabatini, Fabio

University of Sassari, Sapienza University of Rome

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Online Networks, Social Interaction and Segregation: An Evolutionary Approach

Angelo Antoci [1]

Fabio Sabatini [2]

Abstract

There is growing evidence that face-to-face interaction is declining in many countries, exacerbating the phenomenon of social isolation. On the other hand, social interaction through online networking sites is steeply rising. To analyze these societal dynamics, we have built an evolutionary game model in which agents can choose between three strategies of social participation: 1) *interaction via both online social networks and face-to-face encounters*; 2) *interaction by exclusive means of face-to-face encounters*; 3) *opting out from both forms of participation in pursuit of social isolation*. We illustrate the dynamics of interaction among these three types of agent that the model predicts, in light of the empirical evidence provided by previous literature. We then assess their welfare implications. We show that when online interaction is less gratifying than offline encounters, the dynamics of agents' rational choices of interaction will lead to the extinction of the sub-population of online networks users, thereby making Facebook and similar platforms disappear in the long run. Furthermore, we show that the higher the propensity for discrimination of those who interact via online social networks and via face-to-face encounters (i.e., their preference for the interaction with agents of their same type), the greater the probability will be that they all will end up choosing social isolation in the long run, making society fall into a "social poverty trap".

JEL codes: C73, D85, O33, Z13

Keywords: Social networks; segregation; dynamics of social interaction; social media, social networking sites.

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[1] Department of Economics and Business, University of Sassari, Italy. Email: antoci@uniss.it.

[2] Department of Economics and Law, Sapienza University of Rome, Italy. Email: fabio.sabatini@uniroma1.it.

1. Introduction

Social interactions affect a variety of behaviors and economic outcomes, including the formation of opinions and tastes, investment in human capital, access to jobs and credit, social mobility, subjective well-being and the emergence of collective action, to name a few. While face-to-face interactions have reportedly been declining in many countries over the last two decades (Putnam, 2000; Cox, 2002; Costa and Kahn, 2003; Li et al., 2003; Bartolini and Sarracino, 2015), participation in social networking sites (SNS), such as Facebook and Twitter, has steeply risen (Duggan et al., 2015).[3] The advent of online social networks has radically changed the way we interact with others and this change can have major economic and welfare consequences.

In *Bowling Alone*, Putnam (2000) suggested that technology-based private entertainment, such as television, could replace face-to-face meetings and civic engagement in individual preferences. This claim was supported in virtually any empirical test on the role of television, which was found to displace encounters with friends, associational activities and political participation (e.g., Bruni and Stanca, 2008). Following Putnam's argument about television, early Internet studies advanced the "crowding-out hypothesis", according to which Internet use crowds-out social engagement. As television, a unidirectional mass medium, displaced so many activities, it seems reasonable to argue that the Internet, which allows for interactive communication, might induce an even more powerful substitution effect (DiMaggio et al., 2001). The first empirical studies on the relationship between Internet use and face-to-face interactions supported the crowding-out hypothesis (Kraut et al., 1998; Nie et al., 2002). Subsequent studies, on the other hand, found conflicting results, suggesting that the effect of Internet use may vary with users' preferences and personal characteristics (see, e.g., Gershuny, 2003). Yet, these studies are not conclusive; at that time, in fact, using the Internet was predominantly a solitary activity that was connected with private entertainment. The advent of online social networks radically transformed the way that people use the Internet, which largely extended the possibilities to interact with others.

Despite the extent of the transformations brought about by online networking, existing research on the relationship between face-to-face interaction and SNS-mediated interaction is limited. There are empirical studies on the effect of broadband access on outcomes such as social participation and voting behavior (e.g., Bauernschuster et al., 2014; Falck et al., 2014). A few authors specifically addressed the role of SNS in some aspects of social capital, such as face-to-face interaction and trust (Sabatini and Sarracino, 2017). These works put the crowding-out hypothesis into perspective, suggesting that face-to-face and Internet-mediated interaction may rather be complementary. Additionally, while early sociological studies implicitly suggested that there is a risk of segregation

[3] Hereafter, online social networks, social networking sites (or SNS) and online networking will be used as synonyms for the sake of brevity. For a discussion about definitions, see Ellison and Boyd (2013).

of the two populations of Internet users and socially active individuals, more recent works illustrate the emergence of two main types of social actors: those who only interact with others face-to-face and those who develop their social life both online and through face-to-face interactions (e.g., Helliwell and Huang, 2013; Sabatini and Sarracino, 2014).

In addition, a third population of socially isolated individuals who devote an increasing share of their time to work and private consumption seems to be growing in richer and emerging countries (see, e.g., Putnam, 2000; Bartolini and Sarracino, 2015). Antoci et al. (2012) showed how the choice of social isolation might be a rational response, allowing individuals to adapt to the relational poverty of the surrounding environment and to the reduction in leisure time.

To date, however, we lack a theoretical framework to study how social interaction via SNS relates to interaction via physical encounters and to the intentional withdrawal from social participation that was feared by Putnam (2000) in *Bowling Alone*.

We add to the previous literature by developing an evolutionary game model of SNS-mediated interaction. In our simplified framework, agents can choose among three possible strategies of social interaction. Individuals who want to be socially active can adopt two alternative strategies: 1) to interact by means of both SNS and face-to-face encounters or 2) not to use SNS and only develop social relationships by means of face-to-face encounters. The distinctive trait of these two strategies is the use of SNS.[4] Alternatively, agents can opt out from both types of interaction and renounce social participation. This strategy of social isolation may be viewed as a drastic form of adaptation to the conditions of social decay, increasing busyness and declining opportunities for social engagement, a strategy that provides constant payoffs that are independent of the behaviors of others.

The analysis shows that, depending on the configuration of payoffs and the initial distribution of the three strategies in the population, different Nash equilibria can be reached. In particular, we found that the stationary state in which all individuals choose isolation is always locally attractive. Thus, it represents a *social poverty trap*, i.e., an equilibrium, in which no one has an interest in interacting with others and everybody devotes all of their available time to work or to private consumption.

Only the stationary states in which all individuals play the same strategy can be attractive Nash equilibria. The dynamics leading to such states are self-feeding, to the extent to which agents get a higher payoff when they interact with agents adopting their same strategy. When the three

[4] We do not use other tools for online communication, such as emails and voice systems (e.g., Skype), in defining the possible strategies of social participation. This is because such tools are commonly spread across the sub-population of socially active individuals, independently of their use of online social networks. Descriptive statistics from various institutions report that virtually the entire population of online adults uses non-SNS-mediated tools of online communication. Distinguishing them from other types of online socially active individuals would make no sense. This aspect will be further explained in Section 2.1.

stationary states are simultaneously attractive, the social poverty trap is always Pareto dominated by the other equilibria and, therefore, it can be considered as the worst-case scenario.

Depending on the parameters, the stationary state in which all individuals socially participate through SNS may be the second-best scenario, which is Pareto dominated by the equilibrium in which everyone interacts exclusively by means of physical encounters. Social interaction via SNS, in fact, may be interpreted as a coping response that allows individuals to "defend" their social life from increasing busyness and the reduction in leisure time. In this case, the widening of the agents' opportunity set for social interactions can prevent the achievement of the first best scenario. At the same time, however, it allows society to avoid the worst-case scenario of the attractive social poverty trap. In all cases, the achievement of a specific equilibrium depends on the initial distribution of the three ways of social interaction in the population.

The propensity for discrimination of socially active individuals (i.e., the agents' preference for interacting with people adopting their same strategy) defines the structure of the basin of attraction of the social poverty trap.[5] The higher the propensity for discrimination, in fact, the greater the probability that both kinds of agents will end up segregating themselves from the rest of the population, making society fall into the trap.

Our contribution is related to three strands of the literature. The first includes empirical studies that documented a decline in face-to-face social participation in many countries (e.g., Putnam, 2000; Costa and Kahn, 2003; Bartolini and Sarracino, 2015). We add to this literature by providing a theoretical framework that helps us to understand the roots of the decline in participation.

The second strand is that of economists who theoretically and empirically analyzed how the Internet use may affect social capital (Falck et al., 2014; Bauernschuster et al., 2014; Antoci et al., 2012; 2015; Sabatini and Sarracino, 2015; Castellacci and Schwabe, 2017). Antoci et al. (2012) modelled the choice between two means of social participation, based on Internet-mediated and face-to-face interaction, in a framework where the time available for social participation is exogenously given. Antoci et al. (2015) added to previous work by including the choice to withdraw entirely from social participation. The evolutionary framework that is presented in this paper contributes to this body of research in several ways. First, we introduce a new specification of the social interaction mechanism (Section 2.1) that determines the probability of meeting between individuals belonging to each of the three sub-populations considered. Second, the resulting configuration of payoffs (Section 2.2)—which allows the outcomes of interaction to vary according to the type of agent with which people are matched—takes into account the propensity for discrimination, allowing us to study its dynamic outcomes in terms of segregation.

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[5] The classification of dynamic regimes is illustrated in section five.

This latter aspect links our work to a third literature that refers to theoretical studies on social interaction and segregation. Schelling's (1969; 1971) seminal contribution explained how people's preferences for interaction with similar others—and, therefore, for discrimination against different others—generates dynamics that naturally lead to segregation. Bischi and Merlone (2011) developed Shelling's work by formalizing a two-dimensional dynamic system to study segregation. The authors showed how adaptive rules shape evolutive paths that lead to the emergence of different collective behaviors in the long run. When members of a population are characterized by a limited tolerance of diversity, the complete separation of different populations may occur. Radi et al. (2014a; 2014b) further developed this framework by analyzing the role of regulating institutions constraining the number of individuals of a population that are allowed to enter and exit the system.
Our work adds to this literature by illustrating how the configuration of payoffs drives population dynamics towards segregation. If we allow for a configuration of payoffs that reflects a preference for interaction with similar others, then dynamics will lead to the complete separation of the three populations accounted for in our framework. This is consistent with Bischi and Merlone (2011).
The rest of the paper is organized as follows. In section two, we describe the model and analyze the evolutionary dynamics. Sections four and five present the basic results and the classification of dynamic regimes. Section six discusses the possible dynamics predicted by the model for a specific distribution of the different forms of participation suggested by the existing empirical literature. Section seven concludes.

2. The Model

2.1 The Social Interaction Mechanism

We consider an economy made up of identical individuals. In each instant of time *t*, each individual has to choose one of the pure strategies of social interaction mentioned in the introduction of this paper:

1) Interaction via online social networks and face-to-face. We call this strategy *SN* (because its distinctive trait is the use of social networks). The *SN* strategy entails different degrees of SNS-mediated interaction according to individual preferences. In general, we think of *SN* agents as individuals who develop social ties via SNS at their convenience—for example, by using Facebook to stay in touch with friends and acquaintances or to establish contacts with unknown others—and meet their contacts in person whenever they want to or have time.

2) Interaction by exclusive means of face-to-face encounters. We call this strategy *NS* (because its players make no use of social networks). The empirical evidence shows that, despite the steep rise in the use of SNS, a remarkable number of online adults choose not to use them.

The distinctive trait of the two strategies is the use of SNS for social interaction, which has two features: it allows asynchronous and complex interactions and it generates club effects that may favor segregation to the extent to which users receive different payoffs when dealing with other users or with non-users.

3) Social isolation. This is a strategy in which agents prefer to devote all of their time to work and to forms of private consumption that do not entail any significant relationships, either online or face-to-face (Antoci et al., 2015). We call this strategy *NP* (for no participation). *NP* players tend to replace relational goods (e.g., playing in a chess tournament with friends) with material goods (e.g., software for playing chess with a computer). We assume that *NP* agents do not retire from work and that their social relations are limited to on-the-job interactions.

The withdrawal from social interactions modelled with the *NP* strategy may be viewed as a drastic form of adaptation to the conditions of social decay that make *NP* players' payoffs constant and completely independent of the behavior of others. The notion of defensive choices is not new in the literature. Hirsch (1976) was the first to introduce the concept of defensive consumption induced by the negative externalities of growth. This kind of consumption may occur in response to a change in the physical or social environment: "If the environment deteriorates, for example, through dirtier air or more crowded roads, then a shift in resources to counter these 'bads' does not represent a change in consumer tastes but a response, on the basis of existing tastes, to a reduction in net welfare" (Hirsch, 1976, p. 63). Antoci et al. (2007) generalized the study of defensive consumption choices to the case of a deteriorating social environment. If the social environment deteriorates, for example, in relation to a shift in prevailing social values or to a decline in the opportunities for social engagement, then individuals might want to replace the production and consumption of relational goods with the production and consumption of private goods.[6] The authors suggested that the reduction in the time available for social participation could trigger self-feeding processes, leading to the progressive erosion of the stock of social capital.

We assume that the sizes of the three sub-populations of individuals playing strategies *SN*, *NS* and *NP* at time *t* are expressed by the real variables $x_1(t), x_2(t), x_3(t)$, respectively. The size of the total population is normalized to 1, so that $x_1, x_2, x_3 \geq 0$ and $x_1 + x_2 + x_3 = 1$ hold. We establish that individuals enjoying their leisure time—which coincides, by assumption, with their social participation time—are in *L mode*. By contrast, those who are currently working or engaged in private activities that have no effect on the payoffs of others are in *W mode*. All individuals choosing the *NP* strategy are always in *W mode*.

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[6] A peculiarity of relational goods is that it is virtually impossible to separate their production from consumption, since they coincide (Gui and Sugden, 2005).

The social interaction mechanism, which determines the payoffs of each strategy, is described by the following assumptions. In each instant of time *t*:

a) An individual choosing either the *SN* or the *NS* strategy has an *l* probability of being in *L mode* and a 1- *l* probability of being in *W mode*.

b) An *L mode* individual adopting the *SN* strategy has an *n* probability of interacting online with individuals of the same type and a 1-*n* probability of interacting face-to-face with individuals of the same type and with *L mode* individuals playing the *NS* strategy. The values of *l* and *n* are assumed to be exogenously determined (i.e., *l* and *n* are parameters of the model).

Therefore, in each instant of time *t*:

1) A share $l \in (0,1)$ of the sub-populations x_1 and x_2 is in *L mode*. The remaining share, 1- *l*, is in *W mode*.

2) A share $n \in (0,1)$ of the sub-population of size lx_1 interacts online via a SNS with individuals of the same type, while a share 1-*n* of such a sub-population interacts via face-to-face encounters both with individuals of the same type and with individuals belonging to the sub-population of size lx_2.

3) On the other hand, *L mode* individuals playing the *NS* strategy interact with *L mode* individuals playing the same strategy and with the share 1-*n* of *L mode* individuals playing the *SN* strategy and currently interacting via face-to-face encounters.

2.2 Payoffs

According to this game framework:

a) ln is the conditional probability, for an individual playing *SN*, of being (at the instant of time *t*) an *L mode* individual (this happens with probability *l*) interacting online via a SNS (this happens with probability *n*); lnx_1 thus represents the expected size of the sub-population of individuals of this type.

b) $l(1-n)$ is the conditional probability, for an individual playing *SN*, of being an *L mode* individual playing the *SN* strategy and interacting via face-to-face encounters; therefore, $l(1-n)x_1$ is the expected size of the sub-population of individuals of this type.

c) l is the probability, for an individual playing *NS*, of being an *L mode* individual (and, consequently, interacting via face-to-face encounters); therefore, lx_2 is the expected size of the sub-population of individuals of this type.

We assume that every *W mode* individual obtains the payoff α, where α is a strictly positive parameter, independently of the strategy he adopts, and from the distribution x_1, x_2, x_3 of the strategies in the population. Furthermore, we assume that every *L mode* individual obtains a payoff equal to 0 when interacting with a *W mode* individual, while he obtains the payoffs expressed in the following table when interacting with another *L mode* individual:

Table 1: Payoffs of *L-mode* individuals			
	SN player interacting online	SN player interacting face to face	NS player
SN player interacting online	β	0	0
SN player interacting face to face	0	γ	δ
NS player	0	ε	η

The parameter β measures the payoff of an *L mode* individual adopting the *SN* strategy when interacting online with another individual of the same type. The parameters γ and δ measure the payoffs of an *L mode* individual adopting the *SN* strategy when interacting face-to-face with another individual of the same type and with an *L mode* individual adopting the *NS* strategy, respectively. Analogously, η and ε are the parameters measuring the payoffs of an *L mode* individual adopting the *NS* strategy due to the face-to-face interaction with an individual of the same type and an individual adopting the *SN* strategy, respectively.

The expected payoffs of strategies *SN* and *NS* are given respectively by:

$$EP_{SN}(x_1, x_2) = (1-l)\alpha + ln(\beta lnx_1) + l(1-n)[\gamma l(1-n)x_1 + \delta lx_2] =$$
$$= (1-l)\alpha + \beta l^2 n^2 x_1 + \gamma l^2 (1-n)^2 x_1 + \delta l^2 (1-n) x_2$$

$$EP_{NS}(x_1, x_2) = (1-l)\alpha + l[\varepsilon l(1-n)x_1 + \eta lx_2] =$$
$$= (1-l)\alpha + \varepsilon l^2 (1-n)x_1 + \eta l^2 x_2$$

while the expected payoff of an individual adopting the *NP* strategy is given by:

$$EP_{NP} = \alpha > 0$$

The payoffs highlight some points about discrimination. First, a clear separation occurs between those who choose to withdraw from social interaction and all the other players. In a sense, *NP* players choose to segregate themselves from the rest of the population. Second, when *SN* players spend their leisure time interacting via SNS, they *de facto* segregate themselves from the two populations of *NS* and *NP* players, who do not use online social networks.

The sub-populations of individuals playing the *SN* and *NS* strategies can only meet in the context of face-to-face interactions. The two extreme cases $\delta \leq 0$ and $\varepsilon \leq 0$ entail discrimination. In these cases, in fact, when individuals adopting different strategies of participation meet face-to-face, they get a null or a negative reward. As a result, they will prefer to interact with individuals of their same type. For example, *SN* players may want to check what happens in their online networks while having dinner with friends. *NS* players, who are not familiar with SNS, may, in turn, feel uncomfortable sitting at a table where everyone is checking a smartphone instead of talking to each other. If this is the case, the benefits ε of the dinner for *NS* players may be null or negative. At the same time, the impossibility of checking Facebook during face-to-face interactions—due, for example, to the moral obligation to talk—can make *SN* players feel uncomfortable and anxious (e.g., Shu-Chun et al., 2012). In this case, the benefits δ of the dinner may be poor or even null or negative for *SN* players, too. As a result, *SN* and *NS* players might want to discriminate in face-to-face interactions. More generally, players' preferences for their similar type may be interpreted as a matter of homophily. Empirical literature has shown that informal segregation spontaneously emerges in relation to discrimination on the grounds of specific individual characteristics and/or as a result of peer pressure (McPherson et al., 2001). SNS studies have shown that online social networks are so pervasive that they may well be considered as a crucial individual characteristic that prompts a negative bias towards non-users, and vice versa.[7]

On the other hand, *SN* players may receive different payoffs when interacting with others of the same type, depending on whether the interaction takes place online or offline. Several experiments, in fact, have shown that people behave online in a very peculiar way as compared to face-to-face interaction. Kiesler et al. (1984) observed that computer-mediated communication entails anonymity, reduced self-regulation and reduced self-awareness. 'The overall weakening of self- or normative regulation might be similar to what happens when people become less self-aware and submerged in a group, that is, deindividuated (p. 1126). Deindividuation has, in turn, been found to be conducive to disinhibition and lack of restraint (Diener, 1979). Siegel et al. (1983) found that

[7] For example, according to the *Social Recruiting Survey* conducted by Jobvite (2014), 92% of recruiters use social media for evaluating candidates. Furthermore, 94% use LinkedIn, 66% use Facebook and 52% use Twitter. Those who refer to Facebook mostly use the platform to assess candidates' "cultural fit". People without Facebook pages, in particular, are viewed as "suspicious" by hiring managers.

people in computer-mediated groups were more aggressive than they were in face-to-face groups, as measured by uninhibited verbal behavior. Deregulation and disinhibition encourage "online incivility", which includes aggressive or disrespectful behaviors, vile comments, online harassment, and hate speech.

Antoci et al. (2016) argued that online incivility may be a major cause of frustration and dissatisfaction, which suggests that the benefits of the interaction between *SN* players could also be negative ($\beta < 0$) if the interaction takes place via SNS, and positive ($\gamma > 0$) if the interaction occurs face-to-face.

3.2 Evolutionary Dynamics

We assume that the adoption process of strategies *SN*, *NS* and *NP* is determined by the well-known replicator equations in continuous time (see, e.g., Weibull 1995):

$$\begin{aligned} \dot{x}_1 &= x_1(EP_{SN} - \overline{EP}) \\ \dot{x}_2 &= x_2(EP_{NS} - \overline{EP}) \\ \dot{x}_3 &= x_3(EP_{NP} - \overline{EP}) \end{aligned} \tag{1}$$

where $\dot{x}_1$, $\dot{x}_2$, and $\dot{x}_3$ represent the time derivatives of the functions $x_1(t)$, $x_2(t)$, and $x_3(t)$, respectively, and

$$\overline{EP} = x_1 EP_{SN} + x_2 EP_{NS} + x_3 EP_{NP}$$

is the population-wide average payoff of strategies.

Dynamics (1) are defined in the simplex S illustrated in Figure 1, where $x_1, x_2, x_3 \geq 0$ and $x_1 + x_2 + x_3 = 1$ hold. The vertices of S, i.e., the vectors $e_1 = (1,0,0)$, $e_2 = (0,1,0)$, and $e_3 = (0,0,1)$, correspond to the states in which all individuals adopt a unique strategy—respectively, *SN*, *NS* or *NP*.

We denote $e_i - e_j$ the edge of *S* joining e_i with e_j; thus $e_1 - e_2$ is the edge where only strategies *SN* and *NS* are present in the population (see Figure 1), $e_1 - e_3$ is the edge where only strategies *SN* and *NP* are present, and $e_2 - e_3$ is the edge where only strategies *NS* and *NP* are present. As usual with replicator dynamics, such edges are invariant sets.

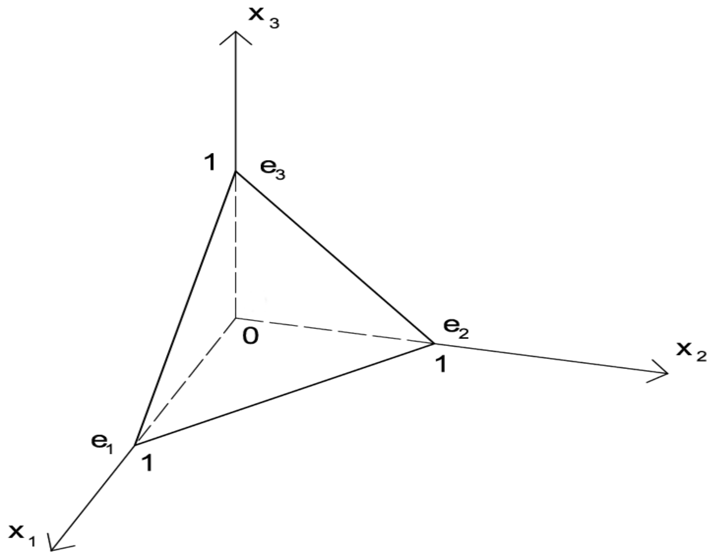

Figure 1. The simplex *S*, where $x_1, x_2, x_3 \geq 0$ and $x_1 + x_2 + x_3 = 1$ hold. The vertices $e_1 = (1, 0, 0)$, $e_2 = (0, 1, 0)$, and $e_3 = (0, 0, 1)$ correspond to the states in which all individuals adopt the unique strategy *SN*, *NS* or *NP*, respectively.

It is easy to check that dynamics (1) can be written in the following form (see, e.g., Bomze 1983):

$$\dot{x}_i = x_i(e_i \cdot A\boldsymbol{x} - \boldsymbol{x} \cdot A\boldsymbol{x}), \quad i = 1, 2, 3 \tag{2}$$

where $\boldsymbol{x}$ is the vector $\boldsymbol{x} = (x_1, x_2, x_3)$, and *A* is the payoff matrix:

$$A = \begin{pmatrix} (1-l)\alpha + \beta l^2 n^2 + \gamma l^2 (1-n)^2 & (1-l)\alpha + \delta l^2 (1-n) & (1-l)\alpha \\ (1-l)\alpha + \varepsilon l^2 (1-n) & (1-l)\alpha + \eta l^2 & (1-l)\alpha \\ \alpha & \alpha & \alpha \end{pmatrix} \tag{3}$$

We will analyze dynamics (2) under the following assumptions:

Assumption I

$EP_{SN}(1{,}0) > EP_{NS}(1{,}0)$, i.e., $\beta n^2 + \gamma(1-n)^2 > \varepsilon(1-n)$: the *SN* strategy is better performing than the *NS* strategy in a social context in which all individuals adopt the *SN* strategy (i.e., $x_1 = 1, x_2 = 0$).

Assumption II

$EP_{NS}(0{,}1) > EP_{SN}(0{,}1)$, i.e., $\eta > \delta(1-n)$: the *NS* strategy is better performing than the *SN* strategy in a social context in which all individuals adopt the *NS* strategy (i.e., $x_1 = 0, x_2 = 1$).

Assumption I establishes a minimal condition for segregation. This condition is always satisfied if β and γ, i.e., the benefits that *SN* players get when they interact online and face-to-face with other *SN* players, respectively, are positive and ε, i.e., the reward that *NS* players get when interacting with *SN* players face-to-face, is negative or equal to zero. In this case, *SN* players will discriminate against those who do not use online social networks, and *NS* players will not have any specific interest in engaging with them. More generally, Assumption I is satisfied if the value of ε is sufficiently lower than β and γ, i.e., $\varepsilon < \beta n^2/(1-n) + \gamma(1-n)$.

Assumption II requires that the benefit δ obtained by *SN* players that meet *NS* individuals face-to-face is sufficiently lower than the benefit obtained by *NS* players when they meet face-to-face with individuals of their same type. This condition is certainly satisfied if $\eta \geq \delta$. In this case, *NS* players discriminate, in face-to-face encounters, against those who adopt the *SN* strategy.

4. Results

It is well-known that dynamics (2) do not change if an arbitrary constant is added to all entries of a column of *A* (see, e.g., Hofbauer and Sigmund, 1988; p. 126). Therefore, we can replace matrix *A* in equations (2) with the following normalized matrix *B,* with the first row made of zeros:

$$B = \begin{pmatrix} 0 & 0 & 0 \\ a & b & c \\ d & e & f \end{pmatrix} =$$

$$= \begin{pmatrix} 0 & 0 & 0 \\ \varepsilon l^2(1-n) - \beta l^2 n^2 - \gamma l^2 (1-n)^2 & \eta l^2 - \delta l^2(1-n) & 0 \\ \alpha l - \beta l^2 n^2 - \gamma l^2(1-n)^2 & \alpha l - \delta l^2 (1-n) & l\alpha \end{pmatrix} \tag{4}$$

According to Assumptions I and II, $a < 0$ and $b > 0$ hold. Furthermore, $f > 0$ always. The dynamic regimes that can be observed under Assumptions I and II can be classified taking into account the following results.

Proposition 1

1) *The stationary state* e_1 *is a sink (i.e., it is locally attractive) if the following condition holds (see matrix (4)):*

$$d = \alpha l - \beta l^2 n^2 - \gamma l^2 (1-n)^2 < 0 \text{ i.e., } \alpha < \beta l n^2 + \gamma l (1-n)^2 \quad (5)$$

but it is a saddle point if (5) does not hold (In such a case, the stable manifold lies in the edge $e_1 - e_2$*, while the unstable manifold belongs to the edge* $e_1 - e_3$*.)*

2) The stationary state e_2 *is a sink if the following condition holds (see matrix (4)):*

$$e - b = \alpha l - \eta l^2 < 0 \text{ i.e., } \alpha < \eta l \quad (6)$$

but it is a saddle point if (6) does not hold (In such a case, the stable manifold lies in the edge $e_1 - e_2$*, while the unstable manifold belongs to the edge* $e_2 - e_3$*.)*

3) The stationary state e_3 *is always a sink.*

Proof: See the Mathematical Appendix A.

Note that conditions (5) and (6) are simultaneously satisfied if the value of the parameter α measuring the (constant) payoff of the *NP* strategy is low enough. Distinct from e_1 and e_2, the stationary state e_3 is always a sink, whatever the value of the parameter $\alpha > 0$ is.

When the pure population states e_1, e_2, and e_3 are sinks, they also are Nash equilibria (see, e.g., Weibull, 1995). In such a case, they can be interpreted as stable social conventions representing self-enforcing configurations of the social environment.

In our model, individuals' welfare evaluated at e_1, e_2, and e_3 is measured, respectively, by:

$$EP_{SN}(1,0) = (1-l)\alpha + \beta l^2 n^2 + \gamma l^2 (1-n)^2$$
$$EP_{NS}(0,1) = (1-l)\alpha + \eta l^2$$
$$EP_{NP} = \alpha$$

The following proposition deals with Pareto dominance relationships among the stationary states e_1, e_2, and e_3.

Proposition 2

The stationary state e_1 *Pareto dominates the stationary state* e_2 *(i.e.,* $EP_{SN}(1,0) > EP_{NS}(0,1)$*) if:*

$$\eta < \beta n^2 + \gamma(1-n)^2 \tag{7}$$

and Pareto dominates the stationary state e_3 (i.e., $EP_{SN}(1,0) > EP_{NP}$) if:

$$\alpha < \beta l n^2 + \gamma l(1-n)^2 \tag{8}$$

The stationary state e_2 Pareto dominates the stationary state (i.e., $EP_{NS}(1,0) > EP_{NP}$) if:

$$\alpha < \eta l \tag{9}$$

Proof: Straightforward.

It is important to note that (8) and (9) coincide, respectively, with the stability conditions (5) and (6). Therefore, if and only if e_1 and e_2 are sinks, they Pareto dominate the stationary state e_3 in which individuals withdraw from social participation. This implies that, in the context in which at least one of the stationary states e_1 and e_2 are sinks, the stationary state e_3 (which is always locally attractive) can be interpreted as a social poverty trap. In the trap, everyone withdraws from social participation and devote all of their available time to "private" activities, including work and consumption that does not entail any significant social relationship. The "social poverty" that derives from this situation—manifesting, for example, in the scarcity of participation opportunities and in the strengthening of materialistic values—makes social interaction difficult and unrewarding. Also note that the Pareto dominance relationship between e_1 and e_2 (see (7)) does not depend on the stability conditions (5) and (6), and, consequently, e_1 may Pareto dominate e_2 or vice versa, independently of their stability properties.

The following proposition concerns the existence and stability properties of the other possible stationary states of dynamics (2), i.e., the stationary states in which at least two among the available strategies, are adopted by (strictly) positive shares of the population.

Proposition 3

1) A unique stationary state in the interior of S (i.e., with $x_i > 0$ all $i = 1, 2, 3$), in which all strategies are played, exists if:

$$\begin{aligned} ae - bd = {} & l^3\{\varepsilon(1-n)[\alpha - \delta l(1-n)] + \alpha\delta(1-n)\} + \\ & + l^3\{(\eta l - \alpha)[\beta n^2 + \gamma(1-n)^2] - \alpha\eta\} > 0 \end{aligned} \tag{10}$$

Such a stationary state is always a source (i.e., it is repulsive). If condition (10) does not hold, then no stationary state exists in the interior of S.

2) A unique stationary state always exists in the edge $e_1 - e_2$ *(not coinciding with either* e_1 *or* e_2*) of the simplex S (see Figure 1); it is a saddle point (with unstable manifold lying in* $e_1 - e_2$*) if the stationary state in the interior of S exists (see point one of this proposition); otherwise it is a source.*

3) A unique stationary state exists in the edge $e_1 - e_3$ *if* $d < 0$ *(see condition (5)) and it is always a saddle point (with unstable manifold lying in* $e_1 - e_3$*). If* $d \geq 0$*, then no stationary state exists in* $e_1 - e_3$*.*

4) A unique stationary state exists in the edge $e_2 - e_3$ *if* $e - b < 0$ *(see condition (6)), and it is always a saddle point (with unstable manifold lying in* $e_2 - e_3$*). If* $e - b \geq 0$*, then no stationary state exists in* $e_2 - e_3$*.*

Proof: See the Mathematical Appendix A.

5. Classification of Dynamic Regimes

Bomze (1983) provided a complete classification of two-dimensional replicator equations. The above propositions allow us to select, among all of the phase portraits illustrated in Bomze's paper, those that can be observed under dynamics (2). In Figures 2-8, sinks (i.e., attractive stationary states) are indicated by full dots, sources (i.e., repulsive stationary states) are indicated by open dots and saddle points by drawings of their stable and unstable branches. The basins of attraction of e_1, e_2, and e_3 are rendered in yellow, blue and pink, respectively. According to Proposition 3 (and to Bomze's classification), every trajectory starting from an initial distribution of strategies $x_1(0), x_2(0),$ and $x_3(0)$—neither belonging to a one-dimensional stable manifold of a saddle point nor coinciding with a stationary state in which more than one strategy is adopted—approaches one of the pure population stationary states e_1, e_2, and e_3. In the following subsections, we will present the complete classification of the possible dynamics regimes that can be observed under (2).

5.1. Regime One: Conditions (5) and (6) Hold

In this context, all of the vertices $e_1 = (1, 0, 0)$, $e_2 = (0, 1, 0)$, and $e_3 = (0, 0, 1)$ are simultaneously attractive and the regimes illustrated in Figures 2 and 3 can be observed. The former—corresponding to the phase portrait number 35 (PP#35) in Bomze's (1983) classification—occurs when $ae - bd \leq 0$ (i.e., when a stationary state in the interior of S does not exist; see condition (10)), while the latter—corresponding to PP#7—occurs when $ae - bd > 0$.

In this context, the stationary state $e_3 = (0,0,1)$ —in which all the individuals play the *NP* strategy—is Pareto dominated by the other locally attracting stationary states. This suggests that the *NP* strategy can be interpreted as an adaptive behavior that agents may want to play to protect themselves from situations of relational poverty and decay of the surrounding social environment. As clearly illustrated in Figures 2 and 3, these regimes are strongly path dependent. If the initial distribution of the different forms of participation is close enough to $e_1 = (1, 0, 0)$, i.e., if $x_1(0)$ is high enough and $x_2(0)$ and $x_3(0)$ are low enough, then the economy converges to e_1, and all individuals adopt the *SN* strategy. On the other hand, if the initial distribution is close enough to e_2 or e_3, then the economy converges to e_2 or e_3.

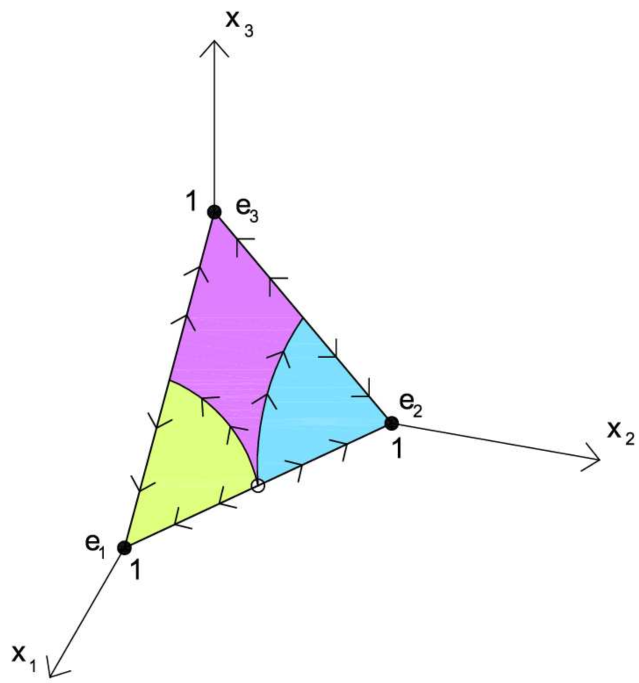

Figure 2. Dynamic regime in which all of the vertices $e_1 = (1, 0, 0)$, $e_2 = (0, 1, 0)$, and $e_3 = (0, 0, 1)$ are simultaneously attractive and a stationary state in the interior of *S* does not exist. The basins of attraction of e_1, e_2 and e_3 are rendered in yellow, blue and pink, respectively.

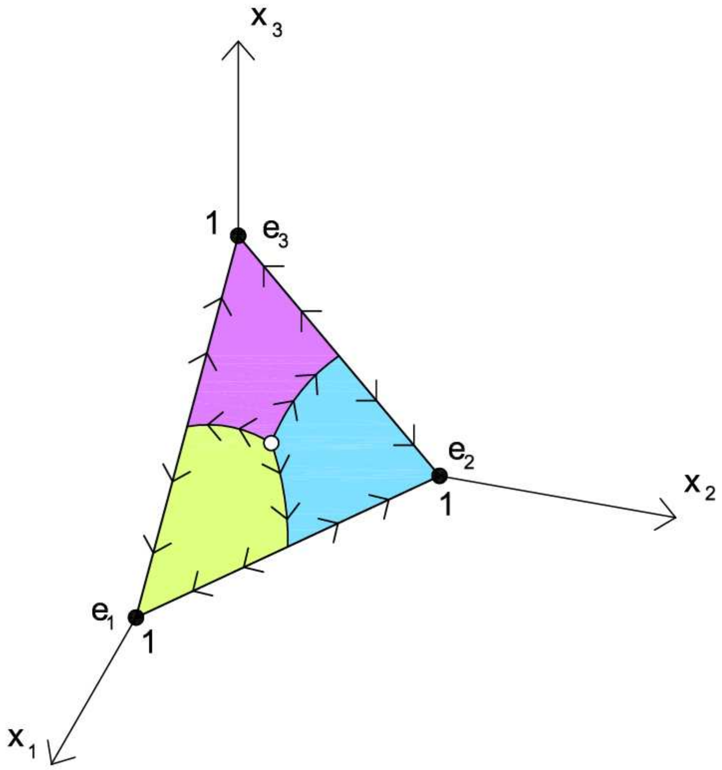

Figure 3. Dynamic regime in which all of the vertices $e_1 = (1, 0, 0)$, $e_2 = (0, 1, 0)$, and $e_3 = (0, 0, 1)$ are simultaneously attractive and a stationary state in the interior of S exists. The basins of attraction of e_1, e_2 and e_3 are rendered in yellow, blue and pink, respectively.

5.2. Regime Two: Condition (5) Holds, But (6) Does Not Hold

In this context, the vertices $e_1 = (1, 0, 0)$ and $e_3 = (0, 0, 1)$ are attractive, while $e_2 = (0, 1, 0)$ is a saddle point. The regimes are illustrated in Figures 4 and 5.

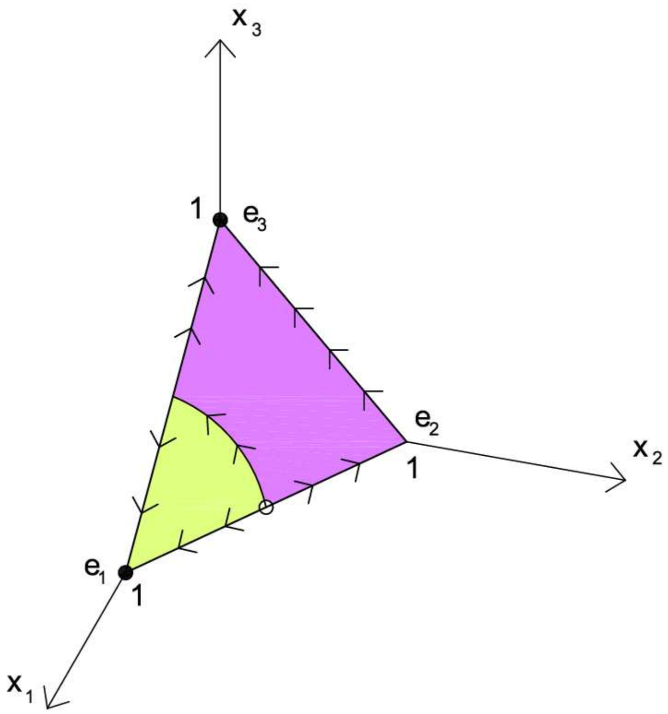

Figure 4. Dynamic regime in which only the vertices $e_1 = (1, 0, 0)$ and $e_3 = (0, 0, 1)$ are attractive, and a stationary state in the interior of S does not exist. The basins of attraction of $e_1$and e_3 are rendered in yellow and pink, respectively.

The regime in Figure 4—corresponding to PP#37 of Bomze's classification—occurs when $ae - bd \leq 0$ (i.e., when a stationary state in the interior of S does not exist; see condition (10)), while the latter—corresponding to PP#9—occurs when $ae - bd > 0$. In this context, the stationary state $e_3 = (0, 0, 1)$ in which all the individuals play the *NP* strategy is Pareto dominated by state $e_1 = (1, 0, 0)$ in which all the individuals play the *SN* strategy. Furthermore, the stationary state $e_2 = (0, 1, 0)$ in which all the individuals play the *NS* strategy is Pareto dominated by both the stationary states $e_1 = (1, 0, 0)$ and $e_3 = (0, 0, 1)$.

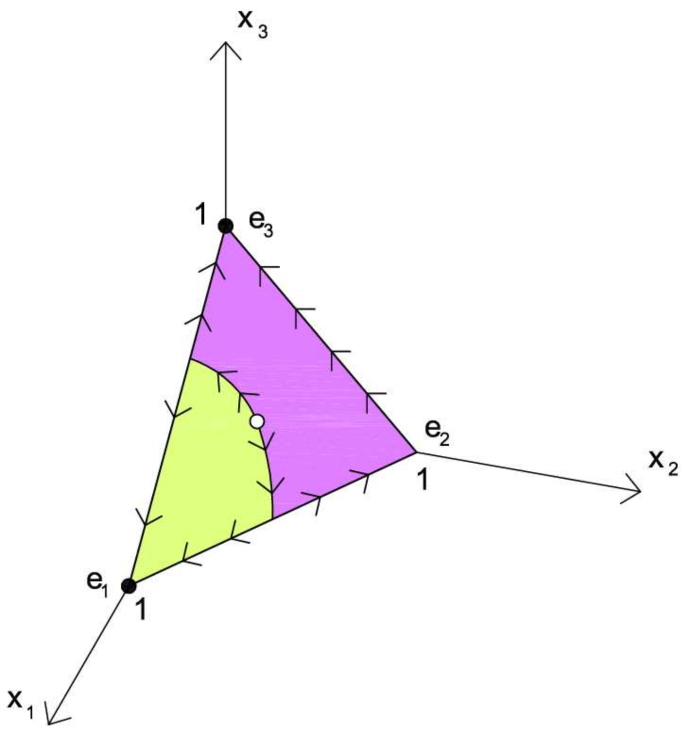

Figure 5. Dynamic regime in which only the vertices $e_1 = (1, 0, 0)$ and $e_3 = (0, 0, 1)$ are attractive, and a stationary state in the interior of S exists. The basins of attraction of e_1 and e_3 are rendered in yellow and pink, respectively.

5.3. Regime Three: Condition (6) Holds, But (5) Does Not Hold

In this context, the vertices $e_2 = (0, 1, 0)$ and $e_3 = (0, 0, 1)$ are attractive, while $e_1 = (1, 0, 0)$ is a saddle point. The regimes are illustrated in Figures 6 and 7. The regime in Figure 6—corresponding to PP#37 of Bomze's classification—occurs when $ae - bd \leq 0$ (i.e., when a stationary state in the interior of S does not exists (see condition (10)), while the latter—corresponding to PP#9—occurs when $ae - bd > 0$. In this context, the stationary state $e_3 = (0, 0, 1)$ in which all the individuals play the *NP* strategy is Pareto dominated by state $e_2 = (0, 1, 0)$ in which all the individuals play the *NS* strategy. Furthermore, the stationary state $e_1 = (1, 0, 0)$ in which all the individuals play the *SN* strategy is Pareto dominated by both the stationary states $e_2 = (0, 1, 0)$ and $e_3 = (0, 0, 1)$.

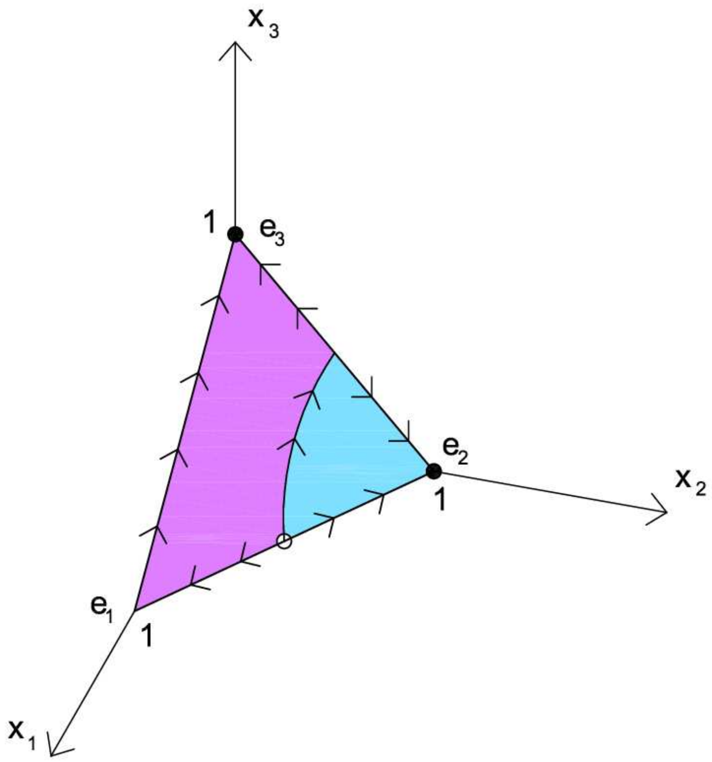

Figure 6. Dynamic regime in which only the vertices $e_2 = (0, 1, 0)$ and $e_3 = (0, 0, 1)$ are attractive, and a stationary state in the interior of S does not exist. The basins of attraction of $e_2$and e_3 are rendered in blue and pink, respectively.

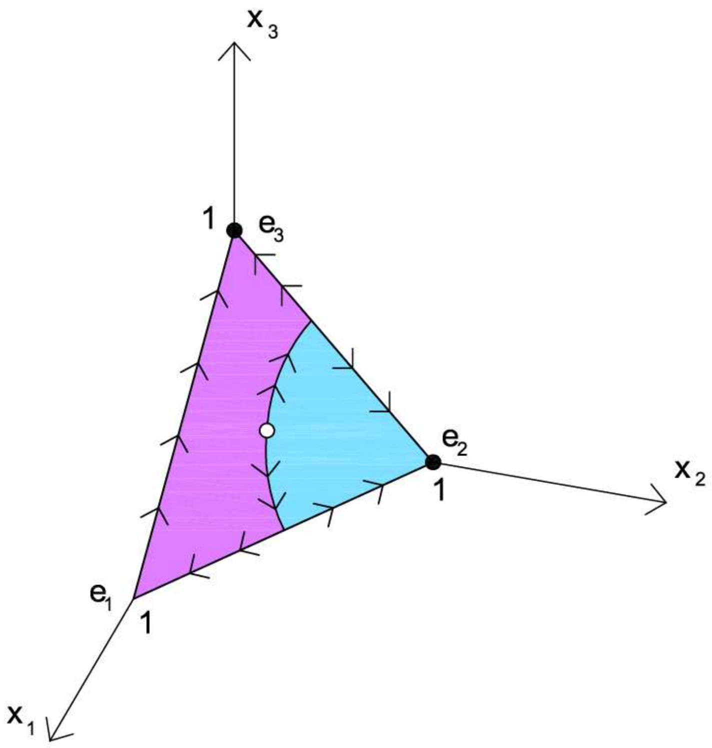

Figure 7. Dynamic regime in which only the vertices $e_2 = (0, 1, 0)$ and $e_3 = (0, 0, 1)$ are attractive, and a stationary state in the interior of S exists. The basins of attraction of e_2 and e_3 are rendered in blue and pink, respectively.

5.4. Regime Four: Neither Condition (5) Nor (6) Hold

In this context, $ae - bd \leq 0$ always holds (i.e., a stationary state in the interior of S does not exist), and the unique dynamic regime that can be observed is illustrated in Figure 8, corresponding to PP#42 of Bomze's classification. In this regime, the unique attractive stationary state is $e_3 = (0, 0, 1)$, in which all individuals withdraw from social participation, which Pareto dominates both the stationary states $e_1 = (1, 0, 0)$ and $e_2 = (0, 1, 0)$.

This extreme scenario may be interpreted as the result of exogenous conditions of social decay, which make social participation (in any form) poorly rewarding. For instance, the scarcity of infrastructures for face-to-face interactions (e.g., meeting places such as public parks, theaters, clubs, associations) lowers the reward provided by the *NS* strategy. Furthermore, the poverty of technological infrastructures for fast Internet access lowers the reward associated with the *SN* strategy.

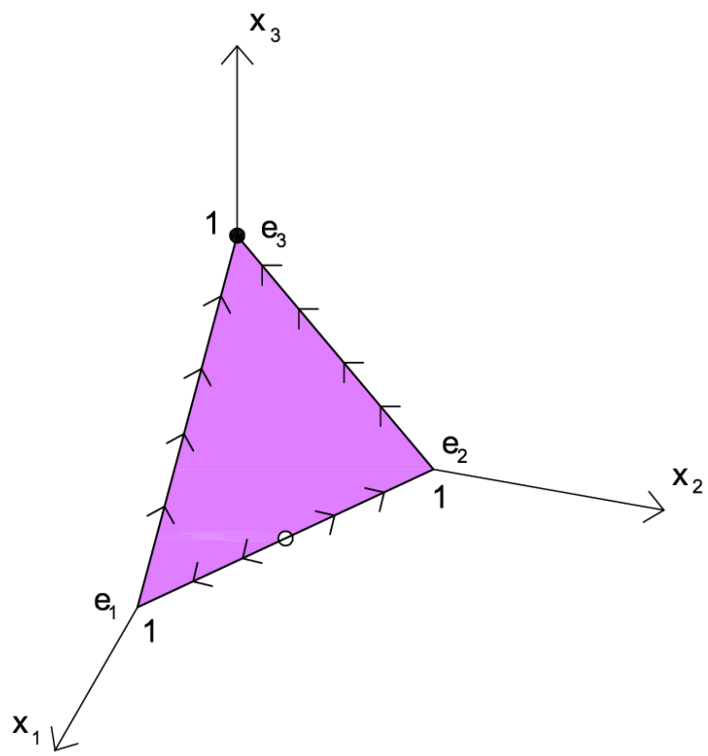

Figure 8. Dynamic regime in which only the vertex $e_3 = (0, 0, 1)$ is attractive. Its basin of attraction is in pink.

6. Discrimination and the Social Poverty Trap

The classification of dynamic regimes illustrated in Figures 2-8 suggests that the structure of the basin of attraction of the social poverty trap e_3 crucially depends on the propensity for discrimination of the two sub-populations of socially active individuals. The higher the propensity for discrimination, the greater the probability that individuals will ultimately segregate themselves, making society fall into the trap.

In fact, the less gratifying the interaction between *SN* and *NS* players, the more attractive the social isolation strategy *NP* becomes. If the rewards δ and ε that *SN* and *NS* players get when they interact face-to-face is particularly low, then they both might be tempted to withdraw from social interaction, whatever the initial share of the sub-population adopting either *SN* or *NS* is. Notice that when condition (10) holds, then a stationary state in the interior of the simplex *S* exists. This condition is never satisfied if the rewards δ and ε are negative and low enough. In such a context, if the stationary states e_1 and e_2 are attractive (see the regime shown in Figure 2), then the basin of attraction of the social poverty trap e_3 is so large that it includes points close to the edge $e_1 - e_2$, where the *NP* strategy is almost extinct, the majority of the population socially participates and the two strategies of social participation (*NS* and *SN*) are uniformly distributed.

However, the basin of attraction of the social poverty trap e_3 does not include the areas in close proximity to the edge $e_1 - e_2$ if the rewards δ and ε are high enough and, therefore, condition (10) is satisfied (see Figure 3). This result suggests that, if the two sub-populations of *SN* and *NS* players have a limited tendency to discriminate against each other—which happens if the rewards δ and ε that the two types of players receive when they interact face-to-face are high enough—then society will be less likely to fall into the social poverty trap in the cases in which the initial level of social participation is high, even if the two strategies *NS* and *SN* are uniformly distributed, as happens in the dynamic regime illustrated in Figure 3. On the other hand, when the reward given by the interaction between *SN* and *NS* players is particularly low, the two strategies ultimately may crowd each other out. A similar crowding-out effect also applies to the dynamic regimes illustrated in Figures 4, 5, 6 and 7. In these cases, the basin of attraction of the social poverty trap e_3 is so large that it also includes the areas in close proximity to the edge $e_1 - e_2$. This means that society can converge to e_3 even if the initial share of the sub-population adopting the social participation strategies *SN* and *NS* is particularly high.

7. Supplementary Result: A Prediction of the Model

There is growing empirical evidence showing that face-to-face interaction is associated with higher levels of well-being than SNS-mediated interactions. Using Italian cross-sectional data, Sabatini and Sarracino (2017) found that subjective well-being is positively correlated with face-to-face encounters and negatively correlated with SNS-mediated interactions. Helliwell and Huang (2013) reached a similar conclusion by comparing the well-being effects of online and offline friendships in a Canadian sample. Kross et al. (2013) examined this issue using experience sampling. The authors text-messaged people five times per day for two weeks to test how offline and Facebook-mediated interactions correlate with aspects of subjective well-being (SWB). Results indicate that Facebook use predicts negative shifts in SWB, while face-to-face interactions show no significant effect. Based on a survey conducted on a representative sample of 2,000 French Facebook users, Pénard and Mayol (2015) found that Facebook interferes with subjective well-being through its effects on friendships and self-esteem. Their results show that people who also use the network to seek social approval in the form of more "likes" tend to be more unsatisfied with their life. Similarly, Sabatini and Sarracino (2016) drew on Italian representative data to show that the use of SNS is associated with lower levels of satisfaction with respondents' income, which was not found to be the case from face-to-face interactions, thereby suggesting that the use of online networks can raise material aspirations with detrimental effects for SWB.

Overall, the empirical evidence suggests the utility of further analyzing the dynamics occurring in the region of the simplex where:

$$EP_{NS}(x_1, x_2) > EP_{SN}(x_1, x_2)$$

In this region, the reward provided by a strategy of social participation exclusively based on face-to-face interactions is higher than the benefits associated with the use of SNS (the *SN* strategy). The following proposition allows for the prediction of the possible evolution of the shares of the population x_1, x_2, x_3 adopting the three strategies in a society, starting from an initial configuration of payoffs that are consistent with the evidence mentioned above, where:

$$EP_{NS}(x_1(0), x_2(0)) > EP_{SN}(x_1(0), x_2(0))$$

Proposition 4

The set in which

$$EP_{NS}(x_1, x_2) > EP_{SN}(x_1, x_2)$$

holds (where the payoff of strategy SN is lower than that of strategy NS) and the set in which

$$EP_{NS}(x_1, x_2) < EP_{SN}(x_1, x_2)$$

holds (where the payoff of strategy SN is higher than that of strategy NS) are invariant under dynamics (2). That is, every trajectory starting from the former cannot enter the latter, and vice versa.

Proof: See the Mathematical Appendix B.

Proposition 4 states that if the payoff associated with the *NS* strategy is initially higher than that associated with the *SN* strategy, then it will always be higher than that provided by the *SN* strategy, unless exogenous perturbations change the model's parameters. As a result, the economy cannot converge to the stationary state $e_1 = (1, 0, 0)$, in which all individuals adopt the *SN* strategy, if it is starting from the region in which $EP_{NS} > EP_{SN}$ holds. This means that almost all of the trajectories starting from such a region will converge to e_2, in which individuals socially participate by exclusive means of face-to-face interactions, or to e_3, in which nobody participates. Only one trajectory can reach the edge $e_2 - e_3$ where the *NS* and the *NP* strategies coexist. In any case, the analysis of dynamics suggests that society will converge to equilibria in which no one adopts the *SN* strategy.

8. Conclusions

In this paper, we developed an evolutionary game model to study the dynamics of different modes of interaction in contexts characterized by the steep rise in the use of SNS and a supposed decline in face-to-face social participation. In our framework, individuals can choose to withdraw from social relations or to interact with others online and offline. The analysis showed that, depending on the configuration of payoffs and the initial distribution of the various modes of participation in the population, different Nash equilibria could be reached. If we allow a configuration of payoffs that is compatible with individuals' preference for similar others, then discrimination will lead to the segregation of the three sub-populations accounted for in the analysis and, ultimately, to the survival of only one of the three. Every trajectory that starts from an initial distribution of strategies neither belonging to a one-dimensional stable manifold of a saddle point nor coinciding with a stationary state in which more than one strategy is adopted will approach one of the homogenous population stationary states.

If the reward for social withdrawal is low enough, then the stationary states in which all individuals play one of the two strategies of participation, e_1 and e_2, are locally attractive. In this case, they both Pareto dominate the stationary state in which everyone withdraws from social interaction, e_3. However, there is no Pareto dominance relationship between e_1 and e_2.

If e_1 and e_2 are attractive, then the former can Pareto dominate the latter or vice versa, but in both cases the equilibria Pareto dominate the social poverty trap e_3. The dynamic regimes are strongly path dependent. If the initial distribution of the three strategies is close enough to e_1, then the economy will converge to e_1. The same can be said for e_2 and e_3. The social poverty trap e_3, on the other hand, is always a sink, whatever the payoff of social withdrawal. In this scenario, the withdrawal from social participation can be interpreted as a defensive behavior in the sense theorized by Hirsch (1976). Individuals, in fact, might want to cope with the deterioration in the social environment surrounding them and/or with the increasing busyness related to their material aspirations by choosing to limit their social relationships to a minimum. This result is related to previous research that studied how growth may cause negative externalities on social relationships and social cohesion (Putnam, 2000; Antoci et al., 2012; Bartolini and Sarracino, 2015). These studies claimed that the rise in material aspirations and the need to work more might tighten time constraints, causing deterioration in the social environment and prompting a gradual withdrawal from face-to-face interactions.

Social withdrawal is self-reinforcing, in that the higher the share of the population renouncing social participation, the poorer the social environment becomes, for example, in terms of social engagement opportunities. People playing the *NP* strategy will ultimately decide to segregate themselves from the rest of the population.

In all of the possible cases corresponding to the stationary states e_1, e_2 and e_3, the segregation entailed by individuals' tendency for discrimination will lead to the survival of only one of the initial sub-populations.

The model also allowed us to study the future of social participation in a world in which social interaction via online networks is less rewarding than offline interaction. This scenario is particularly interesting as it is consistent with findings from the most recent empirical studies comparing the effect of face-to-face and SNS-mediated interactions on individuals' well-being. Our results suggest that dynamics starting from this scenario will lead the *SN* strategy to extinction, which entails that Facebook and similar platforms will disappear.

If we interpret the *NS* strategy more flexibly (and perhaps realistically) as a means of social participation demanding a minimum, instead of a null, interaction via SNS (e.g., *NS* agents may have formally subscribed to SNS, but they actually do not often use them), then the possible equilibria—existing in e_2, e_3 or in the edge between them—entail at least a dramatic reduction in the use of Facebook and other platforms, instead of their definitive disappearance.

Compliance with ethical standards

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Mathematical Appendix A

Dynamics (2) is equivalent (see Hofbauer, 1981) to the Lotka-Volterra system:

$$\dot{X} = X(a + bX) \tag{11}$$

$$\dot{Y} = Y(d + eX + fY) \tag{12}$$

via the coordinate change:

$$x_1 = \frac{1}{1+X+Y},\ x_2 = \frac{X}{1+X+Y},\ x_3 = \frac{Y}{1+X+Y} \tag{13}$$

From which $X = x_2/x_1$ and $Y = x_3/x_1$.

Please note that by the coordinate change (13), the edge $e_1 - e_2$ of the simplex S (see Figure 1) corresponds to the positive semi-axis $Y = 0$ of the plane (X,Y), the edge $e_1 - e_3$ corresponds to the positive semi-axis $X = 0$ and the vertex e_1 corresponds to the point (X,Y) = (0,0) (see Figure 9).

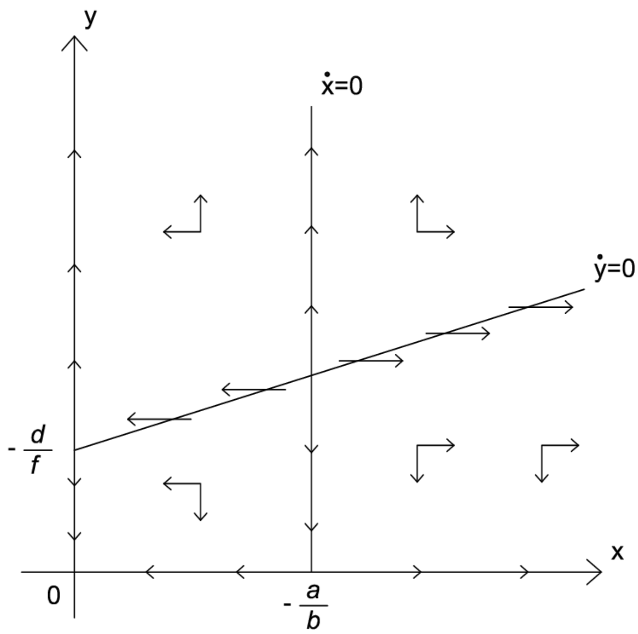

Figure 9. Arrow diagram of the Lotka-Volterra system. The edge $e_1 - e_2$ of the simplex S corresponds to the positive semi-axis $Y = 0$ of the plane (X,Y), the edge $e_1 - e_3$ corresponds to the positive semi-axis $X = 0$, and the vertex e_1 corresponds to the point (X,Y)=(0,0). The set in which $EP_{SN} > EP_{NS}$ holds coincides with the region on the left of the vertical straight line $X = -a/b$.

According to equation (11), $\dot{X} = 0$ holds along the axis $X = 0$ and along the vertical straight line $X = -a/b$>0; furthermore, $\dot{X} > 0$ ($\dot{X} < 0$) holds on the right (respectively, on the left) of $X = -a/b$. According to equation (12), $\dot{Y} = 0$ holds along the axis $Y = 0$ and along the straight line $Y = -d/f - (e/f)X$. Furthermore, $\dot{Y} > 0$ ($\dot{Y} < 0$) holds above (respectively, below) $Y = -d/f - (e/f)X$.

Remembering that $a < 0, b > 0,$ and $f > 0$, we have that a unique stationary state with *X*>0 and *Y*>0, $(\bar{X}, \bar{Y}) = \big(-a/b, -d/f + (ae)/(bf)\big)$, exists if and only if $ae > bd$ (condition (10) of Proposition 3). The Jacobian matrix of system (11)-(12), evaluated at $(\bar{X}, \bar{Y})$, is a triangular matrix:

$$J(\bar{X}, \bar{Y}) = \begin{pmatrix} b\bar{X} & 0 \\ \bar{Y} & f\bar{Y} \end{pmatrix}$$

With eigenvalues $b\bar{X} > 0$ (in direction of $= -a/b$) and $f\bar{Y} > 0$. So $(\bar{X}, \bar{Y})$ is always a repulsive node (this completes the proof of point one of Proposition 3).

By following similar steps, it is easy to verify that:

1) The Lotka-Volterra system (11)-(12) always admits a unique stationary state $(X, Y) = (-a/b, 0)$, with $-a/b > 0$, belonging to the positive semi-axis $Y = 0$ (corresponding to the edge $e_1 - e_2$ of the simplex *S*; see Figure 1). Such a stationary state is a saddle point (with unstable manifold lying in $Y = 0$, and stable manifold lying in $X = -a/b$) if the internal stationary state $(\bar{X}, \bar{Y})$ exists; otherwise it is a source (point two of Proposition 3).

2) The Lotka-Volterra system (11)-(12) admits a unique stationary state $(X, Y) = (0, -d/f)$, with $-d/f > 0$, belonging to the positive semi-axis $X = 0$ (corresponding to the edge $e_1 - e_3$ of the simplex *S*) if $d < 0$. Such a stationary state is always a saddle point with unstable manifold lying in $X = 0$. If $d \geq 0$, then no stationary state with $Y > 0$ exists in the positive semi-axis $X = 0$ (point three of Proposition 3).

3) The state $(X, Y) = (0,0)$ (corresponding to the vertex e_1 of the simplex *S*; see Figure 1) is always a stationary state; it is a saddle point (with unstable manifold lying in $X = 0$, and stable manifold lying in $Y = 0$) if $d \geq 0$ (i.e., if the stationary state in the semi-axis $X = 0$ does not exist, see point two above), otherwise it is a sink (point one of Proposition 1).

The stability properties of the stationary states e_2 and e_3 (points two to three of Proposition 1) and the existence and stability properties of the stationary state belonging to the edge $e_2 - e_3$ (point four of Proposition 3)[8] can be easily analyzed by applying Propositions 1, 2 and 5 in Bomze (1983), who provided a complete classification of two-dimensional replicator equations.

Mathematical Appendix B

The condition:

$$EP_{SN}(x_1, x_2) > EP_{NS}(x_1, x_2)$$

can be written as follows:

$$ax_1 + bx_2 < 0,$$
$$bx_2 < -ax_1,$$
$$X < -\frac{a}{b},$$

where $X = x_2/x_1$. Consequently, in the positive quadrant of the plane (X, Y), the set in which $EP_{SN} > EP_{NS}$ holds coincides with the region on the left of the vertical straight line (see Figure 9):

$$X = -\frac{a}{b} > 0 \tag{14}$$

Along the straight line (14), $\dot{X} = 0$ holds, while the set in which $EP_{SN} < EP_{NS}$ holds corresponds to the region on the right of (14). Since (14) cannot be crossed by trajectories (see Figure 9), the two regions separated by (14) are invariant. Consequently, every trajectory starting from the region in which $EP_{SN} < EP_{NS}$ cannot converge to the stationary state $(X, Y) = (0,0)$, which corresponds to the stationary state $e_1 = (1, 0, 0)$. This completes the proof of Proposition 4.

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[8] Such stationary states do not correspond to stationary states of the Lotka-Volterra system (11)-(12).