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Antoni Rubí-Barceló *

Abstract

This paper exploits a network formation game to analyze categorical thinking as a source of segregation. The link between categorical thinking and segregation was recently suggested by Fryer and Jackson (2008). The present model shows how segregation may emerge even when self-interested agents have no a priori motivation to do so; consequently, this paper supports the argument that segregation may not be malevolent in origin.

Keywords: categorization, network formation, imperfect information, segregation.

JEL classification: J15, D85.

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1 Introduction

Segregation is a pervasive and persistent sociological phenomenon that emerges along many different lines (race, sex, religion, or language among others) and appears in a wide range of situations (residential or occupational segregation, for example). The set of explanatory factors possibly influencing segregation that have been explored by the literature is large. In a labor market environment, the main theories of segregation are based upon taste (Becker, 1971) or statistical discrimination by employers (Phelps, 1972). Papers about residential segregation have pointed out many different factors but individual's preferences have been single out as a critical variable both by economists and sociologists (Clark, 1991). Schelling's neighborhood segregation model is the most widely cited contribution in this literature.

In a series of pioneering works, Schelling (1969, 1971a,b, 1972, 1978) introduced a self-organization model system of two distinguishable types of agent with discriminatory individual preferences for certain neighborhood compositions and then explored the dynamics of this model system. The results show that "micromotives at the local level give rise to macrobehavior at the aggregate (global) level" (p.2 in Pancs and Vriend, 2007) and "even quite color-blind individual preferences produce quite segregated neighborhoods" (p.3 in Epstein and Axtell, 1996).

Nevertheless, most studies investigating the causes of segregation agree that "classical" theories such as taste or statistical discrimination cannot alone explain this sociological condition. The model presented here formally analyzes an alternative and complementary cause of segregation based on the idea of *categorical thinking* analyzed by Fryer and Jackson (2008). Unlike taste discrimination models, the present paper shows that segregation can emerge even if individual preferences are completely color-blind. This model shows that segregation can emerge because of informational asymmetries across the different social groups derived from categorical thinking. To the best of my knowledge this paper constitutes the first formal attempt to motivate this type of segregation from a game theoretical framework.

The informational asymmetries that generate segregation in this model are based upon a cognitive process called categorization. The central idea is that human mind stores past experiences in a finite set of "folders" or categories and that the number of categories is limited. In social psychology a large list of contributions demonstrate that agents process information with the aid of categories (see Fryer and Jackson (2008) for a review). An

extensive list of authors in this field treats some biases such as stereotyping or prejudice as inevitable consequences of categorization (see Allport (1954), Hamilton (1981), Tajfel (1969), Fiske (1998), Markman and Gentner (2001), and Macrae and Bodenhausen (2000)). Fryer and Jackson (2008) presents a formal model justifying that:

"[...] types of experiences and objects that are less frequent in the population tend to be more coarsely categorized and lumped together. As a result, decision makers make less accurate predictions when confronted with such objects".

This lower accuracy with respect to less "frequent" agents is what may explain prejudices or discrimination against minority members. Evidence for a coarser sorting of blacks by employers can be found in Jowell and Prescott-Clarke (1970), Hubbick and Carter (1980), Brown and Gay (1985), and Bertrand and Mullainathan (2003)[1].

Categorical thinking grounds the informational asymmetries exploited in the present paper. In this model agents are featured by a physical characteristic (in general, any observable feature such as race, sex, or language) which is assumed to be payoff irrelevant and by a "qualitative" aspect (productivity, talent or human quality among others) that might be ignored by others and whose value affects others' payoff. Based on categorization evidence, it is assumed that agents' pattern of social interactions affects the accuracy of their predictions about others' qualitative feature. Specifically, this accuracy is lower when predicting the qualitative feature of those agents whose physical characteristic is less frequent in the set of agents who interact with the predictor.

In this model, social interactions are formalized through mutual consent networks. Although a number of contributions to microeconomic theory have used network structures to formalize such diverse issues as the internal organization of firms, employment search, and the structure of airline routes[2], imperfect information have been rarely treated in models of network formation[3]. This is true despite the empirical work which shows that the information of individuals in a social network is limited (see Laumann (1969), Friedkin (1983), Kumbasar, Romney, and Batchelder (1994), Bondonio (1998), and Casciaro (1998)). The present paper formalizes the analysis of imperfect and asymmetric

[1]There is also a literature on racial and ethnic differences in facial recognition (see Sporer (2001) for a detailed review) showing that individuals who interact more frequently with members of a given racial group recognize members of this group better than members of other ethnic groups. This data is consistent with the model of categorization of Fryer and Jackson (2008).

[2]Garicano (2000), Brueckner, Dyer, and Spiller (1992) and Calvó-Armengol (2004) are examples of these issues.

[3]A notable exception is McBride (2006, 2006a) who introduced limited observation in a network formation game.

information in a network formation game and applies this formalization to the study of the effects of categorization on segregation.

One of the key tools in this formalization is the equilibrium concept that allows us to define the principles that determine the stable game resolutions, namely, those networks that do not offer profitable possibilities of deviation to their members. The equilibrium concept used in this paper is the Conjectural Pairwise Nash Equilibrium (CPNE). This concept generalizes Pairwise Nash Equilibrium (PNE) concept[4] by relaxing the restriction that individual's beliefs must be correct. Specifically, CPNE concept allows players to have incorrect conjectures in stable networks, so long as they have no information to contradict those conjectures. Additionally, this paper investigates the effect on stability of a refinement that have been considered in the literature: common knowledge of rationality[5].

Section 2 presents some basic notation and formally defines the network formation game with imperfect information and the stability concept. Following two different frameworks, Section 3 presents the following results: First, categorical thinking may cause segregation in a society in which individuals' preferences are not biased at all. Second, imposing common knowledge of rationality reduces but does not eliminate the possibilities of segregation. Third, the refining power of the "common knowledge of rationality" refinement not only depends on agents' observation capacities (as showed in McBride, 2006a) but also on the payoff structure.

This paper introduces and applies a new stability concept, CPNE, to the study of network formation games with imperfect information. Nevertheless, the main contribution of this paper relates to the implications of categorical thinking on segregation. This paper contributes a formal analysis of a new and complementary explanatory cause of segregation. In line with Fryer and Jackson (2008), the present model shows that segregation arising from categorization emerges even when agents' preferences are completely color-blind. This supports the argument that segregation may not be malevolent in origin.

[4]A network is PNE if no player has incentives to unilaterally deviate and no mutually beneficial link is left aside. See Goyal and Joshi (2006), Calvó-Armengol (2004), and Bloch and Jackson (2006, 2007) for definitions and applications of pairwise-Nash networks.

[5]This refinement was first considered by Rubinstein and Wolinsky (1994) and Gilli (1999) with respect to the Conjectural Equilibrium concept.

2 Model

2.1 Set up

Let $N = \{1,...,n\}$ be the finite set of agents in the population. Players on N are connected by a graph or network g, a collection of direct links that represent binary or pairwise relations between the respective two agents. The set of all possible networks in N is G. The subset of N containing i and j is denoted by ij and is referred to as the link ij. The nodes i and j are directly connected if and only if $ij \in g$. The set of i's direct links in g is $L_i(g) = \{jk \in g : j = i \text{ or } k = i\}$. A *path* in g connecting i_1 and i_m is a set of distinct nodes $\{i_1, i_2,..., i_m\} \subset N$ such that $\{i_1 i_2, i_2 i_3,..., i_{m-1} i_m\} \subset g$. A nonempty set of players $N_k(g) \subseteq N$ is a component of g, if for all $i \in N_k(g)$ and $j \in N_k(g)$, $i \neq j$, there exists a path in g connecting i and j, and for any $i \in N_k(g)$ and $j \in N$, $ij \in g$ implies $j \in N_k(g)$. If $L_i(g)$ is empty for some $i \in N$ then i constitutes a single-agent component. Notice that the set of components of a network g, *i.e.* $\{N_k(g)\}_{k=1}^{K}$, partitions N; thus, $N_k(g) \subset N$ are disjoint and $\bigcup_{k=1}^{K} N_k(g) = N$. Let $g + ij$ denote the network obtained by adding link ij to the existing network g and let $g - ij$ denote the graph obtained by deleting link ij from the existing network. More generally, for every collection of links $l \subseteq L_i(g)$, $g - l$ is the network obtained by deleting all links in l from g. Finally, a set of links $l \subseteq L_i(g)$ is said to be *critical* to the graph g if $g - l$ has more components than g.

Any given agent is characterized in two different dimensions: social identity and quality. The former is a perfectly observable characteristic of agents that may be thought as a physical feature such as race, sex, or language among others. For the sake of simplicity, it is assumed that there are only two different social identities, say red (R) and blue (B). Social identity does not directly affect agents' payoff but information about the agents' second characteristic: quality. Individual's quality must be understood as the inherent value of that individual to all connected agents. For simplicity, it is also assumed that agents' quality can only take two different values, say high (H) and low (L). So, overall, agents come in four flavors: red-high, red-low, blue-high, and blue-low. In order to

make an examination of segregation non-trivial, red and blue agents are both just as likely to be of high quality level or low and there is some agent in each of these four types. Let t_i denote the quality of agent i, so that $t_i \in \{H, L\}$. Let t denote the n-dimensional vector of qualities and T the set of all possible vectors. In this model, this vector t and the particular network structure g characterize the *state of the world*. Let $\mathsf{G} \times \mathsf{T}$ denote the set of possible states of the world. Let $m_i : \mathsf{G} \times \mathsf{T} \to M_i$ be i's message function such that each state of the world yields a message m_i in message space M_i. Unlike g and social identities, vector t may not be fully observed by agents[6] so that agents can receive the same message from different states of the world (imperfect information). Let $\pi_i : \mathsf{G} \times \mathsf{T} \to [0,1]$ be the subjective probability distribution of agent i over the possible states of the world and let π_i denote i's beliefs about the actual state of the world.

Network g represents the pattern of social interactions. Consequently, agents only interact (directly or indirectly) with the members of their respective component. From these social interactions, agents extract information so that the quality of the members of a component is known by all its members. Based on categorization evidence, these social interactions also constitute the experiences that agents store in their mental categories and use to make predictions about the quality of others. The accuracy of those predictions are affected by that categorization. As explained in the introduction, the information obtained by agent i from the members of the less frequent social identity in their component (say red) will be more coarsely categorized and, consequently, i's predictions about the quality of red agents in other components will be less accurate[7]. For the sake of simplicity, it is assumed that if agent i is in a component with more than a half of blue members then she will not be able to detect the actual quality of red agents outside of her component (the quality of all the rest will be perfectly detected)[8]. In what follows this informational structure is referred to as "categorical information".

The strategy of a player consists of making an announcement of intended links. A

[6] McBride (2006) also assumes that agents may ignore part of the structure of connections g.

[7] In case a component has the same number of reds and blues, any tie-break rule can be assumed. The effect of this tie-break rule on the results is marginal

[8] This assumption is consistent with categorical thinking in cases where components are big and have a proportion of blues with respect to reds is close to one or zero. In such components agents of one social identity hardly interact with different-identity agents whereas they "store" many past experiences with members of one social identity. The results of this paper must be thought in this context. More sophisticated

strategy is a mapping function $s_i : m_i \to A_i$, where A_i is player i's action set with $|A_i| = 2^{N\setminus\{i\}}$. Let S_i be player i's strategy set. A typical strategy of player i, s_i, consists on the set of players with whom i wants to form a link. The payoff function can be represented as the mapping $Y_i : \prod_{i\in N} S_i \times \mathrm{T} \to \mathrm{R}$. Let $Y_i(g(s),t)$ denote agent i's payoff, where $s \in \prod_{i\in N} S_i$ and

$$g(s) = \{(ij) : j \in s_i, i \in s_j\}.$$

As in Jackson and Wolinsky (1996), a link between two individuals (i) can be severed unilaterally but (ii) can only be created by mutual consent of the two involved agents. Thus, each strategy vector s generates a unique graph $g(s)$.

Let $g \in G$. For all $i, j \in N$ such that $ij \in g$,

$$mY_i^{ij}(g,t) = Y_i(g,t) - Y_i(g - ij,t)$$

is the marginal payoff to i from the link $ij \in g$. More generally, the joint value to i of l is:

$$mY_i^{l}(g,t) = Y_i(g,t) - Y_i(g - l,t), \text{where} l \subseteq L_i(g)$$

Consider now some link $ij \notin g$. Then:

$$mY_i^{ij}(g + ij,t) = Y_i(g + ij,t) - Y_i(g,t)$$

is the marginal payoff accruing to i from the link ij being added to g.

A component is *completely segregated* if it contains agents of only one social identity. In general, segregation is measured in terms of the absolute deviation from a 50-50 component, *i.e.* a component containing equal number of reds and blues. A component is *h-partially segregated* (or *l-partially segregated*) if it contains high (or low) quality agents of only one social identity. A society is *completely segregated* if all its components are completely segregated. Following these definitions, analyzing segregation will involve studying the distribution of social identities among the different components of the social network rather than detailing the components' internal network structure. For this reason, I

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informational structures complicate the model to a great extent and are left for future research.

do not fully specify a particular payoff function[9] but simply define the basic principles that rule the incentives of creation/severance of critical links. Let p_{N_k} be the proportion of high-quality agents in the set $N_k \subseteq N$ and $\alpha_{t_i} \in [0,1]$. Let $N_1(g) \subset N$ and $N_2(g) \subset N$ be two different components of g such that $i \in N_1(g)$ and $j \in N_2(g)$.

A1. $mY_i^{ij}(g+ij,t) > 0$ if and only if $p_{N_2(g)} \geq \alpha_{t_i}$.

A2. For any critical set of links $l \subseteq L_i(g)$, $mY_i^{l}(g,t) > 0$ if and only if $p_{N_1(g)\setminus N_k(g-l)} < \alpha_{t_i}$, where $N_k(g-l)$ is the component of $g-l$ such that $i \in N_k(g-l)$.

A3. Agent i's payoffs are entirely determined by the component she belongs to.

In words, A1 says that the marginal value an agent obtains for creating a critical link will be strictly positive if and only if the added component contains a sufficiently high proportion of high-quality agents. On the other hand, agent i obtains a positive marginal payoff from severing a critical set of links if and only if the proportion of high-quality agents in the set of former component-mates is sufficiently low. Parameter α_{t_i} can be interpreted as the cutoff value for that proportions. Intuitively, the higher is α_{t_i} the more demanding is agent i with respect to the quality of their component mates. Notice that this cutoff value is allowed to vary across quality types, so α_H may generally be different from α_L. A3 specifies the hedonic nature of this network formation game, *i.e.* agents' payoffs are not affected by other components[10]. Hedonic preferences have been motivated and analyzed in a large number of models of coalition formation, specially those with local public goods or some sort of political interaction as in Guesnerie and Oddou (1981), Greenberg and

[9] Furthermore, such specification could be controversial in an imperfect information setting. If agents have a limited horizon of observability, assuming common knowledge of a specific payoff function may be difficult to justify.

[10] Given the message function specified above and A3, notice that if $m_i(g,t) = m_i(g,t')$ then $y_i(g,t) = y_i(g,t')$. That is, players' information set include information about her realized payoff. This

Weber (1986, 1993), Demange (1994), Bogomolnaia and Jackson (2002). Notice that social identity does not affect agents' payoff, so agents' preferences are color-blind.

2.2 Conjectural Pairwise Nash Equilibrium

The requirement of mutual consent in the link creation combined with the multidimensional strategy space (players can announce any combination of links they wish) involve that the network formation game display a multiplicity of Nash equilibria. If players are allowed to coordinate bilaterally, instead, no mutually beneficial link is left aside and the multiplicity is reduced. The Nash equilibrium outcomes that fulfill this added (coalitional move) requirement are called pairwise-Nash networks. Implicit in the PNE concept is that each individual has full information about the change in her utility arising from any single link deviation, and, as such, the PNE concept is not appropriate if individuals have categorical information. For this reason, the *Conjectural Pairwise Nash Equilibrium (CPNE)* is used in the present paper[11].

Definition 1 *A graph* $g \in \mathsf{G}$ *is a CPNE with respect to vector* t*, utility functions* $\{Y_i\}_{i\in N}$*, message functions* $\{m_i\}_{i\in N}$*, and beliefs* $\{\pi_i\}_{i\in N}$ *if*

(i) $Y_i(g,t) \geq \sum_{t' \in \mathsf{T}} \pi_i(g,t')\ Y_i(g-l,t')$ for all $i \in N$ and any $l \subseteq L_i(g)$,

(ii) for all $ij \notin g$, if $Y_i(g,t) < \sum_{t' \in \mathsf{T}} \pi_i(g,t') Y_i(g+ij,t')$ then $Y_j(g,t) > \sum_{t' \in \mathsf{T}} \pi_j(g,t') Y_j(g+ij,t')$, and

(iii) for each i, $m_i(g,t') = m_i(g,t)$ for any $t' \in \mathsf{T}$ such that $\pi_i(g,t') > 0$.

In words, a network is CPNE if: (i) no player believes that she will be better off by

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restriction on m_i is usually imposed by the literature (Gilli, 1999) in those imperfect information games.

[11] Pairwise-stability is another equilibrium concept that has been extensively used for positive purposes due to its computational (relative) simplicity, and to its ability to generate sharp predictions in many contexts. Nevertheless, Pairwise-Stability is too weak for the purposes of the present work.

deleting a group of existing links, (ii) in any pair of non-directly linked players, at least one player believes that she will be worse off by creating a new link between them and, (iii) no player's beliefs are contradicted by her signal. Unlike Conjectural Pairwise Stability introduced by Mcbride (2006), CPNE networks are robust to unilateral multi-link severance.

Notice that CPNE does not require that probabilities attributed to each state of the world are justified. Instead, it only requires that these probabilities are not contradicted by agents' messages. Rubinstein and Wolinsky (1994) and Gilli (1999) acknowledged this drawback for the Conjectural Equilibrium concept. They consider the imposition of common knowledge of rationality as a way to refine players' beliefs so that each player must reflect optimal play on the part of the other players. This imposition is referred to as the " rationalizability refinement" and the CPNE networks that fulfill this requirement are referred to as *rationalizable* CPNE networks. Imposing common knowledge of rationality involves making signal functions (not actual actions or types) common knowledge. Individual i must justify her beliefs about j's beliefs and actions given her beliefs about j's signal; and j must in turn rationalize her beliefs about k's actions and beliefs given her beliefs about k's signal; and so on.

Before moving to the results, notice that the size of the set of CPNE networks depends on the informational content of messages as follows:

Remark 1 *For a given* t *and* $\{Y_i\}_{i\in N}$*, if the messages* $\{m_i^{'}\}_{i\in N}$ *contain more information than* $\{m_i\}_{i\in N}$ *then a CPNE network under* $\{m_i^{'}\}_{i\in N}$ *is also a CPNE network under* $\{m_i\}_{i\in N}$*, but the converse is not necessarily true.*

Intuitively, the higher is the informational content of messages, the lower is the number of unrealistic beliefs that an agent can conjecture about the actual state of the world. Thus, if the network meets the stricter requirements for CPNE under $\{m_i^{'}\}_{i\in N}$, it will certainly meet the requirements for CPNE under $\{m_i\}_{i\in N}$. For this reason, the equilibrium networks of the present model could also be sustained in other environments with less informative messages.

3 Results

In this section the CPNE concept is used to analyze the effects of categorical thinking on segregation. For the sake of comparison, results are presented gradually: first, I characterize equilibrium networks under perfect information; second, "categorical information" is introduced, and finally I analyze the effects of imposing "common knowledge of rationality". This will allow us to see the effects on segregation of each of these factors separately. Additionally, the analysis is divided into two different frameworks in order to illustrate how the payoff assumptions affect the results.

A complete stability checking analysis would have to specify the internal structure of connections for any given component. As argued above, this is beyond the scope of this analysis because segregation is defined in terms of the distribution of agents across components. For this reason, next results merely characterize the equilibrium partitions (rather than networks). Nevertheless, equilibrium partitions are those that are sustained by some CPNE network. Not analyzing the internal organization of components has two implications:

1) Checking robustness to link severance (first condition of the CPNE concept) can be simplified to a great extent. Given that:

Remark 2 *For any set of players* $N_k \subseteq N$ *there always exists a network* g *such that* $L_i(g)$ *is the unique critical set of links for any* $i \in N_k$ [12].

It can be concluded that if $p_{N_k \setminus \{i\}} \geq \alpha_{t_i}$ for a given set of agents N_k and for all $i \in N_k$, then there will exist a network among the members of N_k that will be robust to link severance.

2) The analysis of the second condition of the CPNE concept can focus on the creation of links between members of different components.

3.1 Framework 1: $\alpha_H > 0$ and $\alpha_L = 0$

$\alpha_L = 0$ implies that low-quality agents always increase their payoff after creating a new critical link. In consequence, segregation by social identity among low-quality agents will never exist in equilibrium because all of them must be located at the same component

g_l independently of their social identity.

PNE networks (*i.e.* the set of CPNE networks under full information) are characterized below.

Proposition 1 *Consider* $\alpha_H > 0$, $\alpha_L = 0$, *and full information. A CPNE network is constituted by either (i) two components completely segregated by quality or (ii) a unique component. The latter equilibrium requires that* $p_{N\setminus\{i\}} \geq \alpha_H$ *for* $t_i = H$.

Proof. Since $\alpha_L = 0$ all low-quality agents must be members of the same component, say N_l. Notice that high-quality agents cannot be scattered across different components in equilibrium. If this was so then each of these components (say N_k) would hold: $p_{N_k\setminus\{i\}} \geq \alpha_H$ where $t_i = H$. Since $p_{N_k} \geq p_{N_k\setminus\{i\}}$, a critical link between these components would be created. In consequence, there are only two possibilities: either all high-quality agents are in N_l or all high-quality agents constitute a different component N_h. Notice that the former possibility can only hold in equilibrium if $p_{N\setminus\{i\}} \geq \alpha_H$.

For any given profile of qualities and social identities, there are exactly two types of partitions that could be sustained by PNE networks. Under full information, society will either concentrate in a unique component or be completely segregated by quality. Complete segregation by quality is the unique equilibrium partition when $p_{N\setminus\{i\}} < \alpha_H$, where $t_i = H$. Social identity does not play any role here in shaping the structure of social connections.

PNE networks are necessarily CPNE, but the converse is not necessarily true. Imperfect information will widen the set of equilibria as follows:

Proposition 2 *Consider* $\alpha_H > 0$, $\alpha_L = 0$, *and categorical information. In any CPNE network, high-quality agents can be scattered across* K *different components (*N_l *and* $K-1$ *additional components). If* $\alpha_H \leq 0.5$ *then* $K \leq 3$. *Otherwise,* K *can be higher.*

[12]For example, a network g such that $ij \in g$ for all $i, j \in N_k$ always fulfill this condition.

Proof. Since $\alpha_L = 0$ all low-quality agents are in N_l. In order to sustain two different components (N_1 and N_2) without low-quality agents in equilibrium, for any pair of agents $i \in N_1$ and $j \in N_2$ at least one of them should believe that the other component contains a proportion of high-quality agents lower than α_H. Unless both components have different majority social identities, this belief is not possible when $\alpha_H \leq 0.5$ because agents in one component will be able to observe the quality of at least half of the members of the other component. Since there are only two social identities, the maximum number of components without low-quality agents when $\alpha_H \leq 0.5$ is 2 and $K \leq 3$. If $\alpha_H > 0.5$, two or more components without low-quality agents and with the same majority social identity can coexist in equilibrium because the proportion of detected members of the other component might be lower than α_H. Thus, agents are able to believe that all unobserved agents are low-quality individuals. For this reason, there can be more than 2 components without low-quality agents and K can be higher than 3.

Therefore, categorical information allows for the distribution of high-quality agents among different components. This can happen when agents' information about other components is sufficiently limited. This information crucially depends on segregation levels. Specifically, if two components have different majority social identities then stability requires sufficiently high levels of segregation. In particular, for any α_H, two completely segregated components without low-quality agents can always be sustained in equilibrium since any of their members can believe that all agents in the other component are low-quality individuals. Therefore, segregation by social identity among high-quality agents could be severe in this case.

The rationalizability refinement will narrow the set of equilibrium networks as follows.

Proposition 3 *Consider $\alpha_H > 0$, $\alpha_L = 0$, and categorical information. A rationalizable CPNE network is constituted by either (i) two components N_l and N_h such that N_l does not contain any high-quality agent of the majority social identity of N_h or (ii) a unique component. The latter equilibrium requires that $p_{N\setminus\{i\}} \geq \alpha_H$ for $t_i = H$.*

Proof. Since $\alpha_L = 0$ all low-quality agents must be in the same component N_l.

Rationalizability involves that players cannot believe that low-quality agents are scattered among two or more components. This has two implications: (i) since agents are able to observe at least one low-quality agent in N_l, this component will be always identified and, consequently, the maximum number of components is two (say N_h and N_l) and (ii) if there are two components, any member of N_l should know that there are not low-quality agents in N_h, so she is always willing to create a critical link. In consequence, stability of a network with these two components requires that agents in N_h believe that $p_{N_l} < \alpha_H$. At this point I claim that this belief is only possible when agents in N_h do not observe any high-quality agent (say i) in N_l. By contradiction, notice that if this was so then rationalizability would imply that they have to believe that $p_{N_l \setminus \{i\}} \geq \alpha_H$. Since $p_{N_l} \geq p_{N_l \setminus \{i\}}$ we reach a contradiction. Therefore, stability requires that agents in N_h do not observe any low-quality agent in N_l; in other words, N_l does not contain any high-quality agent of the majority social identity of N_h. A unique component can also be sustained under the same conditions of the perfect information framework.

Thus, the maximum number of components is two, as in the perfect information case. However, categorical information allows for the existence of segregation by social identity among high-quality agents even after imposing the rationalizability refinement. Notice that case (i) of Proposition 3 can only be sustained if N_l is h-partially segregated. Notice also that in this case a completely segregated N_h can also be sustained in a rationalizable CPNE. In consequence, high-quality agents of the minority social identity in N_h might be systematically excluded from this component by its members as a consequence of being more coarsely sorted due to their scarcity in N_h. This possibility of discrimination affecting minorities is in line with the predictions of Fryer and Jackson (2008) with respect to the negative consequences of categorical thinking on minorities.

As commented above, since $\alpha_L = 0$ low-quality agents will not be segregated in equilibrium. Next, the case where $\alpha_L > 0$ is considered. As expected, segregation among low-quality agents in a CPNE will be sustainable, but this change generates interesting and surprising effects on the set of rationalizable CPNE social structures.

3.2 Framework 2: $\alpha_H, \alpha_L > 0$

As in the previous case, the full information results are presented first.

Proposition 4 *Consider* $\alpha_H, \alpha_L > 0$ *and complete information. In any CPNE all high-quality agents are included in the same component* N_h *and* $p_{N_h \setminus \{i\}} \geq \alpha_{t_i}$ *for any* $i \in N_h$. *Agents not included in* N_h, *if any, must remain isolated.*

Proof. As shown in the proof of Proposition 1 high-quality agents cannot be scattered across different components in equilibrium. Since $\alpha_L > 0$, low-quality agents not included in N_h prefer to stay alone rather than in a component with only low-quality agents. The rest directly follows.

Under full information, the society could be completely segregated by quality or conform a unique component when $p_{N \setminus \{i\}} \geq \alpha_{t_i}$ for all $i \in N$, as in case 1. Nevertheless, when $\alpha_L > 0$ there is a set of intermediate equilibria between these two cases. In those equilibria, all highs and some lows constitute a component N_h as long $p_{N_h \setminus \{i\}} \geq \alpha_{t_i}$ for any $i \in N_h$. Since $\alpha_L > 0$, low-quality agents not included in that component will be isolated. In any case, social identity does not play any role in a perfect information setting.

Let us consider categorical information. Apart from the PNE structures described in the previous proposition, there are other equilibria. In a CPNE, high and low-quality agents can be scattered across different components whenever (i) for any multi-agent component N_k, $p_{N_k \setminus \{i\}} \geq \alpha_{t_i}$ for all $i \in N_k$ and (ii) the distribution of social identities is such that, for any pair of components, the message received by any member of at least one of them (say i) does not contradict the belief that the proportion of highs in the other component is lower than α_{t_i}. Consequently, multiple component configurations are sustainable in equilibrium and segregation can exist. In particular, a society completely segregated by social identity can be sustained as CPNE if the proportion of highs in each social identity group is high enough to hold condition (i) above. Thus, as expected, segregation may be even more severe than in framework 1 because low-quality agents can also be segregated.

Surprisingly, the refining power of the "common knowledge of rationality"

requirement is much higher than in framework 1. McBride (2005) showed that this refining power increases with the informational content of messages. Here, this informational content does not vary across frameworks, so the changes are caused by other factors; by assuming $\alpha_L > 0$, low quality agents face more demanding requirements to keep their component. That restricts the set of rationalizable beliefs about others' actions and, consequently, the set of rationalizable equilibrium networks is reduced.

Proposition 5 *Consider $\alpha_H, \alpha_L > 0$, and categorical information. In a rationalizable CPNE only one high-quality agent j may not be included in the unique multi-agent component N_h. This component is such that $p_{N_h \setminus \{i\}} \geq \alpha_{t_i}$ for any $i \in N_h$. Agents not included in N_h, if any, must remain isolated and j must have the same social identity as the minority group in N_h.*

Proof. Any multi-agent component (say N_k) must contain some high-quality agent and, consequently, $p_{N_k \setminus \{i\}} \geq \alpha_H$. Agents' beliefs cannot contradict this requirement. Thus, a network cannot contain two multi-agent components because if this was so then some pair of high-quality agents would have incentives to create a critical link between them. The same argument applies either if there are two isolated high-quality agents of the same social identity or if there is a multi-agent component N_h and a single-agent component constituted by a high-quality agent of the majority social identity of N_h. Consequently, at most one high-quality agent may remain separated from N_h and she must be of the minority social identity of N_h. Since $\alpha_L > 0$, low-quality agents not included in N_h prefer to stay alone rather than in a component with only lows.

Thus, when $\alpha_H, \alpha_L > 0$ the set of rationalizable CPNE exactly coincides with the set of PNE social structures, except for the case where one high-quality agent of the minority social group of N_h is not included in that component. As in the perfect information case, social identity does not play (almost[13]) any role in the configuration of the

[13]There is one marginal possibility of segregation by social identity among high-quality agents; the isolated high-quality agent can be rejected in equilibrium by the members of N_h as a consequence of being more coarsely categorized by them.

rationalizable CPNE networks[14].

4 Conclusion

This paper presents a simple model of network formation with imperfect information to illustrate the effects of categorical thinking on segregation. According to categorization, the information obtained by the observer from their (direct or indirect) social contacts is stored in a number of categories so scarce that force her to categorize more coarsely the experiences with the members of the less frequent social groups (see Fryer and Jackson, 2008). Consequently, the predictions about the hidden features of the minority members would be less accurate. In line with this general argument, this paper assumes a particular informational structure: any agent can perfectly observe the quality of all linked agents, either directly or indirectly, but only the quality of non-linked agents who belong to the social identity the observer is mostly interacting with. I take advantage of the simplicity of this informational structure to derive clear results concerning the possibilities of segregation in this context. More sophisticated informational structures could capture the essence of categorical thinking more accurately, but complicate the model to a great extent. Nevertheless the analysis of alternative informational structures consistent with categorization constitutes an interesting line for future research.

A general contribution of this paper is the introduction and application of the CPNE concept to the study of network formation games with imperfect information. This concept can be applied to other network formation games, thereby allowing researchers to study the relationship between efficiency, stability and information in other settings. The analysis of alternative payoff structures also constitutes a promising line for further research.

The results of the present paper show that CPNE social structures can be segregated by social identity as a consequence of categorical thinking. In framework 1, high-quality agents can be scattered across different components and those components can be completely segregated by social identity. Minority social identity members are particularly affected. In line with the predictions of Fryer and Jackson (2008), the results show that these agents might be systematically excluded from the component including high-quality agents as a consequence of being more coarsely sorted due to their scarcity.

[14]Rationalizable CPNE networks can include single-agent components. As explained in footnote 10, the informational structure assumed in this paper is not consistent with categorical thinking in these cases. In particular, according to categorical theory, isolated players would have to receive much less information. Assuming less informative messages will allow to sustain equilibrium networks with many isolated players. Nevertheless, notice that only one multi-agent component would be sustainable. Consequently, conclusions

Segregation can be even more severe in the second framework because it can also affect low-quality agents. The extreme case of complete segregation (population is split in two components according to social identity) is sustainable in that framework. The refining power of the rationalizability refinement varies across frameworks. In framework 1, segregation by social identity can exist in rationalizable CPNE but this refinement eliminates (almost) any possibility of segregation in framework 2. The reason of this variation is not the amount of information in the different settings -which remains constant- but the change in the minimum requirements for obtaining a positive payoff. There is an interesting implication of this analysis. To the extent that the "common knowledge of rationality" can be associated to a higher level of "intelligence" one would expect agents with lower "intelligence" to be more likely to organize themselves in segregated societies. This is exactly what we observed in the present paper.

The main contribution of this paper is to show, in a game theoretical framework, that segregation can arise among self-interested agents even when they have no a priori motivation to do so. Equal opportunity laws are usually premised on the notion that intergroup bias is malevolent in origin. In line with Fryer and Jackson (2008) or Krieger (1995), the present paper would suggest that courts should reformulate doctrine to reflect the reality that discrimination and segregation can result from things other than discriminatory intent.

on segregation would not vary significantly.

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