

Signaling and Simulations in Sociolinguistics

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1 Introduction

Humans interact in structured populations, primarily through language. This is nothing surprising. Surprising, however, are now the means to analyze these interactions as never before. Along with game theory, the emerging science of networks has given us a framework for analyzing social systems plausible to both intuition and implementation. Social networks in computer simulations provide a way to envision phenomena like information spread, dialect formation, and language change in a more robust way. With these tools, a multitude of sociolinguistic issues are potential 'objects of study' for a) being delineated with methods from game theory and/or network theory and b) being analyzed by simulations of multi-agent interactions, with the goal of exploring the interplay between social factors and linguistic usage. In this paper, we i) highlight network structure as an important social variable; ii) depict the usage of computer simulations as an appropriate, valid, and powerful technique to analyze sociolinguistic issues; and iii) emphasize game theory's potential as a method for adequately modeling communicative behavior. We conclude that *network theory & game theory in simulation models* represent a powerful combination for the analysis of sociolinguistic phenomena. This makes them a crucial supplement towards enhancing current sociolinguistic experimentation and theories.

The importance of social networks in sociolinguistics has been shown in a number of empirical sociolinguistic studies. For instance, Milroy (1980) and Eckert (2000) examined the network structure of small communities, focusing on the relation between individuals' social network properties and their linguistic performance. Furthermore Labov (2001) and de Bot and Stoessel (2002) considered social networks as determining factors in language change, contact, maintenance and shift. In particular, towards analyzing and constructing a theory about the origins and paths of language change, network structures should be reconsidered as an important factor, as Fagyal et al. (2010a) pointed out: "...network studies in sociolinguistics can provide a starting point for theoretical models of social interactions underlying the spread of novel linguistic variants."

Let us first examine why we should use computer simulations in addition to empirical studies. As Labov (1972b) once pointed out: "the researcher can see the product of change, but not the process." Simulations emulating reality give us the possibility to observe not only the resulting patterns but to also monitor the processes themselves by simultaneously controlling the experimental environment. Thus we have a transition from a mere thought experiment to something that produces quantifiable data on the way that communication progresses in a social structure. This aim is evoked in Nettle (1999b), saying that "A simulation, however rudimentary, is thus an improvement over a merely verbal argument, in deciding what general conditions must obtain for languages to evolve in the way that they do." Further, the enormous complexity of human networks and the huge amount of time in which language change takes place can complicate rigorous empirical studies. "Computer models can provide an efficient tool to consider large-scale networks with different structures and discuss the long-term effect on individuals' learning and interaction on language change.", as Ke et al. (2008) pointed out.

Given the appeal of simulations, how should we construct them? For example, *how do agents interact and influence each other? In what kind of structure are they arranged?* Game theory offers multiple possibilities to deal with these and further questions. In this respect, when we want to analyze language use in a more concrete way in terms of how it happens, namely by considering the communicative act itself, game-theoretic methods have appeal as a recently well-vetted techniques to model communication. This is for a simple reason: the success of a communicative act depends on both participants, speaker and addressee. In this sense "language use satisfies the abstract characteristics of a game in the sense of game theory." (Benz et al., 2010).

With this article we want to give an overview of different research directions considering the application of network theory, computer simulations, and/or game theory in sociolinguistics and fi-

nally present some work combining the approaches and methods from these fields. This article is structured as follows: Section 2 will give an overview of empirical sociolinguistic studies dealing with network structure as a variable driving linguistic change and variation, introducing some basic notions of network theory along the way. Section 3 will present studies applying computer simulations to analyze effects and dependencies in language change. Section 4 will give an informal definition of the game-theoretical model *signaling game* that allows for modeling i) communication situation between agents and ii) in a long-term sense communicative behavior of agents. In Section 5 we present two studies of applying signaling games on social network structures and simulating communicative behavior to analyze specific sociolinguistic phenomena. Finally Section 6 will give an outlook for possible future applications for combining game theory, network theory, and simulations for sociolinguistic purposes.

2 Social Networks

Language is necessarily a social phenomenon, as it emerges as a result of repeated interactions between speakers. Its only constants seem to be variation and change, and these both drive and are driven by social variables. To that end, understanding social networks is indispensable to sociolinguists.

2.1 The Role of Networks in Sociolinguistics

Early work in network-centric sociolinguistic studies focused on the links between the *strength* of network ties and the resulting linguistic data. We detail some of that here, along with the research that contributes to a more nuanced view of embedding as a social variable.

As an example, Ke et al. (2008) simulated language change over a variety of networks, and their methods were motivated by the gravity social networks hold as "determining factors in language change, contact, maintenance and shift (c.f. Labov, 2001; de Bot and Stoessel, 2002)". The natural starting point of many sociolinguistic studies has been connecting the dots between social variables and performance in small communities, and empirical studies of social networks often examine in detail these networks, focusing on the relation between individuals' social network properties and their linguistic performance (c.f. Milroy, 1980). Results include the findings that working class communities often have *close-knit* (e.g., high-density and multiplex) social networks in common. Further, studies have quantitatively shown that individuals' linguistic behaviors are highly correlated with their degrees of integration into the network; e.g., the more integrated an individual is, the less variation (s)he has, and the better (s)he conforms to the speech norm of the community (c.f. Milroy and Margrain, 1980).

Fagyal et al. (2010a) give several examples of a non-trivial intersection between network properties and sociolinguistics patterns. They cite Labov's work in Harlem (Labov, 1972a) that shows greater network centrality correlated with greater social and linguistic influence. Given that networks have multiple ways of measuring a node's centrality, a more nuanced appreciation of these data can now be accomplished. Similarly, social network studies in Belfast (Milroy and Milroy, 1978, 1985) show that leaders and their cohorts were shown to be agents of stability and local speech patterns. Furthermore these studies revealed that people with *weak ties* act as conduits for innovation: "Weak ties provide people with access to information and resources beyond those available in their own social circle" (Granovetter, 1983). Further, the heterogeneity of networks discussed by Eckert (2000) points to the need to better understand the details of network topology and its ability to model speaker interaction.

Speakers display remarkable, yet regular, patterns of performance based on their social situations. The inherent links between structure and performance found in these studies not only make them potential springboards for constructing simulations, but they also highlight the presence of strategic interaction, the central concern of the game-theoretic sections to come.

Like Ke et al. (2008) point out: "In fact, social networks have created a *paradox* in the study of language change: although intuitively one would think that social networks should be an important

factor in determining language change, very few empirical data have been able to show the effect of social networks quantitatively over long periods of time.” And further on: ”This gap can be filled by computer simulations which provides a convenient platform to systematically study the effect of social networks under controlled conditions (Gong, 2007; Parisi and Mirolli, 2007).”

2.2 Social Networks and their Properties

Recent studies on large-scale complex networks in the real world (Barabási, 2002) reveal that most sparsely connected networks are neither regular nor random. Two important features have been discovered in these networks: small-world (Watts and Strogatz, 1998) and scale-free (Barabási and Réka, 1999). The salient properties of such small-world or scale-free networks are a low *average path length* and a high *clustering* (both defined below). Furthermore the scale-free network reveals the presence of highly-connected hubs. These properties often emerge as a result of preferential attachment (e.g., friendships). Understanding these properties and their impact on social interaction can be aided by combining the efficiency of abstraction and the computational heft of simulations.

In general, network properties fall into two categories: *node properties* and *connective properties*. Orthogonal to this categorization is the consideration of structural vs. strategic characteristics. Game theory will provide our canvas for the strategic agent (node) and relationship (link) properties in the later sections, so we now turn to the structural terms and give some basic notions for node and connective properties.

One essential property of a node is its *centrality*. The notion of network centrality seems intuitive, but there are many subtle ways of computing it. Given a node in a network, we can measure its *degree centrality* (number of neighbors), *closeness centrality* (average shortest distance to all other nodes) or *betweenness centrality* (percentage of connecting paths it occupies). Nodes with high values in one dimension might not share the same ranking in others, as we could think of a principal with twenty teachers, each teaching a class of thirty students, a fraction of whom are friends. Furthermore the node property *individual clustering* (the proportion of neighbors pairs being directly connected to each other) expresses the strength of embeddedness into the local structure.

Further, networks and their subsets have connective properties like *density* (ratio of links to nodes), *clustering* and *transitivity* (ratio of fully connected triads). While a high density value of a (sub-)network depicts a dense *global* structure, a high clustering or transitivity value connotes a dense *local* structure. Furthermore the *average path length* of a (sub-)network denotes the length of a shortest path between two nodes averaged over all pairs of nodes in the (sub-)network.

In addition, we can see that the frequencies of speaker interactions can vary across communities, and thus we can think of each link encoding either a relationship or a series of verbal transmissions. These notions, and others for which we lack space, give us a richer view of the structure of social interaction.

3 Simulating Language Change on Social Network Structures

Just as preliminary social data collection can inform the sociolinguist before a study, so can simulations serve as a supplement for testing the impact of social variables on an agent-based speaker network, serving to fill in potential gaps between network studies and understanding the larger speech community (Labov, 2001). One of the first sets of studies using simulations on a social structure to analyze language change, Nettle (1999a,b) abstracts from specific linguistic phenomena and considers a linguistic norm as an *instance of a more general construct*, a so-called *linguistic item* (Hudson, 1996): an isolated element of phonological and grammatical structure, e.g., a phoneme, a words, a word orders structure, et cetera. In Nettle’s sense a linguistic item is a *cultural trait* (c.f. Cavalli-Sforza and Feldman, 1981; Boyd and Richerson, 1985) passed among generations and is possibly changed over time by modification or even replacement through a competing item, instigated through e.g., *imperfect learning* or *language contact*.¹

¹This distinction is e.g., made by Labov (2007), who calls it *Transmission* and *Diffusion* of linguistic change.

An essential question in language change is how new linguistic items can spread and possibly replace old ones. This is subject to the *threshold problem*: in cultural evolution a language learner samples from a fairly large number of people expected to use established linguistic items. The replacement of a new item is therefore quite unlikely, if not impossible, by considering that one plausible learning algorithm should lead to the adoption to the most common item and that the new item might be used among a minority (c.f. Sapir, 1921; Keller, 1994). Nettle (1999b) points out that "New mutants can only become fixed in a language if they can pass a threshold of frequency which in the early stages they never have."

A possible solution is a *biased learning strategy*: learners are biased to new variants which then would have a chance to overcome the threshold. The bias can be *social* (e.g., status, number and influence of users of the new variant) and *functional* (e.g., easier to acquire, produce, or interpret in comparison to the old variant). Nettle (1999b) integrates such biased influences in his account by implementing a version² of Latané's (1981) *Social Impact Theory* (SIT) in his model: the impact of a variant is composed of i) the functional bias of the variant and ii) the social bias as a function over the average status, the average social distance and the number of users of this variant. Nettle's simulations deal with a population of agents in different life-stages arranged on a grid, where spatial distance corresponds to social distance and the grid structure incorporates familial and horizontal social ties. In each simulation step, each agent has to choose between two linguistic items, an already established variant and a new variant. Agents choose that item with the higher impact according to SIT. Nettle wanted to expose to what extend specific circumstances in form of parameters promote the new variant to overcome the threshold of frequency.

Nettle's simulation results show that i) under extreme conditions like high parochialism or mutation rate the new variant can be locally established, but never fan out over the whole society, ii) under a 'social status distribution' according to a *Poisson curve*³ and with also some hyperinfluential agents, a new variant overtakes the whole society from time to time and iii) a higher functional bias can a) make an old variant more resistant to be overtaken by a new one and in return b) facilitate the new variant to replace the old one.⁴ All in all, the results specifically show that functional bias alone fails to explain the changing nature of language. It is only in combination with social status and influence that linguistic change may appear.⁵

Ke et al. (2008) challenge Nettle's results in two aspects: i) they point out that the fact that his model needs hyperinfluential agents to accomplish society-wide language change fails to explain a phenomenon Labov (2001) calls *changes from below*: linguistic change that has emerged in lower social classes; and ii) they regard Nettle's *regular* population structure as unrealistic. Concerning this matter Ke et al. use Nettle's model and change the SIT function by dropping social status and distance⁶ and using social network structures: small-world and scale-free networks. Their results reveal that small-world networks, like regular networks, bring along a high success probability of a society-wide spread of the new variant, but a slow diffusion rate; whereas scale-free networks, like random networks, have a lower success probability, but a fast diffusion rate.

Finally, in a recent study, Fagyal et al. (2010a) use scale-free networks with directed connections denoting the direction of influence. Furthermore they reconsider the possibility of more than two different competing variants. An agent's social status is defined by his influence, which is the number of outgoing connections. Agents in the network can adopt a new variant of direct neighbors with

²This version was already used in simulations by Nowak et al. (1990), but not for linguistic issues, but for public opinion formation.

³It can be shown that across all societies the distribution of wealth forms a Poisson curve (c.f. Wolff, 1998), a curve that has a large cluster around the median and a long tail to the right, i.e., a society with few influential and many averaged individuals.

⁴In other words: If we call a variant with a lower functional bias the marked one, then this result reveals a tendency from marked to unmarked variants in language change.

⁵In another study, Nettle (1999a) uses his SIT simulation framework to support the following thesis: "The smaller the size of a language community, the higher the rate of linguistic change." Here Nettle's simulation results not only support this thesis, but also reveal a promoting character of smaller communities for variants with a low functional bias (unmarked variants), a tendency that is also empirically observable.

⁶In their model every agent has the same social status and is influenced only by directly connected agents.

a probability proportional to the neighbors' statuses. While their standard experiments result in a process where variants spread, stabilize for a while, and are replaced by a new one from time to time, in further experiments they showed that i) with the lack of peripheral agents the first stabilized variant will never be replaced by a new one, ii) with the lack of strongly influential agents there is no society-wide propagation of any variant over time and iii) without agents' consideration of social status by choosing which variant to adopt, no variant spreads society-wide, but competing variants diffuse in a chaotic way.

With these results Fagyal et al. show that two specific agent types (according to their position in the network) have specific roles in the process of language change: the *peripheral low-connected agents* preserves an old variant which at one point probably becomes a new candidate for propagation, and the *central influential agent* induces a propagation of a new variant. Furthermore the third result shows that central and high-connected agents with a high status are powerful propagators of new variants and stabilizers of spread ones. Fagyal et al. finally mention that their work brings support to Nettle's intuition: "the key to diffusion is differential social selection."

These studies revealed that not only is the functional bias of a linguistic variant essential in language change, but the social environment plays an important role as well. This environment includes variables like social status and influence (Nettle, 1999a,b), the structure of the social network (Ke et al., 2008), or the presence/absence of specifically positioned agents (Fagyal et al., 2010a). From a linguistic point of view, all of these studies analyze language change on a highly abstract and general level, defined by the mechanism of a variant *a* replacing a variant *b*. Linguistic variants are items dealt with like a cultural trait. These experiments can also explain the evolutionary processes of other cultural traits like rules, norms, opinions, etc.⁷ In other words, they abstract away from an essential feature of language: to communicate - to convey information from a speaker to a recipient.

Essential reasons that discourage scientists from using simulations could include i) the combinatorial explosion of parameters an enriched simulation brings with it and ii) the lack of techniques to model agent behavior in a more precise but realistic way. The first problem is one every researcher working with simulations has to consider, being well-advised to keep the model based on as many parameters as needed but as few parameters as possible. The second problem is where the promise of game theory reveals itself, in particular when combined with dynamics of learning or rational deliberation.

4 Game Theory and Linguistics

In recent years, the techniques of game theory have become a new research methodology for the study of language use. The basic impetus for this consolidation is the following: a speaker's utterance itself is only effective if a recipient can arrive at an interpretation of it. Communication in the sense of transmitting information works only in the case that the recipient arrives at the correct interpretation of the utterance, i.e., the one the speaker intended to transmit. This approach has seen particular success in modeling pragmatic phenomena as derivative from rational processes much in the same way that semantic processes derive from logical ones (c.f. Benz et al., 2010). This attention to the strategy inherent in communicative contexts has a parallel in game theory's evolutionary side. In other words, when we see conventionalized forms (often driven by social variables or communicative contexts), we are seeing variants displaying a kind of *evolutionary stability*. But how do these conventions arise? One answer is through signaling.

To tackle the problem of conventions in society, Lewis (1969) invented signaling games. He was searching for an answer to the question: "How can linguistic meaning arise and become a convention without prior agreements?" Sans prior agreements and considering that agreements need language, we would come to a paradox: *Language is needed for language to emerge*. Lewis paved a way for refuting this paradox by showing that with the model of a signaling game, conventional linguistic meaning can arise without such agreements. A basic model can be informally described

⁷Effectively the *Social Impact Theory* used by Nettle (and in a trimmed form by Ke et al.) was formerly used in simulations experiments for the spread of *public opinions* in a network (Nowak et al., 1990). Furthermore even the model of Fagyal et al. was used similarly (Fagyal et al., 2010b) to analyze the spread of norms.

as follows: a signaling game is a game between a speaker S and a recipient R . The speaker S wants to communicate a given state or topic t by sending a signal, or message, m to the recipient R . The recipient has to choose an interpretation state, or action, a for the received message. If t corresponds to a then communication was successful and both participants get a high payoff, if not, both get a low (or zero) payoff. The way a speaker (recipient) behaves is called speaker (recipient) strategy.⁸

It is important to highlight a particularly feature of basic signaling games: each message m has no predefined meaning. Lewis' original question was how a message m acquires a meaning t , in other words how speaker and recipient coordinate their strategies such that m is only sent in state t and at the same time only construed by interpretation a appropriate to t . In the spirit of Lewis' model, a linguistic convention is such a ' $t - m - a$ ' mapping emerging as a population of agents play the signaling game repeatedly. But for agents to coordinate their behavior, they have to update their strategies, e.g., by reconsidering previous plays and adapt their behavior accordingly, which is realized by a mechanism called *update dynamics*.

Lewis's signaling games originally evolved in a framework of language evolution, but there are reasons to assume that signaling games are also appropriate to model language change in a sociolinguistic sense. First of all, each kind of actual language use can more generally be seen as a convention. Furthermore language change (e.g., in form of old words are replaced with new words in a speech community) can be seen as replacing an old convention with a new one. In this sense signaling games show promise for understanding sociolinguistic processes. Furthermore when it comes to using repeated games and update dynamics to model cultural evolution, the first models combined signaling games with population-based evolutionary dynamics⁹ (c.f. Skyrms, 1996), but following work takes a more agent-based view by using *imitation dynamics* (c.f. Zollman, 2005) or *learning dynamics* (c.f. Argiento et al., 2009) and on top of that taking sociolinguistic variables like social status and network positions into account, as we'll show in Section 5.

5 Simulating Sociolinguistic Phenomena per Games on Networks

In the following we'll present two studies recently elaborated by using techniques from network theory and game theory in a simulation model. The first study deals with *the emergence of language conventions* (Mühlenbernd and Franke, 2012), inspired by Milroy and Milroy's (1985) study of *speaker innovation*. In the second study we examine *language change through social contact* (Quinley and Mühlenbernd, 2012), a class of phenomena related to Labov's concepts of *linguistic diversity* instigated by language contact and influenced by social status (c.f. Labov, 2007, 2010).

5.1 The Emergence of Language Conventions

Mühlenbernd and Franke (2012) analyzed how the emergence of language conventions depends on the social structure of a population: "This paper probes deeper into the relation between social structure and language evolution in order to further our knowledge of synthetic evolutionary processes in structured populations and thereby to pave the way for a more thorough understanding of the sociological factors of linguistic variability." In this study agents are positioned on small-world networks and their behavior is simulated by repeatedly communicating with direct neighbors by playing a signaling game, as described in Section 4. In this model the simplest variant of a signaling game is reconsidered, the so-called *Lewis game*: a signaling game with two information states t_1 and t_2 , two messages m_1 and m_2 and two interpretation states a_1 and a_2 . For a Lewis game, there exist two different strategy profiles that (i) ensure *perfect communication*, (ii) have specific *properties of stability* in populations of agents¹⁰, and (iii) can be interpreted as *semantic meaning*. These two strategy profiles are called *signaling conventions*, whose emergence process can be seen as *pragmatic evolution*.

⁸See e.g., (Benz et al., 2010) for a short formal description.

⁹Here especially *evolutionary game theory* and therein the *replicator dynamics* plays a major role.

¹⁰E.g., it can be shown that exactly and only these two strategy profiles are *evolutionary stable*, a concept from *evolutionary game theory*. For more details see e.g., Wärneryd (1993).

A primary result of the simulation runs is that both signaling conventions spread over the whole society, distributing the population in *language regions*.¹¹ Interestingly, conventions can arise but never stabilize only with one agent. They always start with one agent but stabilize in local groups, sometimes permeating throughout the society. This resulting pattern corresponds to Eckert's (Eckert, 1989, 2000) ethnographic account of adolescent peer groups' language use in Belten High that reveals multiple small networks with at least one leader in each micro-community engaged in activities chiefly characterizing that group. Furthermore the diffusion process itself is in line with Milroy and Milroy's (1985) classification of speaker innovation, rated according to diffusion success in the following way:

1. speaker innovation may fail to diffuse beyond the speaker
2. speaker innovation may diffuse only in the local community and go no further
3. speaker innovation may diffuse in the local community and then subsequently into other communities via further innovators who has ties with both the relevant communities

The further tasks of Mühlenbernd and Franke's study includes to analyze i) the connective properties of language regions and ii) the node properties of agents characterized according to their role in the emergence process of signaling conventions (all employed properties are described in Section 2.2).

First, the analysis of connective properties reveals that language regions have a higher *clustering* and *transitivity* value than the whole network, with the *density* value not exhibiting such a divergence. This result implies that a locally dense structure in form of cliquishness supports the emergence and stability of local conventions and is in accord with Milroy and Margrain's (1980) hypothesis that "closeness to vernacular speech norms correlates positively with the level of individual integration into local community network".

Second, the analysis of the node properties of agents shows that conventions i) initially emerge by a small number of locally embedded and highly influential agents (high values of individual clustering and degree centrality), called *founding fathers*; ii) spread fast among locally embedded non-central agents (high individual clustering and low centrality values), called *stabilizers*; and iii) are late adopted by globally central agents (low individual clustering and high centrality values), called *late learners* that are predominantly positioned between different language regions.

The role and properties of founding fathers are in accord with results of Fagyal et al. (2010a), who found that "charismatic leaders with strong ties to the local community have also been identified as innovators... The near-equivalents of such central figures in other studies (Labov, 2001; Mendoza-Denton, 2008) led to the proposal that leaders of language change are centrally-connected, highly visible individuals whose influence can extend beyond their own personal networks.". Furthermore, the role of stabilizers enables a fast spread of a (new) convention that would give them the impulsive role in linguistic change. This corresponds to Labov (1994), who postulates that language change emerges when other speakers start adopting and using innovations conventionally; or as Wolfram and Schilling-Estes (2003) pointed out: "it is not the act of innovation that changes language, but the act of influence that instantiates it."

This study illustrates one possibility of applying a game-theoretic model of agent behavior simulated on a social network for the purpose of analyzing a sociolinguistic phenomenon. The analysis deals with forces of language change in general rather than with a particular phenomenon. With the next section we present a similar approach but for a slightly more specific case.

5.2 Language Change through Social Contact

There is a central problem in historical linguistics: time travel has yet to be invented. Nonetheless, the field persists onward through meticulous and intrepid attention to data that are increasingly harder to find. Here is where simulations enter the picture. Although they can never tell us exactly what happened, they can certainly tell us what could *not* have occurred.

¹¹A maximal subset of agents forming a connected subgraph that have acquired the same convention

The matter in question is the Norman invasion of 1066 and its irrevocable impact on the English lexicon. The salient division of meaning space seen now follows a predictable trend: prestige tends toward the items of French origin, and the commonplace has its home with the Germanic words. The theory is that the social conditions of the Anglo-Saxon workers and their French-speaking Norman overlords caused this divergence, but could the results have been different?

The results from Quinley and Mühlenbernd (2012) give us an answer. Here agents placed on a scale-free network played a two-state, single-message signaling game augmented with contexts. A status variable governed the distribution of these contexts, and in the beginning of each trial each agent knew only one message, requiring a context to probabilistically disambiguate the speaker's meaning. Agents were replaced in part by *invaders* having identical topics and contexts but with a new message, and these invading agents introduced their variant while at the same time acquiring the native variant. These two messages emancipated the agents from context dependence in every trial, producing a robust signaling system holding throughout the network.

The what-ifs of history were then addressed by starting simulation trials with different settings. Trial 1 replaced agents with invaders randomly along the social ladder, and it found that half of the simulation runs ended with the expected convention, the other half ended with the opposite conventions of the aforementioned patterns seen in Modern English. To put this in context, this showed that had the Norman invaders replaced the Anglo-Saxons at random, the marked prestige of so many French borrowings in English would not be the case as it is today.¹²

Trials 2 and 3 took the social variables into account. Trial 2 replaced only those agents above a certain status threshold, and it showed that as this threshold increased, so would the probability of the conventions we see today. Trial 3 took this a step further by tying status and structure together: invaders replace agents with not only a high status, but also a high degree of centrality in the network. As mentioned above, both the degree distribution in a scale-free network and the wealth distribution in many societies follow a Poisson curve. This gives us a way to interpret the links in a network as those influenced by our business dealings. By linking the degree of an agent to his status, the study found an even sharper convergence towards the expected convention.

The curious thing not mentioned in the original study was that the mechanisms of context distribution and targeted replacement of agents also has another unique predictive property: it predicts the "change from the bottom" seen in (Labov, 2001). This study may also be a way to sharpen a view of the competition going on between various speakers and the grammars to which they adhere.

6 Conclusion and Outlook

In section 2 we made the case for understanding network structures as a means to explain linguistic variation and change. Here we emphasized the empirical point of view that would later motivate the work done in simulations. In section 3 we gave some examples of computer simulations modeling the emergence of society-wide linguistic phenomena across a panoply of social structures. The crux of many of the experiments carried out up to now (e.g., Nettle, 1999a,b) has been the view of linguistic variants as cultural traits. As such experiments can also explain the evolutionary processes of other cultural traits like rules, norms, and opinions, they crucially abstract away from an essential feature of language: to communicate - to convey information from a sender to a receiver. At this point, game theory comes into play: here we can model a situation between two agents with the goal to communicate successfully. The most prominent version of such a game is the signaling game, which we claim has applications beyond pragmatics. Agent-based simulations of signaling games on networks represent a powerful combination of tools that hitherto were used in isolation. Much more, as a virtual laboratory environment they bring a crucial supplement to any linguist interested in the impact social variables have on the dynamics of language variation and change.

¹²The canonical example used is *swine* vs. *pork*.

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