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Introduction

Our social environment influences much of what we do. To be more precise, individual behavior is often influenced by the *social network* surrounding the individual. For instance, when we form an opinion about a political issue, we are likely to be influenced by the opinions of our friends, family, and colleagues and likewise, we influence them.

Much sociological research has been devoted to showing how various forms of social influence shape individual action (Marsden and Friedkin 1993). However, social networks are not always rigid structures imposed on us. Often, we have considerable control over our own social relations. Returning to our example, we may be influenced by our friends when forming political opinions, but we are also, to a large extent, free to choose our own friends. Moreover, it is likely that our decisions in choosing friends are in part related to those same opinions. Thus, social networks and the behavior by individuals within those networks *develop interdependently* or, in other words, *co-evolve*. What social network structures should we expect to emerge, and how will behavior be distributed in those networks? In a nutshell, this is the general type of problem this book is concerned with. The example of political opinions is one in which social networks and individual characteristics co-evolve and the same holds for many other types of opinions and behavior. This book focuses on the co-evolution of networks and behavior of a particular kind, namely, behavior in *social dilemmas*.

1.1 Social dilemmas and social networks

Broadly speaking, a *social dilemma* is a social situation in which individually rational behavior can lead to suboptimal results at the collective level. We encounter many

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	Cooperate	Defect
Cooperate	3, 3	0, 5
Defect	5, 0	**1, 1**

(a) A Prisoner's Dilemma

	LEFT	RIGHT
LEFT	**4, 4**	0, 2
RIGHT	2, 0	**3, 3**

(b) A coordination game

Figure 1.1 Two social dilemma games. (a) A Prisoner's Dilemma; (b) A coordination game.

social dilemmas in daily life. For example, when two researchers are working on a joint project, each might be tempted to let the other person do the majority of the work while profiting equally. However, if both follow this reasoning, the project will never get done, and there will be no profit at all. Similarly, if there is a rumor that a bank might go bankrupt, it is perfectly rational for every individual client to go to the bank and try to withdraw his or her savings. However, if all clients do this, the bank *will* indeed go bankrupt, and most clients will lose their savings. Another social dilemma arises when a group of people want to participate in an event, say, a protest demonstration. For each participant, it is only worth going to the demonstration if others are going as well. By attending, one runs the risk of being the only participant, in which case there will be no demonstration and one will have wasted one's time. Given this risk, it might be wise to stay at home, in which case the demonstration will indeed not occur.

The situations described above have in common that if individuals try to obtain the most favorable outcome for themselves and behave rationally, the result might be that collectively everyone is worse off than they could have been. In other words, we find a conflict between *individual* rationality and *collective* rationality (Rapoport 1974). Using the terminology of game theory,[1] we can define a social dilemma more formally as a situation (game) that has at least one Nash equilibrium that is Pareto-suboptimal.[2]

While all of the examples above can be classified as social dilemmas in this sense, there are also some differences between them. Roughly speaking, the first two examples can be described as *cooperation* problems, and the third example can be described as a *coordination* problem. While other types of social dilemmas exist, we only focus on coordination and cooperation problems in this book.

The crucial characteristic of cooperation problems is that although the actors involved can benefit from cooperation, they have an incentive to take advantage of each other, which leads to suboptimal outcomes at the collective level. A game-theoretic model for such situations is the famous *Prisoner's Dilemma*

[1] We assume here that the reader is somewhat familiar with basic game theoretical terminology. Good introductions to game theory are Rasmusen (2001) and Binmore (2007), among many others.

[2] The precise definition of the term "social dilemma" is somewhat controversial. As we do not want to argue about definitional issues, it suffices to point out that the definition we use here is less restrictive than the definition used by Dawes (1980), but compatible with the progressively broader definitions by Kollock (1998) and Van de Rijt and Macy (2008). The definition used here is also compatible with the definition by Raub and Voss (1986) of problematic social situations.

(see Figure 1.1a). In this game, each player has two options: cooperation or defection. The players' payoffs associated with each combination of actions are represented as numbers in a matrix. The actual numbers in Figure 1.1 a serve only as an illustration. The relation between the payoffs is what matters. In this game, both players are tempted to play "defect" because this will lead to a higher payoff regardless of what the other player does. If both players defect, they will both earn only 1, which is suboptimal because both could have earned 3 if they had cooperated. However, game theory predicts that goal-directed players will defect because mutual defection is the only Nash equilibrium. Clearly, this equilibrium is suboptimal.[3]

The Prisoner's Dilemma has become the archetypical social dilemma in the literature and has motivated a vast amount of research. It is typically associated with the problem of *social order*, which has to do with the questions of why people cooperate even when they have incentives to exploit each other and why society does not collapse into a "war of every man against every man" (Hobbes, [1651] 1988). The Prisoner's Dilemma has been used to model a wide range of social phenomena, including the production of public goods (e.g., Heckathorn 1996), social exchange (Hardin 1995), and the emergence of social norms (e.g., Ullmann-Margalit 1977; Voss 2001).

In coordination problems, the dilemma is of a different nature. Figure 1.1 b shows a *coordination game* (the labels "LEFT" and "RIGHT" in this game are arbitrarily chosen and have no further substantive meaning). In contrast to the Prisoner's Dilemma, the coordination game no longer demands that to maximize his or her payoffs the player should always perform the same action regardless of what the other does. Rather, each player prefers to perform *the same action as the other player*, that is, to coordinate. Players do not have incentives to exploit one another, but there are incentives to try to work together. Thus, game theory predicts that either both players will play LEFT, or both players will play RIGHT. Once the players have established one of these equilibria, they have no incentive to deviate as long as the other player does not deviate. In this sense, we can consider equilibria in coordination problems as *conventions* (Lewis 1969).

In so-called *pure coordination games*, actors have no preference for one convention over the other, but this is not the case in Figure 1.1b. If both players play LEFT, they both earn more than if they both play RIGHT. Therefore, the equilibrium (LEFT, LEFT) is the *efficient* equilibrium, also called the *payoff-dominant* equilibrium (Harsanyi and Selten 1988). At first sight, it may seem obvious that if the players simply play LEFT, the social dilemma is solved. This game, however, also involves an element of risk. If the row player plays LEFT and the column player plays RIGHT, the outcome is suboptimal for both. However, the burden of the suboptimal outcome is not distributed equally among the players—the column player still earns a payoff of 2, whereas the row player earns nothing. Given that the row player does not know in advance what

[3] The description of a certain outcome as "optimal" does not necessarily mean that this outcome is also desirable from a societal point of view. Some outcomes of social dilemmas that are optimal for the actors involved may actually be quite undesirable for society as a whole; typical examples are collusion between firms or cooperation in criminal gangs.

the column player will do, playing LEFT is risky. In fact, if the row player assumes that it is equally likely that column player will play LEFT or RIGHT, the expected payoff of playing LEFT is lower than the expected payoff of playing RIGHT. The same reasoning holds for the column player. This equilibrium (RIGHT, RIGHT) can be classified as the *risk-dominant* equilibrium (Harsanyi and Selten 1988) because it has less risk.

Although the situation in which both players play LEFT is the efficient equilibrium, it is also the equilibrium with greater risk, and it is therefore not trivial that players will play this equilibrium. This feature makes this game especially interesting for analysis as a social dilemma (Kollock 1998). Another reason to classify this game as a social dilemma is that the mixed equilibrium (in which the players play each action with some probability) is also inefficient (Harsanyi 1977).

Coming back to one of the examples above, every potential participant of a demonstration would rather join a successful demonstration than stay at home. However, if everyone else stays home, he or she would rather stay home too. In the case of a coordination failure (some come to the demonstration and some stay home making the demonstration a failure), the outcome is worse for those who did come to the failed demonstration than for those who stayed home. Many forms of collective action share this feature (Hardin 1995).

Although coordination problems have received less attention in the literature on social dilemmas than cooperation problems, applications in real life are abundant. The analysis relates to many types of conventions, such as etiquette (Elias 1969), standards of speech, or technological standards (e.g., choice of computer operating systems or GSM frequencies). Generally, the coordination game can be used as a game-theoretic model of *social conformism* whenever actors have strategic reasons to align their behavior. Moreover, it can be argued that many social dilemmas that are commonly viewed as Prisoner's Dilemmas could be more fruitfully analyzed as coordination games (Hardin 1995; Kollock 1998). One could say that the value of the coordination game as an explanatory model has been underappreciated in comparison with the enormous amount of attention that the Prisoner's Dilemma has received (Kollock 1998).

Nevertheless, both dilemmas have been studied extensively in political science, psychology, economics, and sociology (as well as in the life sciences, particularly in the case of the Prisoner's Dilemma). The main question in these studies is, under what conditions will actors behave in such a way that they obtain the socially efficient outcome? Social networks can play an important role in answering this question.

1.1.1 Cooperation and social networks

There are different types of answers to the question of why people cooperate in situations such as in the Prisoner's Dilemma. The first type of answer looks for the solution at the individual level and challenges the assumption that people only care about their *own* payoffs. Proponents of this approach argue that people cooperate because they are motivated by fairness considerations (Rabin 1993) or inequity aversion (Bolton and Ockenfels 2000; Fehr and Schmidt 1999; Kolm and Ythier 2006).

Another approach does not abandon the assumption that people are selfish, but instead looks for *social* causes of cooperation—social conditions that provide individuals with incentives to cooperate in social dilemmas, even if these individuals only care about their own payoffs. One particular source of such incentives is that cooperative relations often do not occur in isolation but are *embedded* in a social context (Granovetter 1985). Such "embeddedness" may take several forms. As argued by Axelrod (1984) and others (Taylor 1976, 1987), cooperation may emerge if actors interact repeatedly. This type of embeddedness is referred to as *dyadic embeddedness* (Buskens and Raub 2002). The prospect of a long-term relationship with the same partner may persuade actors to cooperate on the condition that others cooperate as well.

A second type of embeddedness exists in social networks and can be referred to as *network embeddeness* (Buskens and Raub 2002; Granovetter 1985). This occurs when interactions are part of a larger network of relations. The presence of third parties further increases the interdependence between interaction partners as compared with dyadic embeddedness because information about what happened in one interaction may spread via the network and influence other interactions. An intuitive and broadly shared view among social scientists is that social cohesion facilitates the emergence of cooperation, trust, and social norms (Coleman 1990; Homans 1951; Voss 2001), a view supported by much qualitative (Ellickson 1991; Greif 1989, 1994; Macaulay 1963; Uzzi 1996, 1997) and some quantitative (e.g., Burt and Knez 1996; Buskens 2002) evidence.

One class of mechanisms through which this information impacts cooperation in social dilemmas is captured under the heading of *reputation effects*. Actors embedded in networks may be more reluctant to defect because word regarding their behavior will spread and lead to retaliation or social sanctions by third parties. In a game-theoretic analysis Raub and Weesie (1990) show that such reputation effects indeed make conditional cooperation by selfish and rational actors more likely. According to this argument, this type of reputation effect is labeled as *control* because cooperation is promoted by actors' concerns about the outcomes of *future* interactions. Another reputation-based mechanism that can facilitate cooperation through networks is *learning*. Actors may be persuaded to cooperate with a given interaction partner because they have received information that cooperation with this partner is profitable (Buskens and Raub 2002).

1.1.2 Coordination and social networks

While the focus of research on the Prisoner's Dilemma is to recognize under which circumstances people will cooperate, the focus of research on coordination problems is somewhat different. The characteristic feature of a coordination game is that it has *several* Nash equilibria, and a major challenge for game theory is to predict which of these equilibria will be chosen. Theorists have searched for additional mechanisms that can lead to more precise predictions because the standard prediction that rational actors will play a Nash equilibrium is not specific enough. The concepts of *payoff dominance* and *risk dominance* by Harsanyi and Selten (1988) provide some additional guidance, but in many coordination problems payoff-dominant and risk-dominant equilibria do not overlap, and an equilibrium selection problem remains. Analogous to the study of cooperation problems, researchers have turned to *repeated interaction* for a solution (Kandori et al. 1993; Young 1993). In these models, actors play sequences of coordination games and reach a convention in a stochastic adaptive process. A major result from this research is that risk-dominant conventions are more likely to emerge in the long run.

These earlier models relied on global interaction structures in which every actor interacts with every other actor in the population. Later models (Berninghaus and Schwalbe 1996; Blume 1993; Ellison 1993; Kosfeld 1999; Young 1998) introduced social structure by assuming *local interaction* such that actors interact only with some portion of the population. While this can be considered a first step toward introducing social networks into the analysis, these models generally assume only very simple interaction structures such as lattices.

Empirical evidence for network effects in coordination problems comes from experimental studies. Keser et al. (1998) found that it is more likely that subjects coordinate on the risk-dominant equilibrium when they interact in a circle structure than when they interact in small three-person groups. Berninghaus et al. (2002) further investigated local interaction and found that different regular local interaction structures had effects on the likelihood that risk-dominant or payoff-dominant equilibria are chosen. Cassar (2007) compared the effects of different *irregular* network structures on coordination and found that coordination on the payoff-dominant equilibrium is more likely in "small-world" network structures than in random network structures, or structures with overlapping neighborhoods.

Meanwhile, the sociological literature on social networks has traditionally focused on the effects of social networks on the diffusion of behavior and opinions. This literature includes theoretical studies of *threshold models* (Abrahamson and Rosenkopf 1997; Centola and Macy 2007; Granovetter 1978; Valente 1996; Watts 2002), as well as empirical studies on diffusion (e.g., Rogers 1995) and interpersonal influence in social networks (see Marsden and Friedkin 1993). Although these studies neglect the strategic interdependence of actors in the game-theoretic sense, they are conceptually very close to coordination problems, as discussed above; this literature generally assumes that actors face incentives to align their behaviors. Generally, it has been found that the structures of social networks can have important consequences for the extent to which behaviors, opinions, and collective action spread in a population.

1.2 Dynamic networks, co-evolution, and research questions

As Section 1.1 shows, a wide range of theoretical and empirical research from various disciplines suggests that social networks are relevant in determining the outcomes of cooperation and coordination problems. These findings add to the more general notion that social networks have important effects on many types of social phenomena, including (but not limited to) social inequality (Coleman 1988; Flap

2004; Lin 2001), labor market outcomes (Granovetter 1973, 1974), the diffusion of innovations (Coleman et al. 1957), and the spread of diseases (Kretzschmar and Wallinga 2007; Morris et al. 1995). Naturally, the next question is, where do these network structures come from?

Often, an implicit assumption in theories of network effects is that social networks are *fixed structures* or *exogenously* imposed on the actors. While in some cases it may be reasonable to assume that people have little or no control over their social environment (e.g., kin relations), many social relations actually result from people's *choices*. We can typically choose, at least to some degree, who our friends are, with whom we share information, and with whom we want to work. These choices are likely to be constrained by the larger social context (e.g., the availability of meeting opportunities; see Fisher 1982; Mollenhorst et al. 2008; Verbrugge 1977). Nevertheless, this implies that social network structures develop as the result of individual decisions.

Moreover, the notion that networks have important consequences for behavior suggests that people do not only have the *opportunity* to change their social relations, but also have *incentives* to do so. Given that networks potentially produce benefits for their actors, it seems reasonable that actors will consciously form relationships to optimize their benefits from the networks. Sometimes dense networks will be beneficial, for example, to solve trust or cooperation problems (Buskens 2002; Coleman 1990; Raub and Weesie 1990). In other settings, open structures are more beneficial, for example, in competitive settings where access and control of information is of crucial importance (Burt 1992; Granovetter 1973; for the comparison, also see Burt 2005).

A similar message emerges from the social capital literature, which argues that social inequality can be explained in part by differences in resources that people derive from their personal networks (Coleman 1988; Flap 2002, 2004; Lin 2001). It follows that goal-directed actors would strategically invest in relations that are beneficial and end relations that are not.

However, from the premise that network structures are the results of actors' conscious decisions, it does not follow that socially beneficial network structures will spontaneously emerge (e.g., Dogan et al. 2009; Jackson and Wolinsky 1996). Although actors may be able to choose their *own* relations, the larger network structure is the result of the combined choices of all actors. Relational choices of one actor may have consequences for other actors. For instance, by breaking just one relation, an actor may interrupt many indirect connections between other pairs of actors, thereby changing the flow of information in the network. Thus, although network structures may be the consequences of individual decisions, they are often *unintended* consequences of individual action (cf. Coleman 1987; Merton 1936; Schelling 1978).

Much literature has emerged in the past decade on *network dynamics* as a response to questions about the origins of social networks. Although the interest in social networks originated within sociology, problems of network dynamics have attracted a great deal of attention from a number of other disciplines, including economics, mathematics, physics, and biology. Problems of network dynamics have also found

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their way into popular science literature (e.g., Buchanan 2002). As a result, a number of models have been formulated on the dynamics of "small world" networks (Watts and Strogatz 1998), scale-free networks (Albert and Barabási 1999), communication networks (Bala and Goyal 2000; Buskens and Rijt 2008), and other topics (see Goyal 2007; Vega-Redondo 2007; Jackson 2008 for good reviews of this literature).

Many of these models study the formation of network relations *per se*, that is, reasons for network change lie solely in the network structure itself. However, it is likely that the choice of network relations also depends on actual behavior in relevant interactions, namely, on the *content* of relations. After all, one of the reasons to study social networks in the first place is that networks affect *behavior in social dilemmas*. Facing cooperation problems, actors may want to avoid defectors, while in coordination settings, actors may want to avoid those who behave differently and prefer relations with those who behave similarly (cf. McPherson et al. 2001). Thus, on the one hand, networks influence the way people behave in their interactions. On the other hand, individual behavior in interactions also affects the network such that people "themselves constitute each others' changing environment" (Snijders 2001, p. 363). In other words, one can say that networks and behavior *co-evolve*.

This implies a two-sided causality social scientists have only begun to investigate in recent years. A priori, it is unclear if and how the recognition that networks and behavior may co-evolve changes our expectations on outcomes in social dilemma situations. For instance, most arguments on the positive effects of social networks on cooperation problems crucially rely on the assumption that information is disseminated through the network. However, is the transfer of information still reliable enough for reputation mechanisms to function if actors at the same time change the network? Can we expect that the network structures that are thought to foster cooperation (i.e., dense, close-knit networks) will emerge as a consequence of individual strategic action? Similarly, does the ability to change relations facilitate or hinder the emergence of conventions in coordination problems?

The four studies in this book all revolve around such issues. Thus, we can formulate the central questions of this book as follows:

- How do social network structure and behavior co-evolve in different types of social dilemmas?
- Under what circumstances is it more or less likely that networks and behavior evolve into optimal or suboptimal interaction structures?

In summary, we have argued that in order to explain behavior in social dilemmas, we have to study the social networks in which social dilemmas are embedded, and in doing so, account for the evolution of the networks themselves. At the same time, studying social dilemmas in dynamic networks can help us to better understand social networks in general.

Although the field of network dynamics as a research topic is relatively new, it has roots in various disciplines, most prominently in sociology and economics. In the next section, we argue that a fruitful analysis combines insights from both disciplines.

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1.3 Social networks and social dilemmas between sociology and economics

Duesenberry (1960) famously stated that "Economics is all about how people make choices; sociology is all about how they don't have any choices to make" (p. 233). Traditionally, economics has taken individual action as its main focus, whereas sociology has emphasized how individual action is shaped by social context, as exemplified by Durkheim's ([1897] 2002)) classic study of the social antecedents of suicide.

Over the years, attempts have been made to reconcile these apparently incompatible approaches. Some sociologists have adopted modes of theorizing from economics in the form of methodological individualism, rational choice theory, and game theory (Boudon 1981; Coleman 1990; Elster 1989; Hedström 2005; Schelling 1978). These approaches have roots in the early sociology of Parsons (1937) and Weber ([1921] 1976), and are closely tied to the study of the problem of social order (Hobbes, [1651] 1988; Parsons 1937), which is considered to be one of the central problems of sociology. Along with these concepts, some sociologists have also tried (with lesser success) to import the accompanying *tools* of formal modeling from economics into sociology (Coleman 1964; Fararo 1973; Merton 1968).

On the other hand, attempts have been made to introduce sociological arguments about social structure into economic theory (interestingly, it seems that most of these attempts are made by sociologists). One of the most influential arguments was put forth in the seminal paper by Granovetter (1985) who argued that whereas economic theory suffered from being "undersocialized," sociological theory was "oversocialized" (also see, e.g., Coleman 1984). Economics, on the one hand, is criticized for modeling human action as overly atomistic and anonymous without the influence of social context. Sociology, on the other hand, too often takes the influence of social context for granted, to the extent that it is assumed that social norms and values are completely internalized. Ironically enough, this also leads to an overly atomized account of social action.

As a solution, Granovetter proposed to analyze social and economic phenomena as resulting from *individual* (rational) action, which is nevertheless *embedded* in social structures or social networks.

> A fruitful analysis of human action requires us to avoid the atomization implicit in the theoretical extremes of under- and oversocialized conceptions. Actors do not behave or decide as atoms outside a social context, nor do they adhere slavishly to a script written for them by the particular intersection of social categories that they happen to occupy. Their attempts at purposive action are instead embedded in concrete, ongoing systems of social relations. (Granovetter 1985, p. 487)

The collection of studies in this book continues and extends Granovetter's general research program. It is a continuation in the sense that we study goal-directed action as embedded in systems of social relations (i.e., social networks). It extends

Granovetter's ideas by applying a similar logic to the system of social relations *itself*. If social relations are crucial for understanding human action, and if social relations are—at least to some extent—the result of purposive individual action, explanations should also account for the emergence of structures of social relations.

Thus, the approach advocated here aims to contribute to the bridging of the "theory-gap" in social network research, which was identified by Granovetter (1979) who states that empirical sociological research on social networks lacks systematic theoretical foundations (see also Flap 2002). Models that explain *both* causes *and* consequences of social networks as the results of goal-oriented strategic action might provide such theoretical foundations. Other theoretical strategies that also rely on goal-oriented individual action have been proposed (e.g., Snijders 2001), but these approaches typically neglect the strategic interdependence involved in network formation processes.

Granovetter argues that theories about social networks could serve to bridge the gap between macro- and micro-level theories. Following Coleman (1984, 1987, 1990) and Wippler and Lindenberg (1987), we argue that theory on social networks also needs to account for the micro–macro link. Establishing this micro–macro link (or "transformation rules," Wippler and Lindenberg 1987) requires modeling the collective effects of interdependent individual decisions. For this task, the theoretical tools for studying strategic decision making developed in economics are particularly useful. The theoretical strategy applied in this book can be considered as a synthesis of the typical approaches of sociology and economics. On the one hand, it acknowledges the sociological emphasis on social structure, while on the other hand, the standard economics assumption of goal-driven, *strategic* action is maintained. Not surprisingly, this approach adds further complexity to theoretical models. As a result, the studies in this book do not offer more than piecemeal solutions to the many problems that arise when studying the co-evolution of strategic behavior and social networks.

1.4 Approach: Models, simulation, and empirical tests

The recent flourishing of interest in social network dynamics has resulted in the publication of a large number of theoretical models. Many of these models are designed to explain some "stylized fact" about real social networks, such as the small-world phenomenon (Watts and Strogatz 1998) or the emergence of "stars" (Bala and Goyal 2000). However, much less frequently are these models rigorously *tested* empirically. Thus, while Granovetter (1979) identified a lack of theoretical foundations (the "theory-gap") in the very empirically oriented sociological network research at the time, the emergence of a theoretical literature on network dynamics has not yet led to a tight connection between theoretical models and empirical approaches. This is not only a problem for empirical research (as argued by Granovetter 1979), but also for the development of theory. It is hard to judge the appropriateness of model assumptions because many models go untested, thus making it difficult to judge theoretical progress in the field. As we will argue in this section, we think that this situation is at least in part due to the nature of existing theoretical approaches. One of the main aims of this book is to demonstrate how *computational* approaches can be applied usefully to provide a "bridge" between theoretical models and empirical research.

In line with the arguments sketched above, the overall theoretical approach in this book relies on the assumption that both behavior in social dilemmas and network formation are driven by goal-directed individual action. In the theoretical models employed in Chapters 2 and 3, actors choose the actions in social dilemmas and choose the social relations that are beneficial to them. With this approach, we—to some extent—follow the economic literature on networks in which network formation is analyzed as a *strategic decision problem* in the sense that benefits from forming social relations depend not only on an actor's decisions, but also on the decisions of others. *Game theory* was developed to analyze strategic decision problems, and recently, specific game-theoretical tools have been developed to analyze networks (see Jackson 2008, Chapter 11 for a good overview).

While game theory provides important and deep insights into the nature of strategic interaction, such as the co-evolution problems studied in this book, it also has its problems. A first problem is that game theory often makes very strong assumptions on actors' rationality. It is typically assumed that actors are capable of processing all available information, of forming optimal beliefs based on this information, and, being perfectly forward-looking, of choosing an optimal course of action to reach their goals. In game-theoretical models of networks, for example, it is routinely assumed that actors can oversee the entire network, no matter how large the population, and make optimal choices based on that. Game theorists are well-aware that such assumptions are unrealistic for most real-life applications but nevertheless choose this approach for reasons of tractability. Relaxing those assumptions, allowing for incomplete information and bounded rationality, makes models much more complex and finding rigorous mathematical solutions almost impossible.

A second problem is that even if game-theoretical models provide mathematically precise characterizations of expected equilibrium states of the processes under study, these "predictions" are often not very useful for empirical applications. In many cases, analyses predict many different equilibria for a given set of model parameters without guidance on which of these equilibria would be more or less likely to obtain in an empirical situation. This problem is more generally known as the *equilibrium selection problem* in the game-theoretical literature. In addition, game-theoretical models for networks sometimes rely on assumptions on stochastic processes, resulting in long-run predictions of equilibria. For many empirical applications, such long-run predictions are less interesting; typically, we are much more interested in the short-run dynamics of social systems, especially if the time scale of the "long run" is unspecified, as is usually the case.

Because of these reasons, it turns out that purely analytical game-theoretical models, although rigorous, are often difficult to test empirically, leading to the gap between theory and empirical research sketched at the start of this section. One of the core goals of this book is to demonstrate how computational approaches—that is, computer simulation—can be used to close this gap between abstract models and empirical reality. In the social sciences, computer simulation is increasingly used as a theoretical tool to study complex systems (Cederman 2005; Epstein 2007; Gilbert and Troitzsch 2005; Halpin 1999).[4]

Thus, the strategy used in this book can be summarized as consisting of the following steps:

1. First, we formulate a model, taking the form of a formalized set of assumptions that aim to account for the process under consideration (in this case, some co-evolution process).
2. Then, the model is mathematically analyzed to derive some implications from the assumptions. Typically, these implications will be in the form of characterizations of stable states of the co-evolution process. However, as explained above, these implications will more often than not be too general to directly test in empirical research.
3. Therefore, as an in-between step, we use simulation techniques to further explore the implications of the model under a wide range of conditions. The results of these simulations, hopefully, generate predictions that are precise enough to be taken to the data.
4. The final step consists of actually testing some of these predictions. As I explain in more detail below, several empirical strategies are used to test hypotheses.

The pretension of this book is certainly not to showcase this method of "computer-assisted hypothesizing" as a watertight method for solving theoretically complex problems. As will become apparent in the discussion of the various studies included in the book, this method has its problems and is not in all cases successful. Rather, the aim of the book is to demonstrate how such an approach can be applied in practice, and thereby contribute to the debate on the role of formal modeling and the use of simulation methods in the social sciences.

Also, the book should not be read as a practical guide to simulation or agent-based modeling. Other books have been written for this purpose, such as Gilbert and Troitzsch (2005). The studies included in this book were all developed as original research efforts (and most were also published as such) and are discussed here as case studies of the general approach outlined above.

In the remainder of this section, we will sketch the common key ingredients of the theoretical models used in the upcoming chapters a bit more substantively, and discuss the empirical applications and strategies that are used to test hypotheses from these models.

[4] Despite the growing popularity of simulation, a common misconception among social scientists is that simulation is used as an alternative to empirical research. It is important to realize that simulation is a *theoretical tool*, used to *derive* hypotheses that should subsequently be subjected to empirical tests.

1.4.1 Theoretical models

Within the general framework of actor-oriented and strategically interdependent modeling used throughout the book, there are many specific modeling choices to make. What are the action alternatives of the actors? How are costs and benefits of their choices determined? What do they know about the actions of other players? How rational are the actors when making these choices? The chapters in this book apply various approaches to study co-evolution of behavior in social dilemmas and social networks. Nevertheless, the chapters have a number of assumptions in common, which are briefly outlined here.

In every chapter situations are studied in which actors are involved in social dilemmas, modeled as games. Actors can choose *how* to play in these games and *with whom* to play. Their choice of with whom they will play results in a social network, that is, the links in the network consist of interactions in social dilemmas. For example, consider collaborations between researchers in projects. Researchers can choose with whom to work and how much effort to spend on each collaborative project. These choices result in a network of collaborations. In principle, we can also think of situations in which interactions in social dilemmas and relations in social networks exist independently. A neighborhood may face a social dilemma in keeping the neighborhood clean, while there also exists a network of friendship relations between the neighbors. Although this friendship network may be relevant for solving the social dilemma, and vice versa, interactions in this social dilemma and relations in the social network exist independently. Such situations are not analyzed here (see Takács et al. 2008 as an example of a model in this direction).

In choosing how to act in social dilemmas and with whom to play, actors must weigh costs and benefits. In the different models in this book, benefits are determined by the outcomes of interactions in social dilemmas. At the same time, social relations are assumed to be *costly*. The rationale for this assumption is that maintaining social relations takes time and effort, such that people want to maintain only those relations that are *worthwhile* so that the expected net benefits from these relations are positive. The exact specification of these costs and benefits differs between the chapters.

Arguments about *information* are central to many theories concerning network effects on behavior in social dilemmas. For example, the diffusion of information via social networks is often assumed to be the driving force behind network effects on cooperation (e.g., Raub and Weesie 1990). Consequently, assumptions on information also play an important role in the studies of this book. The implications of different assumptions on how the diffusion of information depends on the network are studied in Chapters 3 and 4.

The use of the terms “purposive action” and “strategic” above does not imply that actors are necessarily assumed to be perfectly rational, calculating the costs and benefits of every potential situation and fully anticipating the consequences of their actions. Given the complexity of the processes that are studied, it does not seem likely that human actors involved in these processes would be able to behave perfectly rational. For instance, perfect rationality would imply that actors in a large population would consider the potential costs and benefits of interactions with *all* other actors in the population, anticipate the reactions of these actors, and anticipate the consequences of those reactions for the other actors, the network structure, and so forth. Instead, we model actors as *boundedly* rational (Rubinstein 1998) and account for actors having limited cognitive capabilities. The different chapters use different approaches to model these capabilities. Note that this does *not* imply that we relax the assumption that actors are goal-directed in the sense that they try to maximize their *own* utility. One might instead, for example, assume that people are to some extent altruistic and are not only motivated by their own payoffs, but also by the payoffs of others (e.g., Fehr and Schmidt 1999). This would drastically change the nature of our main explanatory problem, namely behavior in social *dilemmas*. Instead, we assume that actors at least *try* to maximize their own payoffs, but may make less than perfect rational choices in doing so.

1.4.2 Empirical approach

As should be clear by now, a major goal of this book is to not only to develop theoretical models for co-evolution processes, but also to test predictions from these models empirically. To do so, we use two types of empirical research designs: *laboratory experiments* and *survey research*. While traditionally the preferred method of social psychology, experimental methods have also emerged as an important paradigm in economics (for good overviews of experimental economics, see Camerer 2003; Kagel and Roth 1995; Plott and Smith 2008). Experimental studies are less common in sociology (Diekmann 2008) but do have a long history (e.g., Burgess and Bushell 1969). In general, the advantage of experimental methods is that the researcher can purposively manipulate conditions of theoretical interest while keeping other conditions as constant as possible. This allows for direct identification of causal mechanisms that are hard to isolate in nonexperimental studies in which many other factors may confound the mechanisms of interest. Two additional advantages of experimental studies are particularly relevant for research on network dynamics.

First, laboratory experiments are well suited to study details of *individual* decision making. Theoretical models on network dynamics typically imply highly complex interdependencies between actors and at the same time make strong assumptions on actors' rationality. In this context it becomes important to study to what extent actual human behavior in complex social settings deviates from what is assumed in theoretical models and to what extent this affects the predictions from these models.

Second, experimental methods allow for relatively easy testing of hypotheses on the *macro*-level, that is, hypotheses on differences between groups or networks. In observational studies, this is often problematic because the complexity and time-consuming nature of collecting data on social relations typically imposes limits on the number of groups that can be observed. Moreover, studying network *dynamics* ideally requires longitudinal network data, which further complicates data collection. As a result, relatively few datasets are available to test theories on network dynamics (with some exceptions, such as the dataset collected by Knecht 2004 that we analyze in Chapter 5). In laboratory experiments, many small groups can be observed in detail in a relatively short amount of time and group-level conditions can be easily manipulated. In this sense, laboratory experiments provide a useful "early testing ground" for network theories.

Such considerations have led to extensive experimental literature in sociology on *exchange networks* (e.g., Willer 1999). In experimental economics, a number of experiments have been conducted that study either social dilemmas in networks or network formation processes (for a review, see Kosfeld 2004), but there are only a few experimental studies on the co-evolution of networks and behavior (Ule 2005; Corbae and Duffy 2008). Chapter 4 aims to provide further contributions on this topic.

However, experimental methods also have obvious disadvantages. Laboratory experiments typically involve highly abstract settings, use relatively small groups, and are conducted with subjects recruited from a specific subpopulation (i.e., undergraduate university students). As a result, while experiments are highly useful for testing theories "at close range," they risk lacking external validity. It is not always clear to what extent theoretical models that accurately predict behavior in the laboratory can also explain social phenomena outside the laboratory. While lacking the controlled nature of experiments, survey methods conducted in real-life settings are typically stronger in terms of external validity. In sociology, specialized survey methods have been developed to study social networks (Scott 2000; Wasserman and Faust 1994). In Chapter 5, such methods are applied to test hypotheses that are developed in the earlier chapters. By using experimental methods *and* survey methods, we aim to benefit from the strengths of both approaches. On the one hand, we are able to test theoretical predictions in a very direct way in the laboratory, while on the other hand, we can also verify that these mechanisms play a role in more natural social settings that we are substantively interested in.

1.5 Description of the remaining chapters

The approach outlined above is brought into practice in four studies that make up Chapters 2–5 of this book. The first two chapters focus on developing theoretical models for both coordination and cooperation problems, while the subsequent two chapters provide empirical tests of predictions from the models.

Chapter 2 presents a theoretical study of coordination in dynamic networks, that is, situations in which actors not only have a preference to behave as their interaction partners do, but can also choose their interaction partners. A model is proposed in which actors play coordination games with multiple interaction partners (i.e., in networks), but can also choose the partners with whom they interact. We study two types of outcomes in this model. First, emerging behavior and networks might lead to inefficient outcomes for the reasons sketched above. Second, the network might become segregated because actors who do not behave similarly choose to give up their relationships rather than adapt their behavior.

Although possible stable states of the co-evolution process can be characterized analytically, there is typically a large variety of stable states. Therefore, we conduct a simulation study to investigate how emerging network structures and conventions depend on the following: the level of risk in the coordination game, the cost of maintaining relations, and the initial conditions (in terms of the properties of the initial network structure and initial propensities for choices in the game). The results of the simulation provide *predictions* in which network structures and conventions are more likely to emerge under various conditions.

In Chapter 3 the attention is shifted to *cooperation problems*. A common finding in sociological research is that cooperation in social dilemmas is more likely if interactions are embedded in cohesive social networks. It is argued that cooperation is promoted through mechanisms of reputation, social control, and learning. An underlying (and often implicit) assumption in these explanations is that networks are exogenously imposed on the actors and are not subject to change. In this chapter we relax that assumption and study a model in which actors play dyadic Prisoner's Dilemmas while also choosing their interaction partners, so that behavior and social networks co-evolve. Can cohesive networks *and* cooperation co-evolve? Is an exogenously imposed cohesive network a condition for cooperation, or are cohesive networks a *result* of high levels of cooperation? We study these questions using a formal model in which actors are modeled as boundedly rational and base their decisions to cooperate with a given partner on their expectations of the partner's behavior. At the same time, they build or dissolve interactions based on the expected utility of these interactions. To form expectations, actors learn from their own experience as well as from third-party information (i.e., reputation), which spreads through the network. After obtaining some basic analytical results on stable states in this model, we apply computer simulations to study the dynamics of the process in detail.

The following two chapters show how the models developed in the previous two chapters can be tested empirically with the help of simulation techniques. We thereby focus on predictions from the model on *coordination* (Chapter 2). In Chapter 4 the results of a laboratory experiment are described, which tests a number of hypotheses from Chapter 2. In addition, a number of new hypotheses are developed, which focus on the effects of the *availability of information* on emerging behavior and stable networks. The model of Chapter 2 assumes, as is common in the literature, that actors are informed about the behavior of *all* other actors in the population. This assumption is obviously unrealistic, especially for larger populations, and is somewhat at odds with the motivations to study *local* interaction. Therefore, in Chapter 4, we relax this assumption and study a more general model in which actors are informed about the behavior of only a *part* of the network. We compare two variants in particular: the case in which actors are informed about the whole population ("global information," as in Chapter 2) and the case in which actors are only informed about their direct neighbors ("local information").

Following the development of theoretical models on coordination in dynamic networks (Chapter 2) and the experimental tests of these models (Chapter 4), Chapter 5 studies coordination problems again but this time uses an empirical setting outside the lab. We use longitudinal survey data on networks in school classes to study the development of alcohol use among adolescents. We argue that the choice to use alcohol in this setting resembles a coordination game. Based on this argument, hypotheses derived in the earlier chapters are tested again.

Chapter 6 summarizes the results of the preceding chapters and evaluates the merits of the general analytical approach used in the book. Also, we discuss possibilities for both theoretical and empirical future research.

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